MNE7

Access to the Global Commons

Space: Dependencies, Vulnerabilities and Threats

AUTHORISATION

This document has been produced by the United Kingdom's Development, Concepts and Doctrine Centre on behalf of the Multinational Experiment 7 (MNE7) Community. Comments on factual accuracy or proposals for amendment are welcomed by the UK MNE7 Space Subject Matter Expert at:

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SPACE: DEPENDENCIES, VULNERABILITIES AND THREATS

CONTENTS

CHAPTER 1 – MULTINATIONAL EXPERIMENT 7: SPACE

101. **The Multinational Experiment Process**. Sponsored by the United States Joint Staffs J7 Joint and Coalition Warfighting organisation, the Multinational Experiment (MNE) series of events has been running since 2001. Each 2-year experiment is designed to examine a topical defence and security issue and MNE 7 (the latest in the series) is focussed on access to the global commons. The experiment involves 17 participating countries and NATO and runs until December 2012. For MNE 7, the global commons are considered to be:

Global Commons

Areas that are potentially accessible to any and all actors be they states, non-state, or individuals. Although this term is generally applied only to ungoverned access pathways between sovereign spaces or those areas that are outside the jurisdiction of any nation, MNE 7 will also address areas that fall under some degree of national sovereignty when they are relevant to ensuring access to and freedom of action within the global commons.

Global Commons Definition: MNE 7 Campaign Plan Lexicon

MNE 7 Problem Definition

102. Within the overall global commons theme, the specific problem being considered by MNE 7 is:

MNE 7 Problem Definition

Nations and organizations require concepts and capabilities for anticipating, deterring, preventing, protecting against and responding to a disruption or a denial of access to the global commons domains (air, maritime, space and cyber) and for ensuring freedom of action within them, while taking into account their interrelationships.

103. Three environmental workstrands were agreed during the initial experiment setup meetings; maritime, space and cyberspace. The space workstrand addresses the following 3 objectives:

a. Identify dependencies on, vulnerabilities of, and threats to space capabilities.

b. Identify mechanisms to deter, coerce or influence space actors.

c. Develop proposals for mitigation if deterrence fails.

104. Within the participating nations and NATO, Canada, Switzerland, the United Kingdom, NATO Allied Command Transformation (ACT), Poland, South Korea, Sweden and the United States agreed to contribute to the space workstrand, with the United Kingdom leading the first objective, NATO ACT the second and Canada the third. This handbook is the output of the first objective and describes military and civilian dependencies on space capabilities, the vulnerabilities of such systems and the threats that they face. The handbook is unclassified and its target audience is anyone in government, military or civilian organisations who uses, or benefits from, the services provided by space systems. This edition is provided for all MNE 7 participants, who are free to incorporate elements into their own concept and doctrine publications or to publish it for national use as a stand-alone document. The output of the 2 additional workstrands described above may be incorporated into a second edition of this handbook, available by the end of 2012.

105. **Methodology**. The document was produced following study and analysis of a range of existing publications, including:

a. DCDC's, *The UK Military Space Primer*.

b. The Joint Airpower Competence Centre Space Operations Assessment.

c. The MNE 7 Baseline Assessment.[1]

d. The Schriever Wargame unclassified reports.

e. International conference and seminar outputs.

The handbook also included input from civilian and military subject matter experts across the United Kingdom, including the Defence Science and Technology Laboratory. Following initial drafting, the document was reviewed and amended at an MNE 7 Workshop held in London from 12 - 14 October 2011. As such it represents the combined view of the MNE 7 Space workstrand contributing nations.

HOW TO USE THE HANDBOOK

106. **Purpose and Structure**. This handbook is aimed at audiences working in a disparate range of military and civilian, specialist and generalist areas, including policy makers. Some will have considerable experience of space related issues, while others have none, so a main body of text has been created to act as a basic primer. This enables users to develop a basic, but sufficient, understanding of the key capabilities that space systems can provide, while also describing mitigation methods and the potential impacts of loss of space services. Note that a space system includes the ground element, the space element and any supporting links and networks. An important factor in developing an awareness of the limitations of space systems is understanding the different orbits that are available; hence Chapter 2 describes the main orbit types, together with their advantages and disadvantages. Chapter 3 describes what space systems can do, so that the reader can relate these activities to their own specific area of interest and develop an understanding of their own dependencies. Chapter 4 then describes the generic vulnerabilities, hazards and threats relating to space systems so that the reader can again apply this knowledge to their own specialist area. Throughout, where key terminology or concepts are introduced for the first time, the descriptive title is in **bold**, to help the reader easily locate such items.

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[1] The initial MNE 7 investigation into space issues included the production of a baseline assessment into legal norms and practices in space.

107. **Case Studies**. The handbook includes 8 case studies. These illustrate how the information presented in Chapters 2 to 4 is applied in the real world. Some capabilities occur repeatedly throughout the case studies indicating they are key capabilities. The role of space as a communications bearer and provider of accurate timing data, for example, occurs in nearly every case study. The 8 examples used are:

a. Agriculture.

b. Disaster Monitoring and Relief.

c. Civil and Military Maritime Operations.

d. Theatre Missile Defence.

e. Operating in Space.

f. Mineral and Oil Prospecting.

g. Time Sensitive Targeting & Close Air Support.

h. Support to Governance & Security in Remote Districts.

108. **Case Study Methodology**. The case studies take the form of a simple diagram illustrating the main elements of the activity under consideration. Breakout boxes then list relevant supporting services provided by space systems. Against each service, a simple traffic light system is used to indicate the level of dependency that exists on space within the overall process of successful service delivery. Several criteria are evaluated to determine the allocated colour: initially, the ability to use alternate technology and the time period over which the activity can tolerate the loss of space services are considered. This is illustrated in Figure 1.1:

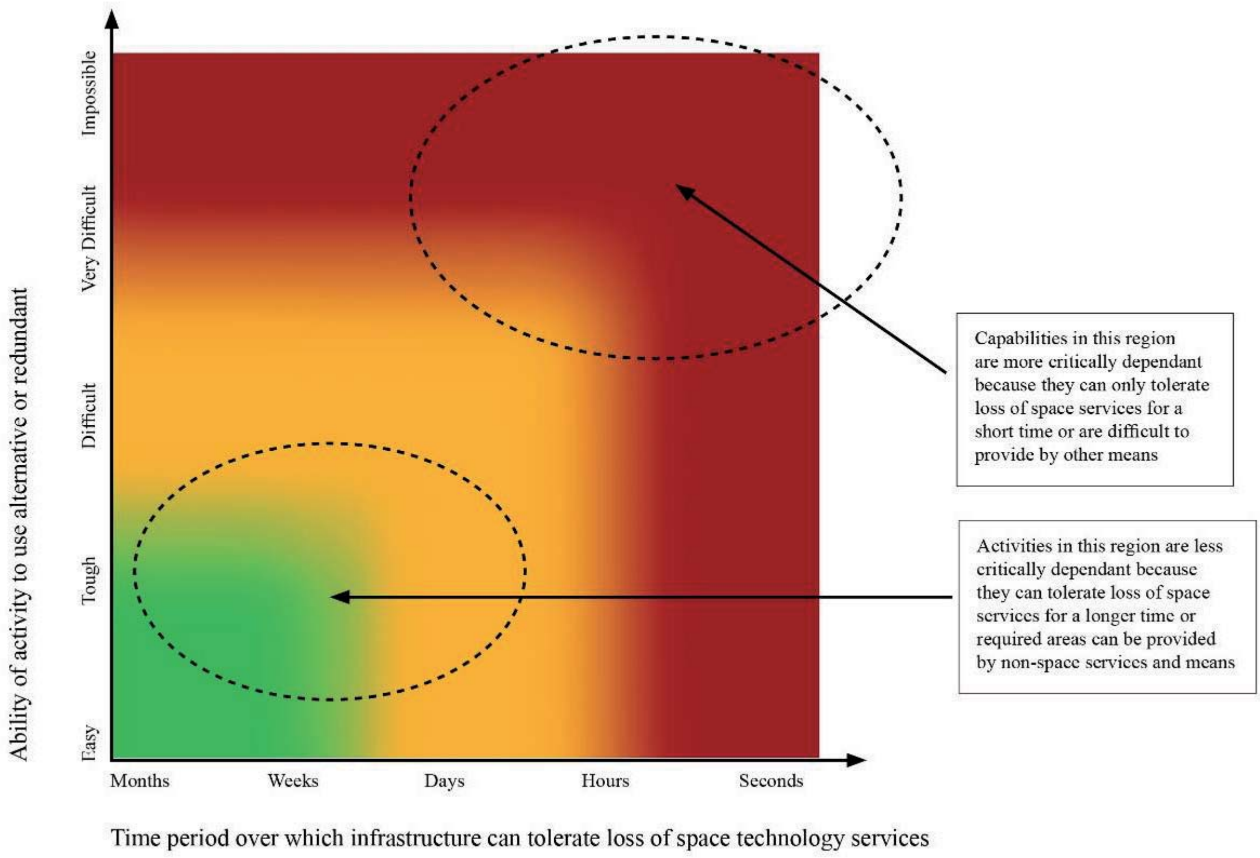


Figure 1.1 – Methodology For Determining an Activity's Dependency on a Space Service

109. Other specific factors are then considered: for example in the commercial sector, the commercial viability or level of profitability of an activity may be dependent on access to space services. For each case study, the level of each dependency was agreed by the MNE7 Space Subject Matter Expert grouping during the main handbook development workshop; as such, it represents their view of the dependency at a generic level. The reader should use the indicated levels as a starting point for considering the values they wish to assign to their own particular application. This will vary from country to country and organisation to organisation, depending on how critical a particular function is or what alternative backup systems may be in place. The resulting assigned levels would be a useful starting point for any further study which aimed to conduct a numerical analysis, as described at the end of Chapter 3.

A NOTE ON SPACE LAW

110. Most of the law relating to space activity is based on international treaties, rather than on customary law or teaching by scholars. The key treaty is the **Outer Space Treaty** of 1967. As of 1 January 2008, 98 nations, including all the major space-faring states, are parties to the treaty, while a further 27 have signed, but not yet ratified. The key provisions of the treaty are as follows:

111. **Weapons of Mass Destruction**. The treaty prohibits the placing of any WMD, including nuclear warheads, in orbit around the Earth. It does not prohibit the stationing of conventional weapons in orbit, nor does it regulate nuclear weapons that pass through space without achieving orbit.

a. **Other Weapons and Military Activity**. The establishment of military bases, testing of weapons of any kind, or conducting military manoeuvres on the Moon, or any other celestial body, is forbidden. The treaty does not, however, limit such activity in Earth orbit.

b. **Sovereignty**. A launching nation maintains sovereignty and jurisdiction over any activity occurring in a manned spacecraft, and a satellite remains the property of its owner.

c. **Peaceful Use**. An overarching aim of the treaty is to promote the peaceful use of space for the benefit of all mankind. There is nothing in the treaty, however, that prohibits military activities such as reconnaissance, missile warning, space surveillance and the use of terrestrial weapons that rely on space capabilities.

112. **Other Space Related Regulations**. The following examples illustrate some of the more commonly encountered laws and conventions:

a. **Rescue Treaty**. The 1968 Rescue Treaty commits signatories to assist in the rescue of spacecraft personnel where able, the retrieval of space objects outside their territory of origin and covers the safe return of people and property to their original owners.

b. **Liability Convention**. This convention renders states liable for damage to people or property caused by their space activities, whether caused in space or on the Earth, and sets out rules regarding liability. Generally, the launching state is responsible for any damage resulting from a launch carried out from that state.

c. **The Registration Convention**. The Registration Convention established a UN register of space objects. As a result, launching nations must create and maintain a public register of orbital elements for objects placed in orbit, and separately notify the UN of such actions. Unfortunately, different nations interpret the convention in different ways and the amount of detail registered varies. As with many issues relating to behaviour in space, there is no enforcement mechanism to ensure compliance.

d. **Limited Test Ban Treaty**. This treaty specifically bans nuclear explosions in space, at least in peacetime. (France and China are not signatories).

e. **Allocation of Geostationary Orbits**. Since a geostationary orbit (see Chapter 2, page 2-6) has a fixed view of the Earth, the limited number of 'stations' above populous areas are particularly valued. Since the vast majority of geostationary activity relates to communications and wide area broadcast functions, the allocation of the orbital slots is coordinated and controlled, by mutual agreement, by the International Telecommunications Union, which is a UN agency.

113. **Debris Mitigation**. The Inter-Agency Space Debris Coordination Committee (IADC), formed in 1993, has laid out Mitigation Guidelines as follows: limit debris release during operations; minimise the potential for spacecraft and rocket body break-up; limit the probability of accidental collision on orbit; avoid intentional destruction and other harmful activities; minimise potential for post-mission break-up; limit the presence of spacecraft in low Earth orbit at the end of mission; and re-orbit satellites above the geostationary orbit at the end of mission.

CASE STUDY 1 – SPACE AND AGRICULTURE

The continuous growth of the world's population requires increasingly efficient agricultural processes to meet the demand for food; these are becoming more and more dependent on space capabilities. Although crops and animals have been raised for millennia without help from space, the capabilities provided by space assets can greatly improve the efficiency of nearly all aspects of food production. This case study breaks the agricultural process into 5 steps; Earth Observation, Cultivation, Processing, Distribution, and Selling. It then provides a qualitative assessment of the contribution made by (and hence dependency on) space capabilities to each step.

Observe

Space is now used to observe the planet to help with crop location. Observation satellites can be used to map (and locate) water and minerals, to record temperature, humidity, and wind velocity, to ensure compliance with local agriculture policy, and to plan the future. There is low dependency on space for the location of minerals and recording of humidity; moderate dependency for the location of water, recording of temperature and wind velocity, and for future planning. Verifying compliance has a significant dependency on space due to the unique view space provides through imaging satellites. Groups and states can also monitor the ground situation and actions of other groups and countries.

Cultivate

Weather forecasting capability is greatly enhanced and moderately dependant on space. From imagery of weather masses to temperature, wind, and rain monitoring, farmers are better able to respond to changes in weather. The Positioning, Navigation and Timing (PNT) capability provided by such systems as the Global Positioning System (GPS) allows for efficient crop spraying, especially by aircraft which reply on GPS for navigation. PNT also increases the efficiency of harvesting.

Process

During the processing of food, enabling utilities and the supporting supply chain have dependencies on space. Generation and distribution of electricity and fuel have significant dependency on space to include PNT communications and Intelligence Surveillance and Reconnaissance. Space Situational Awareness (SSA) has a small, but important, role to play in providing warning of possible national grid induction effects caused by space weather. The supply chain has a moderate dependency on PNT and communications to ensure the required logistic support is provided to the processing plants and includes the tracking, monitoring, and navigation of ships, railways, and road transportation.

Distribution

Distribution dependencies range from low to significant. For example, fleet management on the land has low dependency on PNT. In the land domain, there is a moderate dependency on communication to include the Global System for Mobile Communications network which may have some reliance on space-derived timing for correct operation.

In the maritime domain the dependency becomes more important. PNT dependency increases to moderate, especially in position and navigation. Space communications are used more regularly. There is significant dependency on space for weather forecasting and safety.

Selling

Although not intuitively obvious, there is a moderate dependency on space in the selling of agricultural produce. PNT may be used during transactions and by the banking system during the electronic sale of goods. Satellite communications may also be used during the electronic transfer of funds.

Summary

This case study covers just some of the ways agriculture is dependent on space. It is intended as a guide to prompt the reader to think about other ways in which space may influence agricultural activity. Additionally, this case study should be used to stimulate thinking about agriculture dependencies on the cyber and maritime domains.

Space and Agriculture

Dependency

- Low
- Moderate
- Significant

- Water
- Minerals
- Temperature
- Humidity
- Wind Velocity
- Compliance
- Planning/Futures

- Weather forecasting
- Water Content
- Temperature

Navigation:

- Crop Spraying
- Harvesting

- Utilities
- Supply Chain

Land

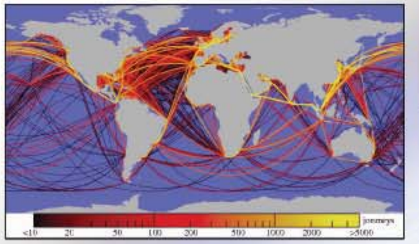
Fleet mgt:

- Position
- Navigation
- Time
- Comms (inc GSM)

Maritime

- Weather Forecast
- Position
- Navigation
- Time
- Comms
- Safety

- Timing
- Comms



Observe → **Cultivate** → **Process** → **Distribute** → **Sell**

CASE STUDY 2 – SPACE SYSTEMS USAGE IN DISASTER MONITORING AND RELIEF

Space systems play a vital role in the forecasting, warning and monitoring of many different kinds of disasters including:

- Earthquakes and resultant tsunami
- Strong winds
- Flooding
- Accidents at industrial installations e.g. nuclear power stations
- Volcanic activity
- Chemical spills (sea/on land)
- Forest and bush fires
- Unexpected and rapid refugee movements

The 1999 International Charter on Space and Major Disasters, originally an initiative of the European Space Agency and the French Space Agency, aims to provide relief organisations with satellite data support in the event of major disasters. Canada joined in 2000 and subsequently a range of organisations including, amongst others, the US Geological Survey, the British National Space Centre (now the UK Space Agency), the National Oceanic and Atmospheric Administration and the national space agencies of Japan, China, India and Nigeria. In the event of a major disaster, the charter can be invoked to provide satellite data from a wide range of space systems. Recent events that have used data from this source include; Haiti in 2010, the New Zealand earthquake relief effort in 2011 and the 2011 Japanese earthquake and tsunami. This case study breaks disaster support into 3 phases; preparation, execution and recovery. It provides a qualitative assessment of the dependency of each on space support.

Preparation

Preparation includes 3 sub-elements; monitor, predict and prepare. For *monitoring* the Earth prior to a disaster, space systems can provide information on meteorology, geomatics,[2] population disposition and space weather. There is a low dependency on space for data on population disposition, as this information can be provided (albeit more slowly) by ground-based organisations. There is a moderate dependency on space for

[2] Geomatics is the discipline of gathering, storing, processing and delivering geographic or spatially referenced information.

the collection of geomatic data and a high dependency on space for the collection of meteorological and space weather data. *Predict* has a moderate dependency on space to provide data that can be used to populate models and simulations. There is a high dependency on space for those models that are used to predict meteorological and space-weather events. *Prepare* requires supporting logistic chains that will have, at best, a low dependency on space as they will rely on provision of PNT for efficient operation. Command and control systems will have a moderate dependency on space for communication links.

Execution

The execution phase includes the previous 2 elements (monitor and predict) with the addition of a report and warning element. During a disaster, it is very likely that earth-based infrastructure will be disrupted and hence dependency on space for ground-truth data will increase. *Monitoring* a disaster will therefore have a high dependency on space for meteorological and space weather and a very high dependency on space for rapid provision of relevant geomatic data. During some events, space may be the only source of updated mapping and geographic data. *Predict* will require space derived data to update predictive models and help with updating earlier planning. The *report/warn* element will have a moderate dependency on space – particularly for communications as disruption or destruction of ground-based communication systems is likely.

Recovery

The *operations support* element of this phase will have a high dependency on space for logistic support due to disruption of ground systems and a moderate dependency for movement. The *execute/sustain* element will have moderate dependency for tactical execution, particularly for communications and updated intelligence. Reachback may have a critical dependency on space communications and hence will have significant dependency on space. The longer term aspects of rebuild will likely require support from a range of space products to be effective and efficient. *Recovery* of personnel and materiel will have a moderate dependency on space to support the logistics and movement functions.

Disaster Monitoring and Relief

Monitor
- Meteorology
- Geomatics
- Population
- Space Weather

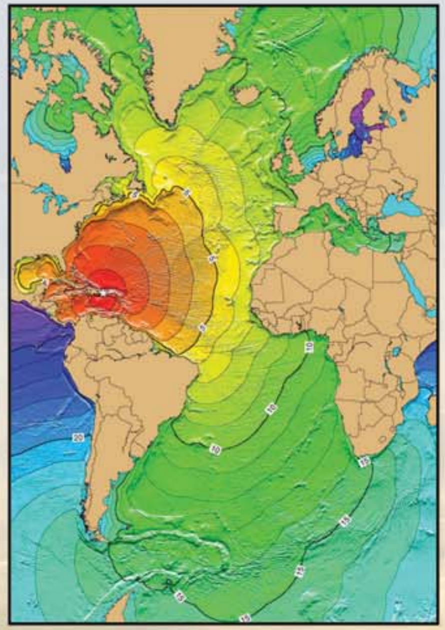
Predict
- Modelling and Simulation
- Data
- Meteorology
- Space Weather

Prepare
- Command & Control
- Logistics

Monitor
- Meteorology
- Geomatics
- Population
- Space Weather

Predict
- Modelling and Simulation
- Update prediciton
- Update plan

Report/Warn
- Command & Control
- Advance Party



Ops Support Planning
- Logs
- Movement

Execute/Sustain
- Tactical Execution
- Reachback
- Rebuild

Recover
- Logs
- Movement

Dependency
- Low
- Moderate
- Significant

Prepare → **Execute** → **Recover**

CHAPTER 2 – SPACE FUNDAMENTALS

201. **Understanding Orbits**. This Chapter gives a brief overview of the unique physical characteristics of space and the different kinds of orbits that satellites can operate in. It summarises the advantages and disadvantages of each orbit type and their effect on a satellite's capability.

This section discusses:

- What is space? Where does it begin?
- The different orbit types and the kinds of satellites that use them.

THE BOUNDARY BETWEEN AIR AND SPACE

202. **Where does Space begin?** While various definitions for the start of space have been proposed (from fixed altitudes above the Earth to others based on orbital mechanics) international law does not define an absolute figure. One example defines the lower boundary of space as the lowest **perigee** (the closest point of a satellite's approach to earth) attainable by an orbiting space vehicle. This is not particularly helpful as there is no indication as to where this may be in practice. In fact, there is no clear natural physical boundary between the atmosphere and space. Beyond 100,000 ft (30 km), air density decreases to the point where conventional aviation becomes impossible; only as altitude is increased toward 100 km does atmospheric drag and frictional heating reduce to the point where satellites become practical. Some commentators therefore quote 100 km, also known as the **Karman Line**, as the boundary that marks the start of space; the 70 km gap between conventional aviation and space is sometimes referred to as **near-space**. In practice, there are few satellites in orbit below 150 km. Note that by international law, aircraft, missiles and rockets flying over a country are considered to be in its national airspace, regardless of their altitude. Orbiting spacecraft, on the other hand, are considered to be in space, even though their altitude may sometimes be less than that achieved by rockets and missiles. This is why space may be regarded as a global

common – spacecraft have free access to the space over any country, regardless of national boundaries.

203. **Orbital Altitudes Drawn to a Common Scale**. The diagram below shows the various orbital altitudes drawn to a common scale with the Earth. Almost all satellites (and space debris) are in low-earth orbit, which is much closer to Earth than is generally realised. The box on the right expands the lower portion of low-earth orbit, to put it in context with other aspects of aviation. Each different orbit is described later in this chapter.

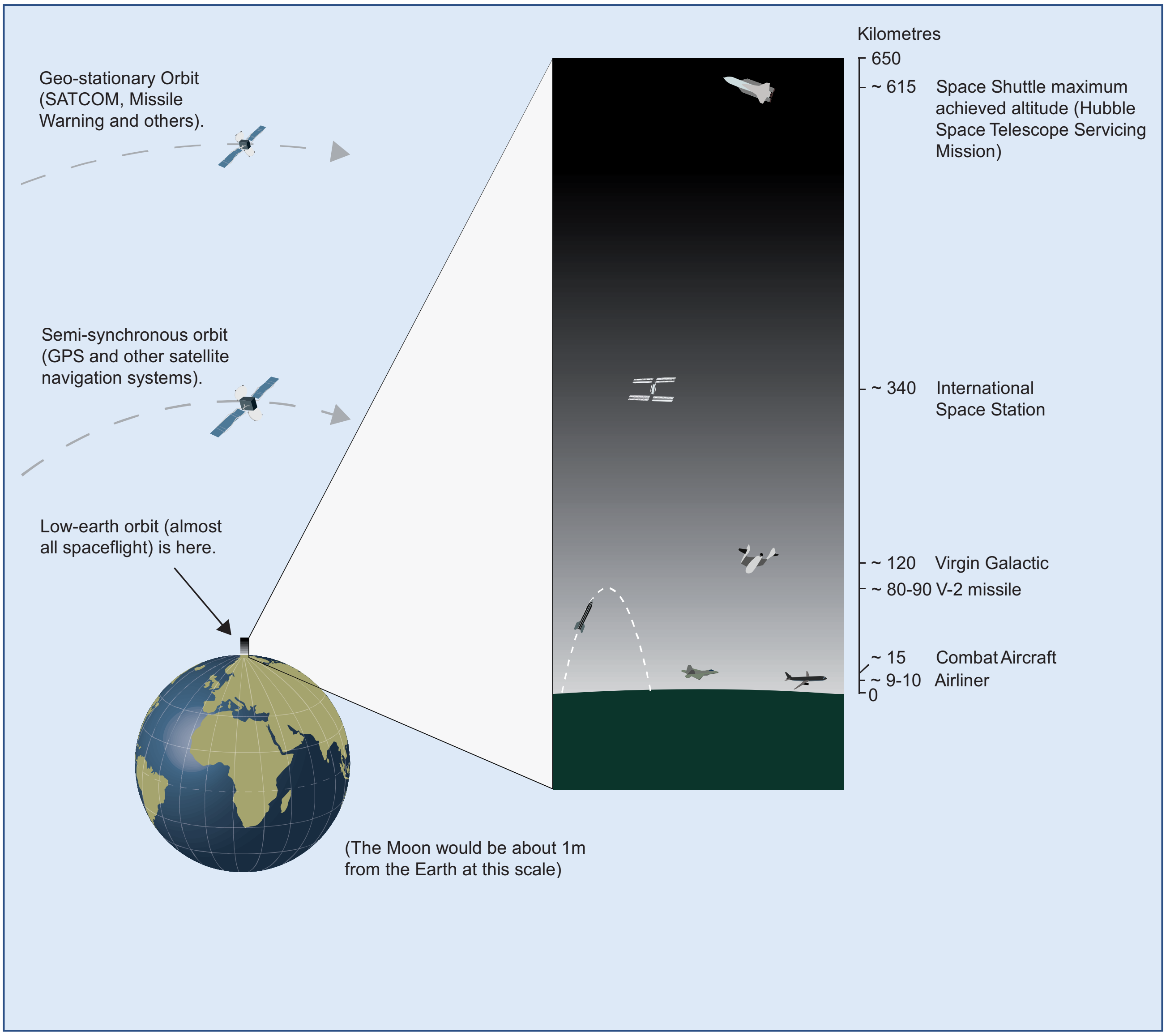


Figure 2.1 – Summary of Orbital Altitudes to a Common Scale

204. **Why Space is Different**. As atmospheric drag reduces from minimal in low orbits to zero in higher orbits, a satellite can be built in any shape or size, although it is likely that parts of it will have been folded in close to the main body during launch so that it will fit inside the launch vehicle. To achieve and maintain a circular orbit the speed of an object needs to be about 28,000 km per hour, at a minimum practical altitude of around 150 km. Even here, there is still sufficient atmospheric drag to cause a satellite to fall to earth after only a couple of orbits unless it is frequently firing its engine. As a general rule, once the perigee of any orbit reaches 560 km or more, the drag becomes negligible and a satellite will normally malfunction for other reasons before the orbit decays. After a satellite is placed into an initial orbit, rockets or thrusters are then used to position it into its final orbit. These thrusters will also be used to keep the satellite in the correct orbit throughout its life, as a number of factors (including the fact that the Earth is not a perfect sphere and its mass is not uniformly distributed) will tend to change its orbit over time. The finite amount of fuel available to conduct such **station keeping** is a major factor in the overall lifetime of a satellite.

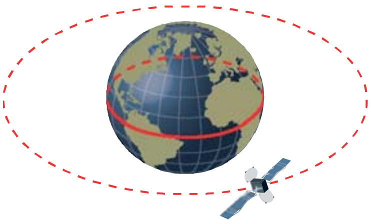
ORBITS AND GEOMETRY

205. **Geometry**. Satellites, like planets, move predictably according to Kepler's Laws.[1] These determine all of the parameters of any particular orbit, including the time taken for one complete orbit, known as its **period**, and its speed at any particular point on the orbit. For a circular orbit, the speed of the satellite will be constant, while for an elliptical orbit the speed will change constantly, being fastest at perigee and slowest at **apogee** – its furthest point from the earth. In accordance with Kepler, as the altitude of a satellite in a circular orbit is increased, its period will increase and speed decrease in proportion. Thus there are an infinite variety of possible orbits and the one chosen will depend mostly on the satellite's mission, possibly limited by the latitude and location of the launch site. Most orbits will involve an element of compromise and once achieved, significant further changes are expensive to make in terms of fuel and hence, satellite life.

[1] Kepler's laws are: The orbit of every planet is an ellipse with the Sun at one of the two foci; a line joining a planet and the Sun sweeps out equal areas during equal intervals of time; and the square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit.

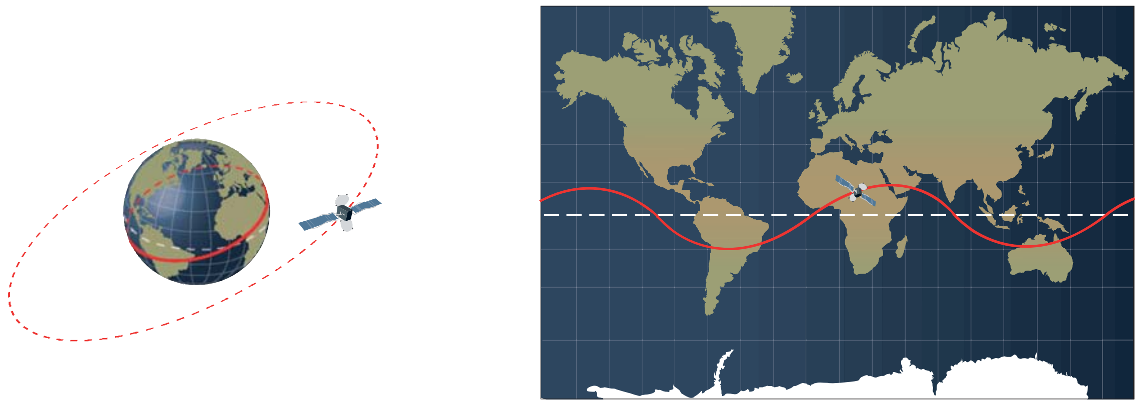
206. **Other Orbit Considerations**. All practical Earth orbits are elliptical or circular - in geometric terms a circle is simply a special type of ellipse. Moreover, the laws of physics dictate that the earth's centre will always be at one of the foci of the ellipse and so, although a satellite can orbit the earth at any angle, the 2-dimensional plane of its orbit will always pass through the centre of the earth. This means that a satellite cannot hover over a particular spot, or follow a line of latitude. Note, however, the special case of a geostationary orbit, described later, where a satellite will appear to hover over a fixed point on the equator. The angle between the plane of the orbit and the equator is called the **inclination**. The **ground track** of a satellite is the trace of its path across the surface of the Earth. If the Earth did not rotate, the ground track would simply repeat itself. However, since the Earth rotates once per day, or 15° per hour, each successive orbit will be offset 15° to the west for each hour of the satellite's period. The inclination of an orbit determines the highest north and south latitude of the ground track. Since all satellite orbital planes pass through the centre of the Earth, an inclined circular orbit will spend equal times north and south of the equator. These concepts are illustrated below:

Ground Track for a Circular, Equatorial Orbit



The satellite above is in orbit over the equator. For a low-earth orbit, its period will probably be in the range 90-120 minutes and its path will lie above the equator.

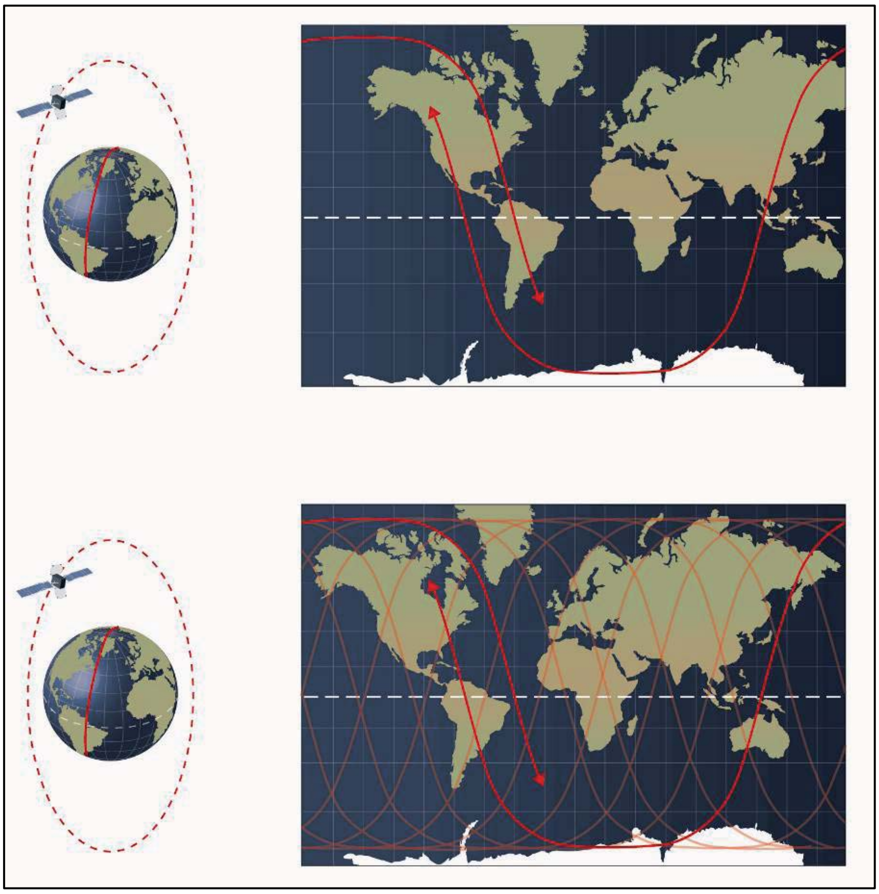
Ground Track for a Circular, Inclined Orbit



The satellite illustrated above is in a circular, inclined orbit. It will spend half its time over the northern hemisphere, and half over the southern hemisphere. The satellite orbit is inclined at 20º to the Equatorial Plane, and the ground track is restricted to lie between latitudes 20ºN and 20ºS.

207. **Low-Earth Orbit**. There is no formal definition of **Low-Earth Orbit (LEO)** but it is generally considered to have an apogee of no more than 1000 km. Inclination can be any angle. At low altitudes, atmospheric drag will limit a satellite's life unless it is periodically boosted into a higher altitude. Operational life will then be dependent on the amount of fuel available. At an altitude of 320 km, without any boosting, life would be expected to be around one year, increasing to around 10 years at 800 km. LEO is ideal for observation, environmental monitoring, small communications satellites and science instrument payloads. Manned orbital satellites, such as the **International Space Station**, generally remain below 500 km to prevent the need for heavy shielding to protect the crew from **Van Allen belt radiation**. Satellites in LEO have the advantage that they pass relatively close to the Earth, so they can use less powerful sensors and transmitters, but will only be in the view of a ground user or station for the short period of time when overhead. For this reason, for some applications it is usual to provide a **constellation** of several satellites spaced around the same or similar orbits to provide continuous coverage. A satellite in circular LEO orbit with an altitude of 850 km will travel at a speed of 24,600 km per hour and have a period of 101 minutes.

Ground Track for a Circular, Highly-inclined (near-Polar) Orbit



The upper illustration shows a single orbit of a satellite in a circular, highly-inclined orbit. Since the Earth rotates by 15° per hour, on each subsequent orbit, the ground track is displaced. The lower illustration shows several consecutive orbits overlaid on the Earth. Eventually, the orbital path may repeat. The orbital altitude (and thus the period) can be adjusted to control whether and how often this happens.

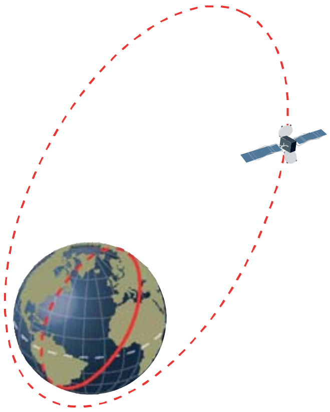
208. **Sun-Synchronous Orbit**. A special case of a LEO is the **sun-synchronous orbit**; it is orientated in such a way that the 'sun-time' at any given point on the Earth is the same each time the satellite passes over it. Thus the illumination level at each pass will be the same, which makes change detection between passes much easier. Some weather and remote sensing environmental satellites use this orbit.

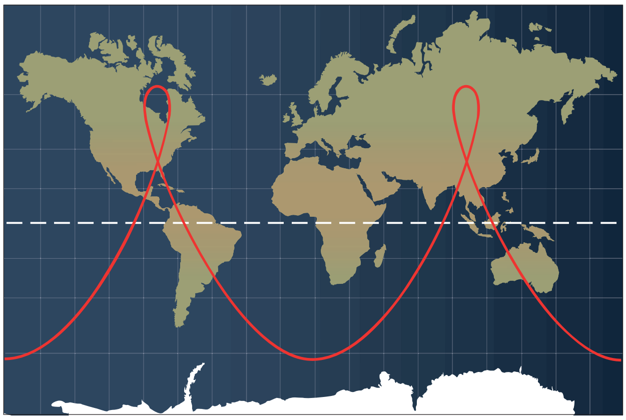
209. **Medium-Earth Orbit**. Again, there is no formal definition of Medium Earth Orbit (MEO), but by convention it is considered to include those orbits between LEO and geostationary orbit. A **semi-synchronous orbit** is a special case of a MEO which has an inclined, nearly circular, orbit which repeats an identical ground trace twice each day; hence the term semi-synchronous. A satellite in a semi-synchronous orbit will have an altitude of around 20,830 km, a speed of around 14,330 km per hour and a period of around 12 hours. The Global Positioning System satellites use this type of orbit (see Chapter 3).

210. **Geosynchronous and Geostationary Orbit**. A **geosynchronous** orbit has a period equal to that of the Earth's rotation - one day. A geosynchronous satellite can have any inclination and will have an altitude of approximately 36,000 km. Varying the inclination of the orbit produces ground traces that fluctuate north and south of the equator in a figure of eight pattern; the larger the inclination, the larger the figure of eight. Some kinds of communication, weather and surveillance or warning satellites use geosynchronous orbits. A **geostationary** (GEO) orbit is a special kind of geosynchronous orbit where the inclination is zero and the orbital plane coincides with the Earth's equatorial plane. To an observer on the Earth, the satellite appears to be stationary in space. The most significant advantage with this orbit is that the satellite provides continuous coverage of specific areas of the Earth and ground antennas do not need to track the satellite. GEO orbits are used extensively for communications, weather and some earth observation activities. Coverage only extends to about 70° north and south of the equator, so alternative orbits will be required if coverage is required in the Polar Regions. In GEO, a satellite will have an altitude of 37,160 km, travel at 11,120 km per hour and have a period of approximately 24 hours.

211. **Molniya Orbit**. Another useful orbit is the Molniya orbit – a special case of a highly elliptical, semi-synchronous orbit. A satellite in this orbit spends 11.7 hours of its 12 hour orbital period in the northern hemisphere. This makes the Molniya orbit well suited for communications satellites intended to provide coverage in the extreme north, where access to GEO is impracticable.

Ground Track for an Elliptical, Inclined Orbit





In accordance with Kepler's Second Law, the speed of a satellite in an elliptical orbit will change throughout its path. This greatly changes its path over the Earth during its orbit; it may at times be rotating faster than the Earth, at other times slower, so its path may at times appear to change direction, and its apparent motion seen from the surface may at times be almost stationary, at other times rapid. In the example shown above, the two tight loops over Canada and Central Asia will take longer than the wide arcs over the southern oceans. This feature has great practical utility as a few satellites spaced around this orbit will give continuous coverage over the northern hemisphere.

CASE STUDY 3 – MILITARY AND CIVILIAN MARITIME OPERATIONS

Effective and efficient co-ordination of military and civilian maritime operations has an increasing dependency on space support, ranging from moderate to significant. Specific aspects of operations may, depending on the urgency of the mission, have a critical dependency on space. This case study breaks down maritime operations, as a process, into five distinct (but in practice often overlapping) functions. These are: Surveillance, Data Collection, Analysis, Planning and Execution. Elements of this process may be considered recursive.

Surveillance

Surveillance from space can provide physically sensed information on ship location by using visual, synthetic aperture radar or infra-red techniques. Additionally, satellite communication systems can be used to rebroadcast or pass digital location information to data collection centres. Space systems can also remotely monitor cluttered littoral and port areas, although the usefulness of the data collected will depend to a considerable extent on the resolution that is available. Additionally, space systems continually survey the oceans (and land) for manually deployed or automatic radio distress signals, and are able to automatically calculate the source of signals or, as is more likely with modern systems, automatically relay GPS coordinates of distressed shipping to regional safety coordination centres. The shipping location, port and littoral surveillance, and safety functions all have a moderate dependence on space. Surveillance of weather systems and collection of meteorological data, a key enabler of maritime operations has a significant dependence on space systems.

Data Collection

Data collection for intelligence and situational awareness purposes is routinely conducted using space systems and there is some overlap with the previous surveillance function. As well as shipping location, maritime operations have a moderate dependency on space for provision of Automatic Identification System (AIS) data and specialised intelligence gathering (details of which are beyond the scope of this document). The AIS is an automatic tracking system used on ships and by vessel traffic services for identifying and locating vessels by electronically exchanging data with other nearby ships and AIS base stations. Previously limited to surface systems with associated line of sight limitations, the system's utility is being considerably extended by the use of satellite monitoring to extend coverage across wide areas. The data collection function has a significant dependency on space for the collection of weather data, including ice flow position data, which may be of critical importance to some maritime operations.

Analysis

The analysis function has a moderate dependency on space for the provision of location, course and speed and intent data. Additionally, there is a moderate dependency on space for estimation of risks to shipping or operations. The analysis function shares common features with, but is distinct from, the data collection function. There is a significant dependency on space for ship status data, particularly the provision of timely data during search and rescue operations.

Planning

The planning function has a moderate dependency on space for asset coordination, evaluation of the environment and the preparation of tasking.

Execution

The execution function has a moderate dependency on space for coordination, tasking and weather data collection tasks. The first two of these require capable space based communication systems. When operations are complex, or have an element of time sensitivity, tasking and coordination may have a significant or even critical dependency on space communication systems. This is particularly relevant when large quantities of data have to be passed in a timely manner.

Military and Civilian Maritime Operations

Dependency

- Low
- Moderate
- Significant

- Shipping Locations
- Weather
- Littoral and port surveillance
- Safety

- Shipping Locations
- Weather
- Ice Flows
- AIS
- Intelligence

- Location
- Course/Speed
- Intent
- Status (SAR)
- Risks to shipping or operations

- Coordination
- Evaluate Environment
- Prepare tasking

- Coordination
- Tasking
- Weather

Surveillance → **Data Collection** → **Analysis** → **Planning** → **Execution**

CASE STUDY 4 – THEATRE MISSILE DEFENCE

The Theatre Missile Defence (TMD) process consists of 4 distinct functions as shown in the diagram on page 2-15. These are; Monitoring and Detection, Tracking, Engagement, and Post Engagement Assessment and Event Management. Underpinning and common to all of these is a command, control, communication and planning function. Although illustrated as a cyclic process, the core function is monitoring and detection, which is conducted on a continuous basis, with the other functions brought into play only once activity has been detected.

C4 and Planning

The C4 and planning activity underpins the whole of the TMD concept. The specialised nature of some of the required activities undertaken to provide situational awareness and environmental monitoring, together with the need for very fast (i.e. high data rate) command and control systems means that this activity has a significant dependency on space systems. A cumulative approach to the individual systems required to support this function may lead some assessments to consider this function to have a critical dependency on space systems.

Monitoring and Detection

This function is the critical first stage of the overall TMD process. Failure of this function would mean the remaining stages of the process may not be activated. Threat prediction/identification, intelligence indicators and warnings, assessment, and warning of imminent launch have a moderate dependency on space. Launch detection of missile systems has a significant dependency on space systems, as it is only from space that the wide area coverage and timeliness required of launch detection can be achieved. Even using space based systems, timeliness is critical due to the short flight times of these missile systems and the need to give sufficient warning to target areas.

Tracking

The tracking function has a moderate dependency on space for the timely and accurate estimation of missile tracking, associated prediction and assessment activities and decision making/warning functions. Cumulatively, the Tracking function may be considered to have a significant dependency on space systems.

Engagement

The engagement function breaks down into track, predict and control/coordinate functions. Depending on the system being engaged and the characteristics of the engaging system, this may be a ground or space based activity. This function is assessed as having a moderate dependency on space systems.

Post Engagement Assessment and Event Management

Three out of 4 of the underlying activities that make up this function; Assess, Decide/Warn and Exploitation have a moderate dependency on space systems. Post engagement reporting may be conducted by space or terrestrial means and hence is considered to have a low dependency on space.

A Note on Space Based Ballistic Missile Detection Systems

Space and ground based launch detection systems are complex and expensive to operate. Hence few nations can afford this capability. Ground based systems require complex and powerful phased-array radars and, while these may provide long range warning of intercontinental missile systems, their fixed locations may have limited utility in certain operational theatres. Some modern military air defence ships have very capable radar systems that could provide mobile ballistic missile warning capability, but these are unlikely to detect launch and may thus provide insufficient warning time. Note, though, that some of these ships may have their own independent engagement capability.

Reliable launch detection over a wide area can only be provided by space based systems, such as the US *Space-Based Infrared System* (SBIRS) which consists of a number of detection packages placed in geosynchronous and highly elliptical orbits.

Theatre Missile Defence

Dependency

- Low
- Moderate
- Significant

Monitoring and Detection

- Threat Prediction/ID
- Indicators & Warnings
- Detection
- Assessment
- Warning

Tracking

- Track
- Predict & Assess
- Decide/Warn

C4 & Planning

- Situational Awareness
- C2
- Environmental Monitoring

Post Engagement Assess & Event Management

- Assess
- Decide/Warn
- Exploitation
- Reporting

Engagement

- Track
- Predict
- Control/Coord

CHAPTER 3 – SPACE-BASED CAPABILITIES AND DEPENDENCIES

301. An understanding of the basic capabilities of space systems, including ground-based elements and associated networks and data links, is important if the associated dependencies, vulnerabilities and threats are to be understood. Therefore the main part of this chapter acts as a space primer to provide the basis for further discussion.

This Section considers 4 ‘pillars’ of space capability:

- Positioning, Navigation and Timing, commonly abbreviated to PNT.
- Communications.
- Intelligence, Surveillance and Reconnaissance.
- Space Situational Awareness.

302. **Civil/Military Balance**. Due to the high development costs and security restrictions placed on the technology, early earth-orbit capability was largely developed for military use. However, technological advances, coupled with greatly increased civilian demand, have led to a rapid expansion in civil-sector development and services over the last 20 years. This has resulted in civil capabilities generally matching or exceeding military capabilities, particularly in the areas of communications and earth observation. Cost and security factors do, however, still restrict most PNT and Space Situational Awareness activities to the military sector. It should be noted that where capability is offered on a commercial basis, the information will be available to nations with no indigenous space capability and possibly to potential adversaries too. However, use of civilian surveillance data also provides a convenient way of sharing information between coalition partners when data derived from classified military systems would not otherwise be available.

POSITIONING, NAVIGATION AND TIMING

303. The United States operated **Global Positioning System**, (GPS**),** is the most widely known of several Global Navigation Space Systems. Its principal output is very accurate, atomic-clock derived, timing information which is used both as a time reference and to generate position information. The GPS system aims to keep at least 24 satellites in service (currently ~30), which are arranged in a constellation that ensures 3 to 4 are continuously visible to a user anywhere in the world. A ground-based receiver compares the time signals from multiple satellites in the constellation and, using the differences in reception time of the signals, computes its own position. There are two modes, military and civil, the former being encrypted and the latter not. While the civil mode is normally accurate to within 15m or better, it can be degraded, regionally or globally by the military operators. Where greater accuracy is required in civilian applications, such as during airfield approaches or in ground surveying, local ground transmitters can pass correction factors to receivers that allow accuracy within several centimetres.

304. The GPS system is actively managed by ground controllers to ensure that each satellite's on-board clock remains synchronized and each satellite's orbit is very accurately known. The spread spectrum technique used to transmit GPS data means that the power of the received GPS signal on Earth is very low, so low in fact that it is effectively buried in the background noise. While clever techniques can easily recover the signal from the noise, its low power means that even a jammer radiating only a few milliwatts of energy can prevent any receiver within several kilometres from receiving the signal. Military systems can mitigate the effects of this by using electrically steerable antenna arrays that maintain the satellite signal while blanking out a jamming source, but civilian systems are unlikely to have this capability.

305. Some alternative global navigation space systems are available now; others still in development will be available in the next few years. Using multiple systems is another way to provide end users with some redundancy against individual system failures and possibly some jamming. Whichever system or systems are chosen, they all use broadly

the same principles and techniques to provide the same services as GPS. The main alternatives are:

a. **Galileo**. The **Galileo** system is currently being developed by the EU and other international partners. Its operation is very similar to GPS, using the same frequency-band to transmit the satellite signals, although with a different encoding method. It is designed to provide global coverage when complete, with a range of services expected to become available from early 2014. The similarity in signal structure and operating frequency between GPS and Galileo would make development of a dual-mode receiver relatively simple, although current GPS systems are not forward compatible with Galileo. As it is a commercial system, there are some important differences from GPS in the way that it is used; for example there are varying levels of service that can provide greater accuracy than the basic, free, service. There will also be certain guarantees of the level of service provision and/or warning of degradation. This will be essential for commercial users who wish to offer safety-critical systems, such as precision aircraft landing systems, where continuous knowledge of the data integrity of the information in the system is essential to guarantee safety of flight.

b. **GLONASS**. The **GLONASS** system was originally developed by the Soviet Union and is now being refurbished by Russia and India. GLONASS is a global system, similar in concept (and frequency-band) to GPS and Galileo.

c. **Beidou/COMPASS**. **Beidou** is a regional system developed by China. China is now considering extending the system to provide global coverage under the new name **COMPASS**.

d. **Other Systems**. India and Japan are both developing systems aiming to provide regional coverage.

306. **Uses of PNT data**. The timing and data signals received from different satellites in a global navigation system can be combined to

determine a user's position, time or velocity. This includes height information relative to the world model used by the system (for GPS, the earth model is WGS84). Information from GPS can be mixed with local data from an inertial navigation system to provide a very accurate navigation solution, even during short periods where the satellite signals cannot be received. GPS navigation is used very widely by land, air and maritime vehicles and by personnel on foot. When installed in a weapon system, such as a missile or bomb, it can also provide guidance to a target location. For less demanding applications, hand-held or vehicle mounted GPS receivers can be used and even the simplest of these can provide timing information that is almost as accurate as an atomic clock. Typical military and civilian systems and applications that use global navigation space systems data include:

Military Uses of Global Navigation Space Systems
Survival radios that can report location automatically
Mine location fixing and clearance operations
Sophisticated radio encoding techniques
Radar timing
Cryptography and anti-jamming techniques that use very accurate timing information to encode information or that synchronize frequency-hopping radio systems
Personnel and platform navigation
Data-Links that share information among users by synchronizing transmissions. Each user is allocated a time slice in which to broadcast data and the finer and more precise these slices can be made, the more users can be supported or the amount of data carried increased
Precision guidance of munitions

Civilian Uses of Global Navigation Space Systems
GPS-based aircraft precision instrument approach systems that remove reliance on ground-based navigation aids
Semi-automated airspace management systems which receive and collate aircraft re-broadcast GPS data (such as the soon to be widely deployed Automatic Dependant Surveillance – Broadcast system
Embedded GPS capability that provides regular updates of an item's basic position information. Examples include cameras that record position on digital imagery, high value item asset tracking and management systems and, increasingly, augmented reality systems
Provision of timing data to control or time-stamp such activities as financial transactions, power grid and pipeline management and synchronization of landline and mobile, telecommunication systems

COMMUNICATIONS

SATELLITE COMMUNICATIONS

307. Communication beyond visual line of sight is an enduring military requirement and, although conventional high frequency radio systems provide some capability, there can be considerable constraints. High frequency radios often provide poor voice quality due to interference from atmospheric effects, lack of portability due to the required antenna size and very slow data-rates when used for digital signals. Normally, there will also be a compromise between range and portability, particularly when two-way communication is required. Range is limited by the power that can be transmitted or, by terrain/horizon masking.

308. Satellite Communications (SATCOM) overcomes these limitations by allowing very high, ultra high or even higher frequencies, with their inherent advantages of quality and capacity, to be relayed via space. With these systems, a ground station transmits a signal to a satellite which then rebroadcasts it: either across a wide area for many users, or

routed directly to a single user. Signals may be broadcast to a satellite via a hand-held transceiver, or through the normal communications network to a remote satellite ground station. At the satellite, the received signal is processed to remove noise and any embedded routing information is extracted. The data is then rebroadcast on a different downlink frequency to the end user. Perhaps the most well known of these systems are commercial systems in geostationary orbits, such as **INMARSAT** and **INTELSAT**. Note, though, that whilst geostationary orbits cover most of the globe, they do not provide cover over the Polar areas. The **Iridium** system demonstrates another approach to providing global and mobile telecommunications that does provide coverage in Polar areas. This system uses an extensive (at present around 65) constellation of satellites in LEO. The constellation is organised so that from any point on the Earth's surface, a satellite is continuously visible, though each moves rapidly across the sky while in view. An Iridium handset establishes a connection and communicates directly with one of the satellites; traffic is then routed in the same way as with a mobile phone system. Iridium phones can also interface directly with ground telephone systems via one of three ground stations.

309. Growth in the requirement for SATCOM access by both military and civilian users has been relentless and at times of peak demand, each sector can have a considerable dependence on the other. The advantage to the military of using civilian systems is that they only need to procure a basic level of service to meet key peacetime needs and then procure spare civilian capacity in times of crisis. This approach also provides increased resilience as the risk of military systems failing, for whatever reason, is mitigated by using many different systems and suppliers. The disadvantage of such arrangements is that when demand from the two sectors coincides, priority will usually be given to whoever is prepared to pay the most at the time.

310. **Military Use of SATCOM**. Military use of communications satellites, particularly by those nations that support overseas deployments, or which have geographically large territories, is high. For remote locations, a terrestrial communications infrastructure may not be practical or have been destroyed or denied, and SATCOM may be the only option available. Specific military uses include:

Military Uses of SATCOM
Strategic backbone communications between deployed forces and home base
Control of unmanned aircraft
Broadcast of information into, out of, and within a theatre of operations
Timely dissemination of intelligence, surveillance and reconnaissance data, in particular to remote locations
Situational awareness systems, including Blue Force Tracker

311. **Civilian Uses**. Potential civil uses of SATCOM include:

Civilian Uses of SATCOM
Carrying telephone calls between continents
Very Small Aperture Terminals (VSAT), which are used extensively to pass data from remote locations to central hubs and control stations. Examples of industries that use these systems include the National Stock Exchange, the US Postal Service, the energy sector and Wal-Mart.
Wide area broadcasting such as satellite television. This sector includes a number of novel applications such as the XM Sirius ® satellite radio service. As well as a range of music, sport, news and other entertainment channels, the system also broadcasts a continuous weather radar map of the continental USA. When this information is integrated into lightweight avionics displays, it can provide almost all the advantages of an onboard weather-radar, without the cost, weight and complexity normally involved.

INTELLIGENCE, SURVEILLANCE AND RECONNAISSANCE

312. **Intelligence and Surveillance**. Surveillance of the Earth from space to gain intelligence was the earliest military driver for developing space access. In fact, reconnaissance satellites were being planned before rockets were available to launch them. The performance of these satellites was, and remains, highly classified. However, as sensor technology in the civil sector has improved, many of the techniques used by military systems have migrated into the civilian domain. Examples of civil use include narrow-band imagery for monitoring Earth resources, particularly in support of agricultural production (see Agriculture and Space case study) and use of imagery as a basis for mapping, planning and other geographical applications. Civil users have also benefited greatly from the improved accuracy of weather forecasting made possible through the extensive use of meteorological information collected by satellites. Examples of such data that can be collected from space include: surface temperature and temperature profile with increasing altitude, wind velocity, wave height and swell direction, cloud height, atmospheric moisture content, ice flow tracking and visual imagery showing the location of weather formations. As with SATCOM, military planners have become increasingly dependent on civilian surveillance capability, particularly if military systems are degraded, over-tasked or simply in the wrong orbits.

313. **Surveillance and Resolution**. Resolution is the ability to discriminate between objects or events; the resolution that can be achieved by any particular space product is critical as to how useful it may be. There are many factors that will determine what level and kind of resolution is required to support any particular task, and over-concentration on one may lead to poor choices regarding the others. The following factors should be considered:

a. **Spatial Resolution**. Spatial resolution is the ability to resolve physical detail, or how small a target can be before it cannot be distinguished from its surroundings. For a satellite, the principal limit to the spatial resolution that can be achieved is the orbital altitude and the slant range created by a target being displaced from a satellite’s ground track. Commercial imagery that allows objects with dimensions as small as 50 cm to be distinguished is now commonly available, although 1m resolution is more common. In panchromatic mode, the GeoEye-1 satellite can collect images with a ground resolution as small as 41 cm.

b. **Temporal Resolution and Coherent Change Detection**. Often, the goal of reconnaissance is to detect changes between one picture of a scene and another taken previously. Selection of orbit, as described in Chapter 2, is very important as repeated overflight at the same local time of day on successive days may have distinct advantages in change detection analysis due to consistent and predictable illumination of the target. At non-visual wavelengths different factors may dominate, but these may still favour particular times of day.

c. **Spectral Resolution**. Targets will often be either more or less obvious at specific wavelengths of light. Thus it is common to observe a scene at multiple wavelengths and then compare and contrast the results of each. The success of this technique depends more on sensor performance than orbital dynamics, though this may again be influenced by illumination. Sometimes, different images from different satellites may have to be compared to allow an analyst to detect changes. This can be complicated as, to be successful, the ground tracks of multiple satellites must coincide near a target within a similar time.

d. **Radiometric Resolution**. Radiometric resolution is a description of the effective bit-depth which the sensor is capable of recording data at. The number of bits in, for example a black and white image, indicates how many greyscales can be displayed and ranges from 8-bit, which has 255 greyscales, to 16-bit which will have 65,535.

314. **Spots and Swathes – Choosing Resolution**. Many modern imaging systems have sensors that can vary their field of view in the same way that a zoom lens works on a camera. This usually leads to a trade-off between the area that can be covered and the resolution of the final image. The user should therefore be careful to request only the

actual resolution required for a specific task. Some flexibility in resolution demanded may increase the choice of which collection system or sensor to use, allow re-exploitation of already collected data and, by collecting a larger field of view, may allow a single image to satisfy several requests. If wide-area coverage is required, where adjacent images are ‘stitched’ together, accepting lower resolution will allow the ground to be covered in fewer swathes, greatly shortening the production time. This may be particularly important where the satellite ground track is such that there will be a long delay between adjacent passes over the target area.

315. **Imaging and Surveillance**. There are many types of imaging sensors available and the most common work best in either the visual or infra-red spectrum. Most modern systems have digital sensors that provide a surveillance picture using panchromatic, multi-spectral or hyper-spectral techniques. These terms are described below:

a. **Panchromatic Imaging.** Black and white digital sensors or photographic film are best suited for certain applications as they have greater sensitivity than colour sensors. Images produced by these systems are known as **pan-spectral** or **panchromatic**. The disadvantage is that colour information, which can be useful in analysis, is lost.

b. **Multispectral Imaging**. Multi-spectral images are made by combining separate monochromatic images, taken through, typically, red, green and blue filters, to create a single **multi-spectral image**. In a multi-spectral system, the detectors may also be optimised for the near, mid and far Infra-Red bands, and in principle could also include ultra-violet information at one end and radar information at the other. The image produced will have many colours which represent the different frequency bands chosen, rather than the actual visual image that would be seen by the human eye.

c. **Hyperspectral Imaging**. This technique collects information as a set of images; each image representing a range of the electromagnetic spectrum or spectral band, rather than the discrete frequencies that comprise a multispectral image. The images are combined to form a 3-dimensional data set known as a **data cube**. The cube contains a vast amount (often several hundred megabytes) of numerically complex data which can be subjected to a range of analysis techniques.

d. **Applications of Multispectral and Hyperspectral Images**. Some multi-spectral images are similar to a normal visual picture, but with additional data overlaid. More complex processing allows other useful information to be extracted and displayed, such as evidence of disturbed earth or the presence of individual chemicals or minerals. For this task, organisations such as NASA and the United States Geological Survey have published catalogues of many minerals and their spectral signatures. Hyperspectral techniques have particular utility in prospecting, environmental monitoring or agriculture, where crop growth and mineral content can be monitored. In agriculture, the requirement for fertiliser and estimates of moisture content in specific areas can be determined as well as identification of the presence of agricultural disease or pests such as the Pine Beetle, which has spread in North America. Certain crops, such as Poppy, can also be identified.

316. **Infra-Red Imaging**. Infra-red detectors have traditionally been much harder to fabricate and operate than visual systems and the production of reliable, high performance, staring infra-red arrays is a relatively recent achievement. While infra-red detectors can function in daylight, they have specific application for night surveillance, where they are ideal for differentiating temperature. Images produced using infra-red sensors are excellent for determining the status, or even presence, of factories and power-plants, equipment such as ships or submarines, and natural events such as flows of water and forest fires. Weather forecasting also relies on the infra-red characteristics of different amounts of water-vapour in the atmosphere. Ballistic and theatre missile launch detection is another specialised application of infra red sensors.

317. **Nuclear Detonation Detection**. Separately from detecting the launch of missiles, there was also great interest during the Cold War in detecting nuclear detonation or **NUDET**. The signature of the burst of gamma and x-rays produced by a nuclear explosion is very distinctive and easily detected from space. The electro-magnetic pulse from an exo-atmospheric nuclear explosion can also be detected from space. The effect of this electro-magnetic pulse can be so catastrophic on satellites that experiments to measure the effects were abandoned in the 1960's. Military satellites are specifically hardened to withstand the effects of nuclear explosions, although this inevitably adds to their weight, complexity and cost. NUDET payloads are hosted on a variety of satellites including the GPS constellation.

318. **Radar Payloads**. **Synthetic Aperture Radar** or **SAR** systems are used extensively by both military and civil satellites. SAR radars can see through cloud and provide images during day and night passes, although they do require a sizeable energy source. SAR radars are able to detect oceanographic features such as fronts, wave velocity and wave height, as well as provide high resolution images of ground features that provide similar information to a visual image. Another mode can detect moving targets such as vehicles, ships and helicopters.

SPACE SITUATIONAL AWARENESS

319. To operate successfully in space, it is necessary to develop **Space Situational Awareness** (also known as **Space Domain Awareness**) analogous to air or maritime situational awareness. The first requirement is to monitor the number and nature of launches into space. While countries and commercial companies vary in their willingness to share space launch data, launch detection from space is simple using the same infra-red sensors used to provide missile-launch warning (see below). Infra-red launch detection data thus provides a first estimation of potential orbit characteristics. Radar-based missile-warning systems, used to supplement infra-red launch detection, can detect items en-route to orbit as soon as they are above the horizon of the radar site or in range of an airborne platform. Indeed, such systems now normally have a secondary role in helping to update the **Space Track Catalogue** – this is a continuously updated register of all items in space and their orbital

parameters. Given their size, few launcher/payload combinations pose problems for radar detection. Ground-based optical and laser-based systems can also provide accurate orbit data on satellite tracks and orbits. Satellite observation can also be carried out from space, immediately obviating the significant limitations placed on ground systems by weather and the atmosphere. Capability (and counter-capability) in this area is relatively immature, but the potential is clear. Applications might include close-up inspection of other satellites, as well as surveillance of the immediate vicinity of a satellite as a defensive measure.

320. **Missile Warning**. The advent in the 1960's of nuclear missiles launched from remote land-locked sites, and with flight times of the order of 30 mins, required new technologies to provide appropriate warning time to initiate a response. The answer was space-based surveillance systems that detect missile launch by sensing the characteristic infra-red signature of a missile rocket present during the boost phase. For the US and its allies, warning is currently provided by the US **Defense Support Program** or **DSP** system. The system comprises a number of surveillance satellites in GEO that scan large areas of the earth, looking for the characteristic boost phase infra-red plume, and providing basic location and trajectory information. The Defense Support Program is being replaced by a system called the **Space-Based Infra-Red System** or **SBIRS**. SBIRS has elements in both GEO and HEO to provide comprehensive coverage. Initial detection data can be used to give an indication of flight-path, likely target area and time to impact. Increasingly, as the performance of these systems has improved, they have become dual use and are frequently used to give civilian aid agencies and scientific communities warning of events such as forest and large building fires and other environmental observations. The systems also have tactical utility against theatre ballistic missiles and during the first Gulf War in 1991, SCUD missile launches were detected in Iraq and the information used to provide tactical warning and cueing.

321. **Other Aspects of Space Situational Awareness**. Space Situational Awareness underpins offensive and defensive **Space Control** activities. Space situational awareness involves more than

simply cataloguing orbital characteristics – other data that may be collected include:

Calculation of ground track or footprint	Warning of any unexpected manoeuvre or change of orbit
Communications between satellites and ground segments, confirming system serviceability and status	Measurements of size, shape and other characteristics that may indicate purpose
Correlating tracking data over time to determine the purpose of a system	Collection of space weather information to provide advance warning of damaging radiation
Debris tracking	

322. **SSA Systems**. A number of nations have, or are developing, systems that contribute to SSA. Some have concentrated their research effort on radar systems, while others have focussed on optical systems. However, no single nation has the geographic coverage, nor the mix of approaches needed, to provide a full SSA picture. A collaborative endeavour is more likely to achieve success.

CASE STUDY 5 – THE SPACE ENVIRONMENT

This case study differs from previous ones; it considers how operations in space are conducted and managed in practice against the continuous presence of threats and hazards. The output is not a process that contributes to specific terrestrial activities; rather it is how the space and ground segments of space are themselves successfully managed. As noted in Chapter 1, space operations are very different from air operations and comparisons may be misleading. A major factor with many space systems is military secrecy and commercial sensitivity. Most military systems are very highly classified and so reliable data on many aspects of military space operations is simply not available through open or unclassified sources. Commercial systems are more open about aspects of the data and services that can be provided - after all, they exist to sell these services to a variety of end users. Commercial considerations will, though, still preclude open publication of many aspects of system operation, in order to protect intellectual property or commercially sensitive information. The study considers space operations through 4 separate functions that support the overall ‘operate in space’ process. These are: Monitor Space, Analyse, Plan Operations, and Conduct Operations. Further detail on elements of the first two of these functions is provided in the main text throughout the publication.

Monitor Space

The low earth orbit region, is increasingly crowded and hence continuous monitoring of the space environment is required to provide the essential situational awareness needed to operate effectively. There are a number of hazards from both man-made and natural sources, as well as man-made threats that may affect the ability to operate safely. Hazards and threats are described further in Chapter 4. Data collection may be conducted using a range of sensors including ground optical (including laser ranging and imaging) and radar as well as space based electro-optical systems. Third party data collection of the characteristics of space vehicles is an extremely sensitive issue, particularly for military systems.

Analyse

Regardless of the sensitivities, analysis can provide considerable information about the capabilities and function of different satellites. Published launch data (including launch site), combined with an understanding of Kepler's laws and historical observation data provides a good understanding of a satellite's current and potential orbits. For a satellite to manoeuvre and operate, a propulsion system and power generating (normally solar, but may be nuclear) system are required. Knowledge of satellite size and deduction of likely propellant mass will give an indication of either satellite life (through the fuel expenditure required for station keeping) or the amount of orbit variation that can be achieved (through the fuel expenditure required to change orbit). Orbit characteristics such as LEO, MEO, GEO, and shape (circular/elliptical etc) will give further indication of the task to be undertaken by the satellite; some orbits are better suited to some tasks than others. Approximations of solar array and antenna sizes will further indicate the likely power available and operating frequencies. Traditional intelligence collection activities will give further indicators of system capabilities.

Plan Operations

The previous 2 functions will enable production of a recognised space picture – normally in the form of tabular data in a 'Space Catalogue'. These might be for military use only or openly published. Depending on the data available to each producer, each database will vary in the number of objects reported and their accuracy. Few nations are capable of independently producing comprehensive and accurate space catalogues. Once a space catalogue has been produced, it is possible to carry out a conjugation assessment and prediction and hence to develop a warning system of potential space collisions.

Conduct Operations

Normally, only warnings of potential conjunctions are issued and it is left to individual satellite operators to decide when or if avoiding action is warranted. The operator will develop a tailored manoeuvre plan (designed to expend the minimum amount of fuel possible) and then conduct the manoeuvre. Once complete, details of the new orbit may be incorporated into the space catalogue.

The Space Environment

Hazards

Natural:

- Solar Weather
- Meteorites

Man-made:

- Debris
- Congestion
- RF Interference

Threats

- Kinetic
- Cyber
- Dazzle
- RF Jamming
- ASAT

Data Gathering

- Ground Optical
- Ground Radar
- Space EO

- Published Launch Data
- Kepler's Laws
- Historical Observation
- Intelligence

- Recognised Space Picture
- Conjunction Assessment and Prediction
- Develop Warning System
- Develop Manoeuvre Plan

- Conduct
- Manoeuvre Plan
- Assess and feedback to Analysis

Monitor Space → **Analyse** → **Plan Operation** → **Conduct Operations**

CASE STUDY 6 – MINERAL AND OIL PROSPECTING

Space products are used extensively to support natural resource extraction, with most steps having either a moderate or significant dependency. For many, the use of space products will be a key factor in enabling the resource to be extracted economically, safely, or in a timely fashion. Some elements, such as third party remote monitoring for attribution, can only be conducted from space. This case study examines 4 steps in the process: prospect, exploit, third party oversight and consequence management.

Prospect

Space-based surveillance and reconnaissance systems are used extensively in producing mapping products and subsequently detecting resources, from minerals and ores, to water and even oil. While ground-based systems or teams could replicate these outputs, this would add greatly to the cost and time of locating resources. Even when used, they will normally be guided by space observation to the best locations to test for the presence of various resources. Positioning, Navigation and Timing (PNT) provided by GPS and other space-based navigation systems are critical for many *prospect* activities. Although alternate terrestrial systems are available, these may not have the required accuracy or coverage in remote areas. In any case, the increased adoption of GPS outputs has led to many of the ground or sea based alternates being decommissioned. In remote areas, SATCOM (SATCOM) may be the only way to achieve command and control and reporting.

Exploit

The *exploit* function can be broken down into a number of lower level activities. All activities have a moderate, to significant, dependency on space; in most cases the significant dependency will again be created by the requirement for space provided PNT. Extraction and distribution, by land or maritime transportation, will have similar dependencies to those already noted in the agriculture case study. In remote areas, SATCOM may be the only means available to control and report on the exploit activities, particularly if timeliness or large amounts of data are factors. Space-based environmental monitoring, for pollution or accidents, may often provide the first indication that something has gone wrong.

Third Party Oversight

A range of organisations may undertake third party oversight; from government monitoring of licensed (or unlicensed) commercial companies, to international monitoring bodies such as the UN, or Non Governmental Organisations such as 'Transparent World'. These use space-based observation to ensure compliance with environmental regulations and for rapid assessments to be made of the scale of problems when they arise. Where individual nations refuse to allow monitoring teams on the ground, space-based observation may be the only means by which bad or illegal behaviour can be identified and attributed to the parties responsible. An example of this could be finding the source of pollutants in a river system that passes through several countries.

Consequence Management

Because of the large scale of many resource extraction activities, or the toxicity of many of the products, accidents, or even simple neglect, can rapidly have major consequences. In many cases, the timeliest detection of problems will be provided by space-based systems – particularly in remote areas. Sometimes, the organisation responsible for an issue may not even be aware of problems. The *consequence management* function has the highest dependency on space and all of its sub-activities are likely to be significantly dependent on space. Sometimes, problems arising from resource extraction may be so great that they are on the scale of environmental disasters. In such cases, large numbers of people and equipment may need to be deployed in complex operations to contain, repair and mitigate the issue. These are likely to have a significant dependency on PNT and communication systems, as well as requiring timely weather warning and forecasting.

Conclusion

The outputs or services provided by space-based systems are vital to mineral and oil prospecting and exploitation. Without such products, many resources could neither be extracted at all, or to do so, would be uneconomic. It is assessed that, overall, this process is one of the most highly dependent on space.

Mineral and Oil Prospecting

Dependency

- Low
- Moderate
- Significant

Prospect

- Mapping
- Detection
- Ground Team Support
- Exploitation Planning

Exploit

- Facilities Emplacement
- Extraction
- Resource Distribution
- Sustainment
- Environmental Monitoring
- Operations Management

3rd Party Oversight

- Monitoring
- Attribution

Consequence Management

- Planning
- Monitoring
- Execution

CHAPTER 4 – VULNERABILITIES, HAZARDS AND THREATS

401. **Introduction**. Once a nation or organization has determined that it has dependencies on space capabilities and identified which of these are critical, the next step is to identify potential vulnerabilities, hazards and threats so that appropriate mitigation strategies can be developed. This chapter lists the main vulnerabilities of space systems and identifies the main hazards and threats that may be encountered. Because security concerns preclude detailed discussion of the vulnerabilities of specific systems, the hazard and threat information should be used as a tool to infer the underlying vulnerabilities of particular systems.

In this Section you will find discussion on the main vulnerabilities, hazards and threats relating to space systems. As well as an introduction to the concept of Critical National Infrastructure, this includes:

- Definitions of Vulnerability, Hazard and Threat
- Natural hazards including space weather, micro-meteorites and human derived hazards
- Threats, including anti-satellite weapons and techniques
- A short section on mitigation and the impact of space system failure

DEFINITIONS

402. The MNE7 Lexicon defines, vulnerability, hazard and threat as follows:

a. **Vulnerability**. This can have any of 3 meanings: (1) *The susceptibility of a nation or military force to any action by any means through which its war potential or combat effectiveness may be reduced or its will to fight diminished.* (2) *The characteristics of a system that cause it to suffer a definite degradation (inability to perform the designated mission) as a result of having been subjected to a certain level of effects in an unnatural (man-made) hostile environment.* (3). *A weakness in* *information system security design, procedures, implementation, or internal controls that could be exploited to gain unauthorized access to information or an information system.*

b. **Hazard**. *A condition with the potential to cause injury, illness, or death of personnel; damage to or loss of equipment or property; or mission degradation.* For the MNE7 Space workstrand, a hazard's source can originate in the natural environment, or as a consequence of human activity.

c. **Threat**. *Any combination of capabilities able to cause a range of negative effects on assets, or on access, with a perceived intention to use these capabilities to reach a negative effect.* A threat differs from a hazard, as it requires both capability and intent. The latter indicates that it is human, rather than environmental, in origin.

SPACE SYSTEM VULNERABILITIES

403. **Space Element**. The space element of a space system is vulnerable to:

a. Damage or destruction caused by the harsh radiation environment of space.

b. Collision with micrometeorites and space debris.

c. Hardware, software or design failures that may be difficult to attribute to any specific cause.

404. **Space and Ground Element**. The space and ground-based elements of a space system are vulnerable to:

a. Kinetic attack.

b. Electronic attack (LASER dazzle, radio frequency jamming, EMP).

c. Computer network attack.

405. **Ground Element**. The ground-based element of a space system is vulnerable to:

a. The effects of terrestrial weather such as flooding, wind damage and lightening strike.

b. Loss of supporting utilities such as electrical power and water supplies.

c. Physical attack by ground or air forces.

The issues are explained further below. Additionally, it should be noted that since much space capability is provided on a commercial basis, there may be times when access is either denied by a competitor or simply unaffordable.

NATURAL HAZARDS

406. Apart from the ever present threat of meteorites, almost all hazards to space capabilities come from the Sun. Principally, these manifest themselves as increased electromagnetic noise, ionospheric interference or prolonged impact by energetic charged particles. The various phenomena resulting from the Sun's activity are collectively termed **space weather**; this is analogous to, but different in effect, from terrestrial weather.

Space Weather

407. Space weather is caused by changes in solar activity. This results in increased or decreased levels of cosmic rays, solar flares, coronal mass ejections and other natural phenomena. Space weather will have different effects on spacecraft as follows:

408. The sun emits a **solar wind**; a stream of charged atomic particles ejected from its upper atmosphere at high speed. Although the particles are very small (mostly electrons and protons), they impact continuously

on the satellite's surface that faces the sun and at significant speeds. The effect is cumulative and measurably alters a satellite's orbit over time. It can also introduce rotation of the spacecraft by generating asymmetric forces on specific parts of the craft. Specific effects associated with the solar wind include:

Solar Wind Effects
Electronic components. Individual charged particles can penetrate electronic components and corrupt computer memory or physically damage electronic circuits. Some effects will be the result of individual high energy impacts, but continuous lower energy impacts can have a long term damaging effect on the reliability of electronic components.
Outer surfaces and sensors. The continuous impact of solar particles on the spacecraft's outer surface can also cause physical damage to the satellite's structure. Delicate components such as sensors or solar panels will gradually degrade. A decrease in the output power of a satellite's solar panels of around 15% over a period of 7 years is not un-typical. Single solar proton events, while relatively rare, can reduce performance by as much as 2% for each event. This effect can be mitigated, if a period of loss of service is acceptable, by orienting the edge or end of the panel toward the sun, thereby minimising the number of particles striking the working face of the array. This does, however, rely on appropriate warning that an event is about to occur and assumes that disruption of service is acceptable.
Electric charge. Electrically charged particles, most notably electrons, accumulating on the surface of the craft can transfer their charge to its structure in a process called **spacecraft charging.** This can induce the build up of significant voltages across insulated parts. When these discharge, they can do severe damage, or create spurious signals which may cause equipment to malfunction – it has been known for these events to trigger thrusters which may spin the satellite out of control or point sensors away from the earth.

Solar Wind Effects (Continued)
Atmospheric changes. Increased solar activity warms the outer layers of the atmosphere, causing it to expand outwards from the earth. This can affect the orbit of satellites and space debris by increasing drag; this will also create significant work for space surveillance networks as they will need to update the space catalogue ephemeris data of all affected objects.

409. **The Effects of Space Weather on the Earth**. Extreme space weather events can also disrupt, damage or destroy earth based systems and infrastructure. While most of the effects are outside the scope of this handbook, the following space related events may occur:

a. **Effect on Radio Communications**. Interaction between charged particles and the upper reaches of the atmosphere (specifically the **ionosphere)** affects the reliability of radio communications, most notably in the frequency bands that depend on particular atmospheric properties to achieve long ranges.

b. **Ionosphere Changes**. Changes in the ionosphere due to variations in the level of solar radiation will affect GPS accuracy. To counter this, GPS satellites broadcast ionospheric model parameters and use different transmission frequencies that can be compared in the receiver to improve estimation of ionospheric delay. Nevertheless, errors in estimating ionospheric delay remain one of the primary sources of GPS positional error. Various agencies monitor space weather and issue a forecast of how this will affect GPS accuracy. These forecasts will be of particular importance to military users relying on GPS guidance to achieve precise delivery of weapons.

c. **Infrastructure and Network Damage**. Just as unwanted charges and currents can build up on spacecraft, similar mechanisms resulting from magnetic storms created by the interaction of energetic events and the earth’s magnetic field can induce currents in large metal structures on Earth. Buried metal pipelines, power distribution grids and other cabled installations can all be affected, or even destroyed, if the event is severe enough. Space based sensors are used to monitor solar activity and provide warning of major events so that systems, particularly electricity generation and distribution grids, can be shut down in an orderly fashion, or configured to provide some protection from solar events.

410. **Natural Meteorites**. The Earth, and anything orbiting it, naturally collide continually with meteorites and micro-meteorites originating from elsewhere in the solar system. Size will vary from substantial to negligible. On Earth, we are protected from small meteorites by the atmosphere; shooting stars are particles, typically no bigger than gravel grains, burning up as they enter the atmosphere. In space, there is no such protection and there is little scope for approach warning. Mitigation is therefore a combination of accepting the negligible, but non-zero, risk of a substantial impact disabling a satellite and designing robust structures to absorb the very small impacts that are more likely.

411. **Degree of the Effects**. These effects will cause issues for all four of the space pillars described in Chapter 3. The degree of effect and duration will vary and there are some consequences that will be very noticeable within specific pillars. For example, satellite communications capability could be considerably degraded by the increased noise generated by charged particles in the upper atmosphere. The same phenomena could affect global navigation space systems by raising the background noise above the level at which the navigation signal can be reliably extracted. Again, space weather monitoring and forecasting are increasingly used to mitigate or forewarn of these events. Recently, satellites have been placed in Sun orbit to improve space weather data collection and to provide increased warning time of large solar events.

MAN-MADE HAZARDS

412. Space systems may face hazards that are the unintentional consequences of human activity, most commonly collision with space debris.

413. **Man-made Debris**. Since the earliest days of the space programme, Earth orbit has become increasingly cluttered with debris of various kinds. Some is unavoidable, such as time-expired satellites that have run out of fuel or finished their mission, or spent rocket cases that remain in orbit after launching their payload. Other instances are accidental, varying from tools dropped by astronauts to failed components and even tiny flecks of paint shed by space vehicles. Since these objects are all in orbit around the Earth, ground-based sensors can potentially track them if they are above a certain size. For objects that are too small to track, the only possible mitigation of the risk of impact is for satellites to be as robust as possible. There are several issues relating to orbital debris:

a. **Debris Dispersal**. If an object detaches from an orbiting body, no matter what its size, it will initially follow the same orbit, varied only by the event that caused the breakup. This means that debris may take weeks, months or even years to separate from its source; even clouds of objects, created by explosive events, will only slowly disperse once the initial explosion is complete. Depending on altitude and velocity, such objects may remain in a stable orbit for extended periods of tens or even hundreds of years.

b. **Cascade Failure**. While there are about 800 active satellites in Earth orbit, the US DoD Space Object Catalog now provides details of nearly 21,000 space objects, each larger than around 10 cm. In addition, there are an estimated 300,000 items of untracked debris between one cm and 10 cm in size. There are growing fears that as the orbital space around the Earth becomes increasingly cluttered, a future collision may create a runaway chain of events that creates collision after collision, rendering some orbits unusable for centuries. This is known as

Kessler Syndrome. As examples of what can happen, on 10 Feb 2009, the Iridium 33 and Cosmos 2251 satellites collided at an effective speed of over 42,000 km per hour. The impact created 382 observable debris pieces from the Iridium satellite and 893 from the Cosmos satellite. This event considerably increased the operating risk of the other satellites in similar orbits. In 2007, a Chinese anti-satellite test weapon destroyed the Fenyung 1-C satellite creating a debris field of 900 tracked objects and approximately 35,000 pieces larger than one cm. The debris objects ranged from 200 to 3,850 km in altitude, effectively endangering all satellites in LEO.

c. **Mitigation of Cluttered Orbits by Debris Clearance**. The preferential use of certain orbits, such as GEO, compounds the collision risk by concentrating large numbers of platforms in discrete bands. There is growing awareness of the problem of congestion and innovative proposals have recently started to appear to create space systems that would be dedicated to collecting debris, either returning it to earth or boosting it beyond GEO. There are, however, serious security concerns to overcome, particularly from the military space community, before the concept becomes reality.

414. **Frequency Fratricide**. Frequency fratricide, both unintentional (hazard) and intentional (threat), has the potential to become an increasing problem. One of the major difficulties with operating satellites is not how close they can be operated physically, but rather how the limited numbers of radio-frequency bands on which they rely for operation are allocated to operators. Adjacent satellites cannot operate on the same frequency without interference and it is the task of the International Telecommunication Union, a specialised agency of the United Nations, to coordinate the shared use of the radio spectrum and to promote international cooperation in assigning satellite orbits. Occasionally, loss of satellite control may lead to a rogue satellite wandering across other satellites' orbits and potentially causing radio interference. A recent example of this was in Apr 2010, when the Galaxy 15 satellite, in GEO orbit at longitude 133° West, stopped responding to ground control signals. It began to drift away from its assigned position

and was not recovered until the end of December 2010, by which time it had wandered across to longitude 93° west. As a result of the malfunction, other Galaxy satellites had to be repositioned to provide the original Galaxy 15 capability and other companies' satellites moved out of its way as it changed orbit.

415. **Design or Component Failure**. Availability may be compromised by simple mechanical or electrical failure of components, which may also be associated with poor design. Remote diagnosis of the cause of failure and attribution can take considerable resource; therefore thorough prior analysis of the likelihood of the failure and a proper understanding of the degree of resilience in the affected system is essential. For critical national security applications, such as missile warning, even transient failures may be totally unacceptable and rapid understanding of what has failed and why is vital, particularly if an adversary also knows details of the failure.

THREATS

416. Adversaries may have their own ability to develop counter-space capabilities or may acquire them from a third party. While specific details of the capabilities and techniques that may be used are beyond the classification of this handbook, general near and far-term threats may include the following:

a. **Direct Attack**. Direct kinetic or cyber attack can be mounted against both ground and space segments of a space system. This would include attacks on computer systems used to control satellite functions and on networks designed to collect, process and disseminate mission data. Physical attacks against ground segments could affect any of the 4 space pillars and have significant long terms effects; most commercial operators do not have spare ground control stations to which they could easily switch operations in the event of loss of a major facility. The loss of space surveillance sensors for the space situational awareness mission could be extremely serious as it would severely reduce a national or coalition capability to provide early warning of impending attacks. The issues of cyber vulnerabilities and threats to space, and other complex systems are examined separately in a parallel MNE7 Cyberspace workstrand; as such they are not considered in any further detail here. Suffice to note that the cyber security of space systems should be treated in a similar manner to that of any critical ground-based system.

b. **Electronic Attack**. Ground or space radio frequency jamming equipment can be used to degrade space system links. Additionally, since the signal format of the GPS signal is in the public domain, it would be relatively easy for ground or aircraft-carried transmitters to generate a spoofing signal. Such systems, though generally illegal, are widely available on the open market.

c. **Laser Blinding**. The imaging portion of a reconnaissance platform is inherently susceptible to damage, either temporarily or permanently, if a strong enough illuminating beam can be injected into the optical system. The fact that any such optical systems are designed to focus incoming light/radiation onto the imaging chip or plate enhances this effect. While a ground or air-based system is the most likely source of attack, an anti-satellite system in space would be much closer to a target and thus require a much less powerful illuminating beam. If the satellite operator is aware of the threat, protection may be possible by closing an iris or shutter on the imaging system or by manoeuvring the satellite attitude or track; the mission failure resulting from such mitigation activity would, however, mean that the adversary had achieved their aim. Also, forced manoeuvring will mean the unnecessary expenditure of fuel, which will shorten the satellite's operational life. Conversely, one advantage of this attack mechanism is that it does not create a debris cloud.

d. **Electromagnetic Pulse Weapons**. Electromagnetic pulse weapons are capable of degrading or destroying ground and space-based system electronics. One method of attacking satellites would be to use a nuclear device to create an internal system-generated **electro-magnetic pulse**. This kind of attack would require the satellite to be in line-of-sight of the detonation; the system-generated electro-magnetic pulse being a consequence of the effect of the received gamma radiation from the detonation. A recent technical report from the US based Defense Threat Reduction Agency noted that LEO satellites are at serious risk of collateral damage from high altitude nuclear detonations.

417. **Anti-satellite Systems**. Anti-satellite (ASAT) systems have been developed that may be either direct ascent from earth, or co-orbital. A direct ascent weapon is essentially a surface or air-to-space missile, while a co-orbital ASAT is one that assumes a similar orbit to a target, before attacking by one of the mechanisms as described earlier. Direct ascent requires less energy than a co-orbital attack as the missile only needs to reach the satellite – it does not need to achieve orbit. Because there is no atmosphere in space, an exploding warhead (i.e. one that does not rely on the missile directly hitting the satellite) will not produce a shockwave. Instead, fragments wrapped around the warhead will be ejected when it explodes and the subsequent damage mechanism relies on the direct impact of these fragments with the satellite. A kinetic attack such as this could lead to unanticipated second and third order effects as neutral and friendly satellites may well be affected. Examples of direct ascent systems are the Chinese anti-satellite test of 2007 and the US interception of one of their own satellites in 2008.

418. **Satellite Servicing and Debris Collection Systems**. Several companies and nations are proposing or supporting initiatives to create space systems that either service satellites in space to extend their life, or that collect and remove debris from cluttered orbits. There is concern that such systems could have a dual use, by providing a hostile anti-satellite capability.

OTHER THREAT ISSUES

419. **Dependency on Commercial Systems**. With the incessant growth in demand for satellite communication, no nation can provide all of the required capability through state owned assets. Instead, significant capacity is bought from commercial sources. As a result, nations increasingly find themselves in direct competition for available resources with commercial and non-governmental organisations. This

manifests as a threat in two ways. First, increasing competition may mean that there is no spare capacity available to be purchased, resulting in a loss of capability. Second, while there may be capacity available, commercial pressures may drive costs up to unsustainable levels. As recently as Mar 11, *Space News* noted that the US Department of Defense was experiencing price increases of as much as 300% for renewal of commercial satellite communications contracts. Consequently, a nation may not be able to afford to purchase all the capacity it requires, again leading to a reduction in capability. This situation is exacerbated by the fact that governments are likely to require extra capacity for short-notice activities such as conflict intervention and disaster relief. These are exactly the same events that drive demand in the media and NGO sectors, and hence create scarcity.

420. **Rogue Launch**. It is feasible that rogue nations, unable to receive their desired orbit or frequency allocation from the ITU, could decide to launch independently of the international community. This could raise the threat of collision or frequency fratricide.

SYSTEM FAILURES

421. **Attribution and the Importance of Understanding Space Systems**. The wide range of potential damage mechanisms that can affect satellite systems means that failure can be sudden or gradual, and predicted or unexpected. It may be impossible to attribute a cause to a failure quickly, for example to differentiate between technical failure, debris impact or malicious action. Even a suspicion of malicious action may be hard to attribute to a particular source, particularly if it is the result of a cyber attack.

422. **Long Term Effects**. While short-term failures in space systems could have a serious and immediate impact on individual users, long-term failures could be much more problematic. This is particularly so for military systems, which tend to be relatively few in number, with key capabilities often provided by single or small numbers of platforms. Special features built into military systems such as anti-jam receivers would also be lost, increasing vulnerability further. As well as the loss of

capacity or even a complete service, the cost of contracting commercial alternatives, if practicable, would be significant.

423. **Mitigation of Loss of Space Systems**. When military satellites were first brought into service, any dependencies they created were obvious. In many cases the failure mitigation strategy was easy to identify as it involved simply reverting to a previous capability. For example, the reconnaissance task could revert to air-breathing platforms, communications to land-lines or HF Radio and so on. More recently, the spread of space-enabled capability, its increased uptake by many military and civilian sectors, and its increasing transparency to the end user, has had a number of impacts.

a. **Difficulties with Identifying Interdependencies**. Firstly, realisation of where the dependencies lie has become increasingly difficult. High-capacity SATCOM, with associated large dish antennae outside the military or company HQ, is easy to recognise as a space-enabled capability. However, the consequent dependency on space is probably largely transparent to the end user inside the building, or indeed the recipient on the other side of the world. An Iridium mobile phone looks much like a normal GSM terrestrial mobile phone and a casual user may not even realise that the Iridium system is implicitly reliant on satellites. Even a knowledgeable user may be unaware of the extent, large or small, that their normal landline or mobile long distance call may be dependent on space for either control timing or transmission of some part of the connection. Another example may be the users of meteorological data and associated forecasting, many of whom may be completely unaware that most of the data they are using derives from space and that the legacy meteorological data collection systems on which they previously depended may no longer exist.

b. **Third party dependencies**. One particular concern for managers and planners is gaining an accurate understanding of how much space dependency, and hence risk, they are carrying through third parties. Nowadays it is common for supply chains to be literally that – a lengthy chain of loosely connected organisations, which come together for a particular task or mission. Many elements of a task will be sub-contracted and sub-sub-contracted. If an organisation relies on a third party that does not understand (or even misunderstands) its own dependencies, it will be impossible to assess accurately the overall risk.

c. **Mitigation Issues**. As dependence has grown, the practicality of existing mitigation strategies may need to be challenged. Robust replacement capability may be identifiable, but if it is of lower capacity, less responsive, or users lack the appropriate training, then the effect of any loss will still need to be quantified. For example, the military operating concept of reachback is used to keep the deployed footprint as low as possible by keeping subject matter expertise on call at the home base. Such a process may be so reliant on SATCOM connectivity that the process becomes impractical if SATCOM is unavailable. Another example would be the inexorable increase in reliance on global navigation space based systems for aeronautical and maritime navigation. Since these systems are cheap, accurate and easy to implement, they raise increasing questions over the need to continue funding traditional air and sea navigation aids such as VOR, DME and Loran. Even if these systems are retained as reversionary modes for navigation, their accuracy is insufficient to support the anticipated requirements of future air traffic management systems and users may need refresher training before use.

424. Mitigation of loss of space capability is a major issue and the subject of a separate objective workstrand within the overall MNE7 Space Outcome. This workstrand will deliver its results in mid-2012 and the information may be incorporated into a 2nd edition of this handbook.

CRITICAL NATIONAL INFRASTRUCTURE

425. **The Critical National Infrastructure Concept**. When analysing the presence of dependencies, vulnerabilities and threats, it is useful to agree what exactly these factors may be applied to. This gives rise to the concept of **critical national infrastructure** which, for the purposes of this handbook, is defined as '*the facilities, systems, sites and networks necessary for the delivery of the essential services upon which daily life depends*'. As an example, in the UK nine critical national infrastructure sectors have been identified. These are:

Communications	Government
Emergency Services	Health
Energy	Transport
Finance	Water
Food	

Other countries and organisations may use a different list according to national priorities, but it is likely to be similar. It should be noted that the position of a sector in the list does not signify any particular priority, as these will again vary with circumstances.

426. Not everything within a national infrastructure sector will be critical. Within each sector there will be certain critical elements, the loss or compromise of which would have a major, detrimental impact on the availability or integrity of essential services. In extreme cases, this can lead to severe economic or social consequences or to loss of life. These critical elements together make up the overall critical national infrastructure and may be physical (e.g. sites, installations, pieces of equipment) or logical (e.g. information networks, systems). The key questions are:

a. What role does space play in each of these?

b. How is the capability reduced if the space element is removed?

427. **Critical National Infrastructure Vulnerability Assessment**. Once a critical national infrastructure and associated critical elements have been defined, an assessment can be conducted to determine specific vulnerabilities. In the UK, an approach has been developed based on reliability theory, using information from structured interviews to estimate the potential failure rate of each activity under consideration. These questions are focused upon 4 key themes:

a. Estimate the time-to-failure if a space service is removed.

b. The effectiveness of backup services (if they exist).

c. The underlying importance of the space service to the activity.

d. Agreement on an activity importance weighting (probably directed by the body coordinating the study).

These themes are explored during the interviews and numerical values are applied to each of them according to a pre-agreed scale. The end result is a **Space Dependency Metric** which ranges from 0 to 100 (low to high). These should be considered as relative values rather than absolutes and can be used to rank different activities or groupings within the study against each other. This allows finite resources to be best targeted at the most critical areas of dependency and also help to create understanding of business continuity issues at a national level. It can be seen that the importance of an activity within the critical national infrastructure is considered, as well as its vulnerability to the loss of space derived capabilities.

CASE STUDY 7 – TIME-SENSITIVE TARGETING AND CLOSE AIR SUPPORT

In an unclassified document, it is only possible to generally detail how space may support military missions. There are, however, many issues that can be read-across from the other case studies. Specialist staff should be consulted by military planners (before and during operations) to ensure that space dependencies, vulnerabilities and threats are well understood and, if necessary, mitigated. The latter, may not always be possible, be extremely expensive or too complex to achieve in practice. This case study considers how space contributes to military aviation, in particular unmanned aircraft operations, command and control networks and data-links, and weapon targeting.

Manned and Unmanned Aviation Issues

All military aviation is significantly dependent on space, in particular the PNT of GPS, or similar systems. Many of the mapping updates required in remote areas will need to be provided by satellite observation. Access to accurate meteorological forecasts and data will be critical in pre-mission planning and execution. All modern aircraft navigation and mission systems, manned and unmanned, will need a GPS feed to achieve the navigational precision demanded by complex tasks. Wide-area jamming of GPS is difficult, but localised jamming is relatively easy, using simple systems that can be purchased on the internet. Unmanned aircraft, operated from remote locations, will require considerable satellite access for both the command links that control the aircraft and for the data links that provide sensor data back to the operator. Satellite bandwidth will invariably be the limiting factor on how many, and where, such aircraft can be operated. Such capability can, however, provide enormous advantages whereby, for example, small local ground teams can launch and recover aircraft which are handed off to operators based anywhere in the world. This greatly reduces the in-theatre footprint, reducing the strain on both the logistics supply chain and force protection.

Command and Control Networks and Datalinks

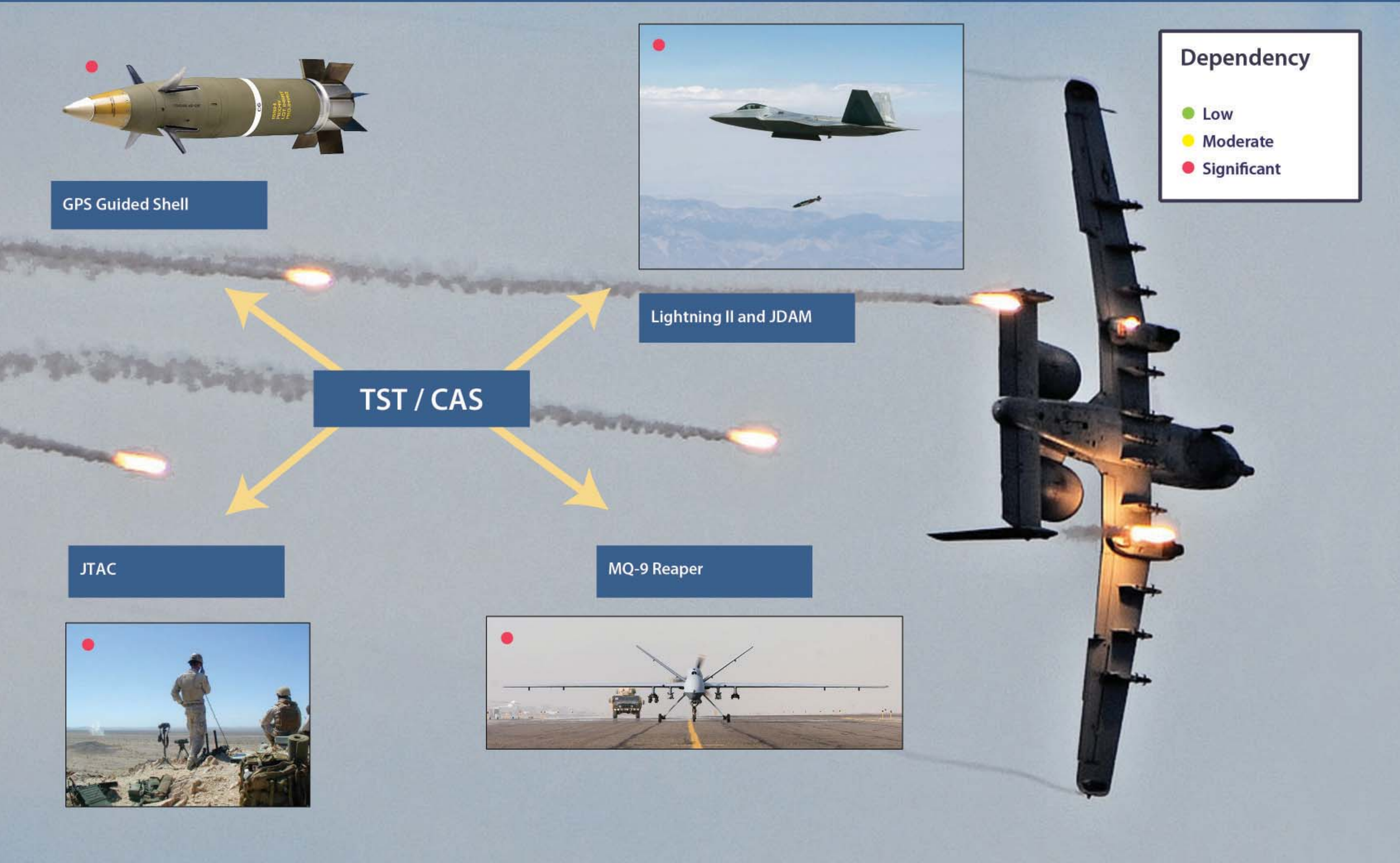
For many operations, satellite communications will be essential to provide command and control of air assets and to co-ordinate their activity with ground forces. During close air support and some time-sensitive targeting missions, air activity may be co-ordinated and directed by a Joint Terminal Attack Controller (JTAC). In remote areas, satellite communications will be essential if this task is to be successful. Where secure communications and data links are established, the timing signal from GPS will be used to ensure that frequency hopping systems remain synchronised with each other. In addition, much of the data on the recognised air picture will be self reported by units using GPS position data. Blue force tracking systems may also rely on PNT.

Weapons

Air munitions increasingly rely on GPS to achieve the precision demanded by modern operations. Public opinion, intense media scrutiny and the law of armed conflict have driven armed forces to develop more-and-more accurate weapons. These ensure that collateral damage and civilian casualties are minimised. Many of these, including ground-fired GPS guided shells and the Joint Direct Attack Munition (shown in the accompanying diagram being launched from the Lightning II Joint Strike Fighter aircraft) require a GPS navigation input to achieve the desired accuracy. Modern weapons may have additional inertial navigation systems or be capable of being laser guided from the air or ground, so that they can operate in a GPS-denied environment. Such modes do, however, increase cost and risk and reduce flexibility, as laser guided weapons will need to have their targets laser marked, from the air or ground, during delivery. Internal inertial navigation systems may require a position update from the aircraft system prior to launch and this may well be derived from the aircrafts own GPS position. Overall, GPS systems can generally be used in a more flexible ‘fire and forget’ mode.

As can be seen from the above, military air operations are very dependent on space systems and in particular GPS. In fact, it may be surmised that the current western way of warfare has developed specifically around the capabilities provided by space-based systems. This is causing some concern, particularly as the level of dependency is often not fully appreciated. While considerable work is being undertaken to understand how these dependencies may be mitigated, there may not always be a solution or if there is, it may not be affordable.

Time Sensitive Targeting and Close Air Support



CASE STUDY 8 – SUPPORT TO GOVERNANCE AND SECURITY IN REMOTE DISTRICTS

This case study is unusual in that it focuses on a specific problem, rather than a generic issue or process. Initially, it was based on the personal experience of one of the MNE 7 team members as to how space was used to facilitate and enable elections in Afghanistan. It has since been expanded slightly to illustrate how space might contribute to enabling activities in any remote area that lacks established logistic routes or extensive ground-based fixed communication networks.

In this instance, the process was broken into the following 5 stages: *observe, prepare, secure/shape, execute and sustain.* Rather than a generic single indicator of the level of dependency, the individual contribution of 4 space activities: PNT (P), Intelligence, Surveillance and Reconnaissance (I), Communications (C) and Weather Forecasting (W) were identified. These were then colour coded red, amber, green, as in the other case studies, to indicate the level of dependency. All are shown on the accompanying case study diagram.

Observe

Before operations can be conducted into remote areas, significant data collection will be undertaken. Since access by military forces and government officials may, in some cases, only be safely achieved by helicopter insertion, high quality mapping and intelligence will be required. Often, this may be conducted over a period of weeks or months so that appropriate situational awareness can be achieved and patterns of life established. The mapping function may also include the development of lists of suitable helicopter landing areas. These will require weather observations and surface moisture measurements from space, so that the risk of dust, a major hazard to helicopter landings in some regions, can be assessed.

Prepare

Where access by road is limited, officials and equipment such as ballot boxes will have to be airlifted to a range of locations. Additionally, intelligence gathering aircraft may be used to identify ingress and egress routes and to monitor for suspicious activity around any roads that are available. As with any aviation activity, this will be significantly dependent on space based PNT, Communications and Weather forecasting. While local forces may manage with tactical VHF or UHF ground communications, it is likely that coalition forces will require access to satellite communications both during this stage and in the following *secure/shape* and *execute* phases.

Secure/Shape

This stage may have a lower dependency on space for some elements than the other stages in the process, but a moderate to significant dependence on satellite communications is likely to occur. The dependency on access to rapidly updated weather forecasting and warnings will depend on the local meteorological characteristics of each location.

Execute

Airborne operations, troop deployment, command and control and establishment of a secure environment are likely to be at least moderately dependent on P, I and C. If surveillance is provided by one of the more complex types of unmanned aircraft during this phase, dependence on space communication links for both remote aircraft control and transfer of data will rise to significant. Satellite communication links are invariably required when unmanned aircraft are operated in 'Beyond Line of Sight' Mode. Threat warnings, particularly of the location of enemy forces and any impending hostile action will require extensive access to satellite communications, both for ground force communications and for coordinating supporting air assets. Any fixed wing aviation will also be significantly dependant on space-based PNT.

Sustain

Support to elections may only be one element in a campaign conducted in remote areas. Longer-term nation-building sustainment activities such as location of water sources for wells, development of agriculture, provision of updated mapping to name but a few, will all be dependent to some degree on space support.

Support to Governance and Security in Remote Districts

P - PNT
I - ISR
C - Comms
W - Weather

Observe
- Mapping P I C W
- Intelligence P I C W
- Demographics P I C W
- Social Networks P I C W

Prepare
- Data Fusion C
- Operational Planning P I C W
- Training Forces:
  Local P C W
  Coalition P C W

Secure / Shape
- Info Ops C
- Deployment of Forces P I C W

Execute
- Support to Government Forces P I C W
- Provide Security P I C W
- Deploy/Recover P I C W (e.g. Ballot Boxes)

Sustain
- Development Activities P I C W
  Agriculture
  Wells
  Mapping
  etc

LEXICON OF ACRONYMS AND ABBREVIATIONS

NOTES:

1. **Generic and Specific Acronyms/Abbreviations**. Some abbreviations listed below are generic, with wide meaning; others are specific, usually to a nation or, a particular service/organisation. The latter case is indicated by prefixing or including the appropriate qualification in brackets in the description.

2. **'Named' Space Missions**. Names given to space missions, or series of missions are often descriptive (for example, CORONA, Hubble Space Telescope), rather than serving as abbreviations or acronyms, though there are exceptions.

ASAT	Anti-Satellite
BMD	Ballistic Missile Defence/Defense
C/A	Coarse Acquisition (code or signal within the GPS system)
COPUOS	(United Nations) Committee on the Peaceful Use of Outer Space
EHF	Extremely High Frequency (ITU Frequency Band Designation)
ELF	Extremely Low Frequency (ITU Frequency Band Designation)
EM	Electromagnetic (radiation)
EMP	Electromagnetic Pulse
ESA	European Space Agency
GEO	Geostationary Orbit

GMDSS	Global Maritime Distress and Safety Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HEO	Highly-Elliptical Orbit
HF	High Frequency (ITU Frequency Band Designation)
ICBM	Intercontinental Ballistic Missile
IR	Infrared (radiation)
ISR	Intelligence, Surveillance and Reconnaissance
ISTAR	Intelligence, Surveillance, Target Acquisition and Reconnaissance (UK terminology)
ITU	International Telecommunications Union
LEO	Low-Earth Orbit
MEO	Medium-Earth Orbit
NASA	National Aeronautics and Space Administration (US government agency)
NUDET	Nuclear Detonation (detection)
OST	Outer Space Treaty
PAROS	Prevention of an Arms-Race in Outer Space

PNT	Positioning, Navigation and Timing
SALT	Strategic Arms Limitation Talks/Treaty
SAM	Surface to Air Missile
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communications (generic term)
SATNAV	Satellite Navigation (generic term)
SBIRS	Space-Based Infra-Red System (US missile-launch warning system)
SHF	Super-High Frequency (ITU Frequency Band Designation)
SSA	Space Situational Awareness
TMD	Theatre Missile Defence
UAS	Unmanned Aircraft System
UHF	Ultra-High Frequency (ITU Frequency Band Designation)
UN	United Nations
UV	Ultraviolet (radiation)
VHF	Very High Frequency (ITU Frequency Band Designation)
VLF	Very Low Frequency (ITU Frequency Band Designation)
VSAT	Very Small Aperture Terminals
WAAS	Wide Area Augmentation System (relating to GPS)
WMD	Weapons of Mass Destruction