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User report

Editor: Lars Höstbeck

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Executive summary

The importance of space assets has increased for both civilian and military applications. As the technology matures, the number of applications has grown. On a daily basis, most people use systems that in one way or another depend on space assets.

FOI has carried out this study with the aim of creating an inventory of functions and challenges related to space assets that are of interest to the Swedish Armed Forces (SwAF).

The study shows that space assets can be of use to the Swedish Armed Forces in a variety of ways. In Network Centric Warfare, space-based systems would seem to be important if not essential. Such systems could benefit the Swedish Armed Forces in all its four main tasks: to defend Sweden against armed attack, to uphold the territorial integrity of Sweden, to contribute to peace and safety to the world and to support Swedish society in times of crisis. Its greatest value would be in the field of international operations.

In the short term, the fastest way to ensure access to space is to buy services from commercial actors. In the longer term, SwAF should develop a military space strategy. A prerequisite for such a space strategy is to increase our understanding of the threats and possibilities associated with the military applications of space technology.

Three special areas of interest regarding space issues are satellite-related functions, anti-satellite systems and modification of the ionosphere.

For satellite related functions there are a number of applications of military interest, for instance remote sensing, early warning of ballistic missiles, communication, navigation, NBC-indication, signal intelligence and strategic as well as tactical reconnaissance. One common factor for these applications is the need for an increase in our ability to gather and analyze information due to the fact that the amount of data available will increase with access to space-based sensor systems.

There is extensive non-military knowledge about satellites today and the same is true for sensor systems that we might wish to mount on a satellite. The part that is missing is the knowledge about the combination of satellite and payload as a system for military use.

Regarding anti-satellite systems there are several different threats aimed toward the satellite or its communication channels. There are not any anti-satellite

systems in operation right now but their existence ten years from now is possible. The possibility to interfere with the communication channel between the satellite and the ground station already exists today.

Knowledge about these threats is essential to be able to appreciate threats against satellite systems and to estimate the risks of being dependent on satellite information for military needs.

The ability to modify the ionosphere gives rise to a number of military applications. Basic research on this area is required to create the ability to evaluate the possibilities. There is considerable knowledge about the physics related to the ionosphere that is connected to the research about aurora borealis[1] at the Institute of Space Physics in Kiruna, Sweden. There is no research regarding military applications in this area though.

Given the expected value of space assets to the Swedish Armed Forces and the interest shown by other nations in space-related systems, the study suggests that a process for gathering knowledge and information about military applications of space assets should be initiated. Starting with armed forces requirements, a Swedish Armed Forces space policy should be developed so that military, civilian and commercial space assets are taken into consideration. Most important is to study how space-based systems can be used to support Swedish troops in peace support operations abroad and how to increase interoperability by knowledge about and access to space based systems owned by coalition parties.

For the purpose of evaluating whether it is realistic for the Swedish Armed Forces to have their own military satellites or not, a study should be initiated to show a cost and feasibility analysis of a Swedish military satellite.

A military strategy should concern Sweden’s need to use space. The question of how to acquire the capacity to launch satellites should be further studied from these needs.

[1] Northern lights

Acknowledgements

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During 2002 a number of space related projects have been started within the Swedish Armed Forces and linked authorities. It is of interest to seek international cooperation in this area and therefore useful to have an English version of this report.

RAND made a translation of this report mainly for their interest only but it was not a complete line-for-line translation. This document is put together based on their translation with some modifications and with supplementary information from the original report. FOI has a written permission to use RANDs version based on Gustav Lindstrom’s unofficial English translation, Space and Defence, January 2002, Santa Monica, CA:RAND. Copyright RAND 2002.

Stockholm, Sweden
2003-01-07

Sandra Lindström

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1 The mission

Within the frames of strategic commitments at FOI, a decision was made to carry out a preliminary study with the theme of Space and Defence. The purpose of this project was to make an inventory of those space related functions, applications or technical systems that are or can become essential for the Swedish Armed Forces within the next 20 years and to establish which suppliers have the necessary capacity to provide these.

The project was carried out from March to May 2001 as a concentrated study with project members from different backgrounds. The project manager was Lars Höstbeck, Division of Systems Technology. Those involved in this project were:

Ola Hamnér, Aeronautics
Erik Berglund, Defence Analysis
Niklas Wingborg, Weapons and Protection
Marie Andersson, Sensor Technology
Anders Lindblad, NBC-Defence
Sylve Arnzén, Systems Technology
Ulf Ekblad, Command and Control

The project was carried out during a preliminary meeting on the 14th of March and a residential workshop between the 25th of April and the 26th of April with research in between. The group limited the task to the following questions:

What problems related to space-based systems would be important for the Swedish Armed Forces' ability to carry out their four main tasks?

What knowledge exists today and who are the actors within and outside of FOI that have this knowledge?

This report begins with a chapter entitled '**Space – what, how and why?'** that provides basic information concerning space, the characteristics of the environment and gives brief information about different satellites and why it is important to engage in space issues.

The next chapter, '**Strategies for engagements in space issues',** brings up relevant facts from a Swedish national strategic point of view and asks whether the Swedish Armed Forces should engage in the development of space systems.

The chapter '**Military functions for and in space'** presents different functions, applications, techniques or capabilities that are important to the Swedish Armed Forces within the frame of their four main tasks. The chapter is divided into three sections: Satellite related functions, countering satellites and sensors jamming together with modification of the ionosphere.

The last chapter '**Conclusions and further work'** summarizes this report and provides some suggestions for further development of this topic.

2 Space – what, how and why?

Space-based and space-related systems and methods have become more and more important for civilian applications as well as military ones ever since the first satellite Sputnik was launched by the former Soviet Union in 1957. Considerable functions that we today take for granted, for instance long distance telephone calls or access to a wide range of international TV channels, are dependent on space-based techniques. The increasing commercial investments in space technology show that the market is maturing. According to Oberg (1999), commercial interests invested $100 billion in commercial systems between the start of space activities and 1997. The figure for 2000-2005 is expected to be around $150 billion.

2.1 How to map out space

The part of space that today constitutes an environment for military as well as civilian and commercial interests is in a broader context a thin layer around the earth. One way of defining space is to state that it begins at that altitude above the earth beyond which weather balloons and airplanes cannot reach, about 40 km height. Another way would be to say that space begins where it is possible to place a satellite in orbit, at about 160 km above the surface of the earth. Both of these distances are small compared to the earth's radius of about 6378 km at the equator. That part of space that is of interest today ends, in principle, at the geo-stationary orbit at an altitude of 35,800 kilometres. To appreciate what a comparatively small area this is, we note that the distance to the moon is approximately 380,000 km and to the sun roughly 150 million km.

The atmosphere is the part of the surrounding area that contains matter and rotates with the earth in its rotation around its own axis. The atmosphere is divided into a number of layers called the troposphere, stratosphere, mesosphere and ionosphere (thermosphere). An overview of the layers is given in figure 1.

Temperature and air pressure are the factors which determine the boundaries between the different layers. The troposphere, which is closest to the surface of the earth, has the greatest air mass and it is there that the variations, which lead to weather changes, occur. Clouds usually stay within the troposphere. The stratosphere contains the ozone layer that protects the earth against UV radiation. Life here is impossible without pressurized cabins and a supply of oxygen.

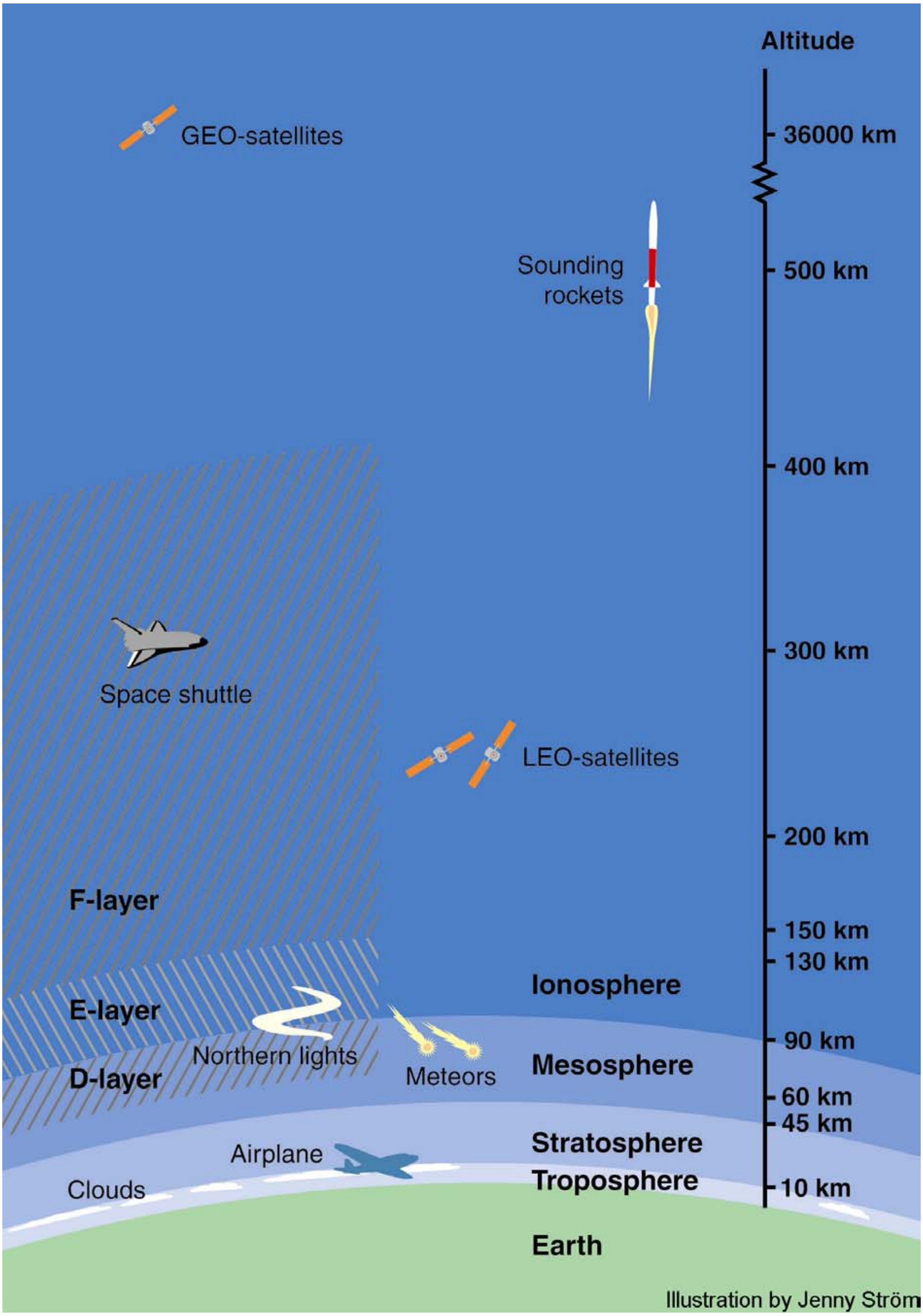

Figure 1 - A description of how the atmosphere is divided into sections

The next layer is the mesosphere that reaches up to about 80 km and here the temperature falls to the lowest in the atmosphere, to about -90° C. This layer is the last one that has a similar chemical composition to the layer closest to the earth.

Above the altitude of 80 km, the matter in the atmosphere exists in the form of ionized gas, plasma. This part of the atmosphere is called the ionosphere and is of great interest for both civilian and military applications. An example of this is the fact that radio waves are reflected by charged particles in the ionosphere and bounce back to earth, which allows communication over the horizon (OTH).

The last sphere necessary to mention is the magnetosphere of the earth. This concept refers to the area in space, which is not spherical, where the magnetic field of the earth dominates over the interplanetary magnetic field. Closest to the sun, the magnetosphere reaches out about 10 earth radii (about 63000 km) but it varies according to the solar wind among other factors.

Table 1
Examples of satellite orbits

Satellite	Height (km)	Inclination
TeleX[2] (Geostationary)	35 800	0°
GPS-satellites	20 200	55°
Hubble-telescope	590	28,5°
Mir[3]	390	51,6°
Remote sensing satellites (Reconnaissance)	Circular orbits between 100 and 1 000 km	Varies between 0 and 100 degrees
Viking	810 - 13530	98,6°
Freja	600 - 1760	63°
Astrid 1	1000	83°
Astrid 2	1000	83°
Odin	600	97,8°

[2] TeleX was put out of operation in 1999 and was moved out of the GEO orbit.
[3] Mir re-entered the atmosphere in March 2001 and crashed into the Pacific Ocean.

2.2 Satellites

A satellite is always 'falling' around the earth's centre of gravity. This means that all satellite orbits align with the equator or intersect the equator at a fixed angle called inclination, see table 1. The larger this angle is, the closer the orbit of the satellite is to the poles of the earth. A satellite with an inclination of 90 degrees (the orbit perpendicular to the equator) will reach its northerly/southerly point over the pole.

A satellite orbit is either circular or elliptic. Satellites at a lower altitude move faster than satellites at a higher altitude. An example of a satellite in low earth orbit (LEO) is displayed in figure 2. To change the altitude of a satellite's orbit the satellite's velocity parallel to the orbit has to be adjusted, not the velocity perpendicular to the orbit, according to Montenbruck, O and et al. (2000).

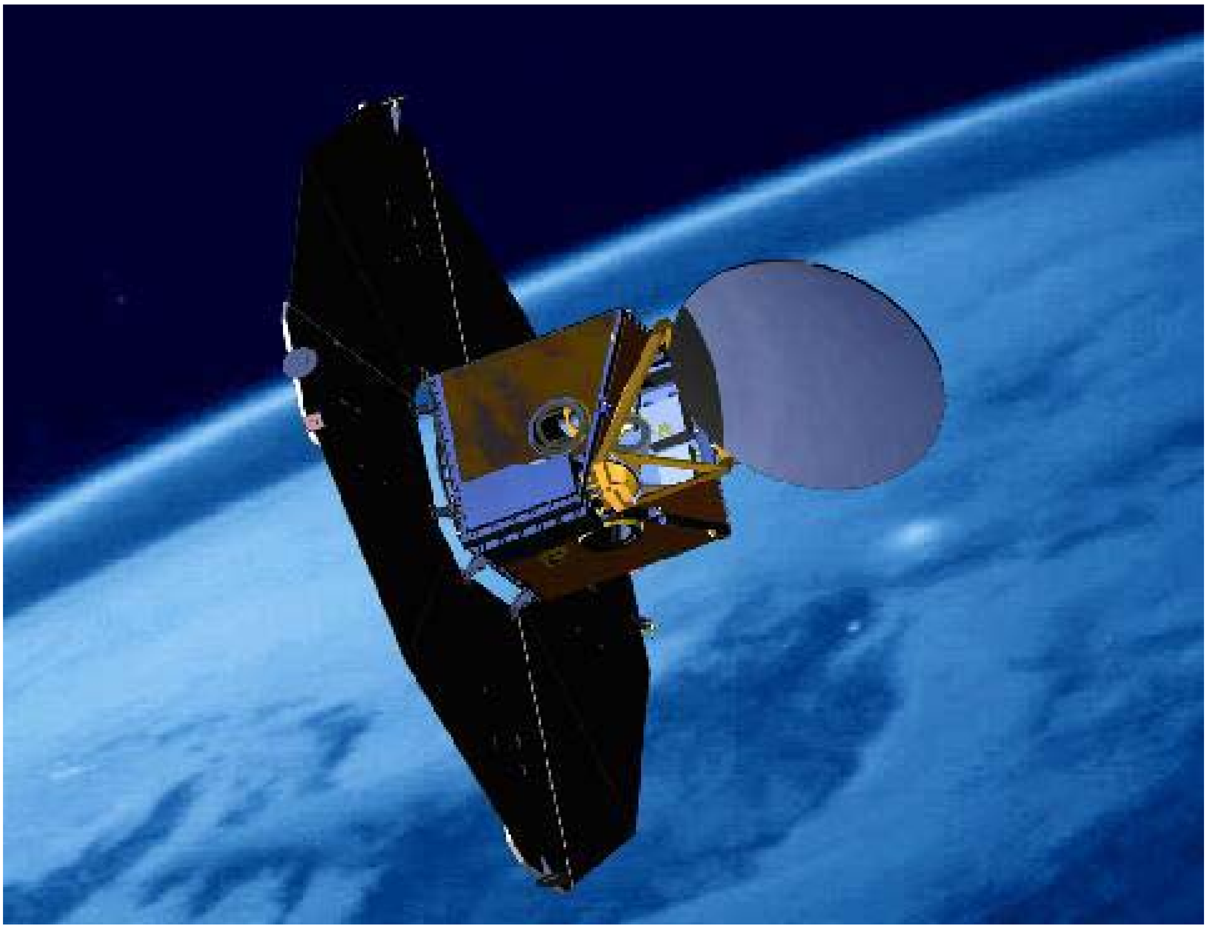

Figure 2 - Swedish research satellite Odin that was launched the 20th of February 2001 from Svobodny in Siberia

The fact that the satellite as well as the earth is rotating will result in a satellite not necessarily passing over the same point above the earth every revolution. The geostationary (GEO) orbit is the only orbit where the satellite appears to stay above the same point but there are a great number of orbits that have such characteristics so that the satellites repeatedly pass over the same points above the surface of the earth. Since every satellite orbit has to rotate around the earth's centre of gravity the only possible geostationary orbit is an orbit that is exactly parallel with the equator.

2.3 Launch and life limits

Satellites have a limited lifespan that is determined by their electronic system, fuel supplies and air resistance. Which of these factors turns out to be the weakest link depends on the satellite's orbit. The time a satellite spends in orbit is referred to as its orbital life and is dependent on the initial altitude of the orbit, see table 2. The lower the altitude, the greater the air resistance slowing down the satellite and thus the more fuel that will be needed to adjust the orbit. The time the satellite is operational and located in the correct orbit is referred to as its design life.

Table 2
Orbital life for satellites at different altitudes[4]

Height (km)	Orbital life
250	1 month
450	10 years
1000	1000 years

A realistic estimate is that the design life of a satellite in a low earth orbit is between 5 and 10 years. For a geo-stationary orbit, the design life approaches 15 years.

To be able to have access to a satellite in orbit at a certain time there is a choice between two strategies: to always have a satellite ready in orbit or to launch a satellite as per need. The first alternative implies that new satellites would have to be launched at regular intervals to replace those that fail. The second alternative means that a satellite always has to be ready for launch on demand.

[4] According to Sven Grahn, Swedish Space Corporation.

Depending on the time factors regarding the launch, there might have to be a launch vehicle rocket readily available. The shortest time possible for launch is calculated to be three months, providing that a rocket and satellite are readily available. However, such a rapid effort can be costly since one must be able to pay to get first in line for launch. The great costs for ‘launch on demand’ and the waiting period of three months make the first alternative, to always have a satellite in orbit, preferable.

One way to cut back on the waiting period would be to have a national ability to launch satellites. Such an opportunity will also provide independence regarding other areas such as restrictions on export and other similar issues.

Figure 3 - The American rocket Pegasus under a B-52. Pegasus is here used to place a satellite into orbit from an airplane (Photo by NASA)

In a study by LUTAB[5], financed by FMV, the idea of launching satellites with a launch vehicle that is released from a 37 Viggen plane is presented. The Rimfaxe launch vehicle is able to launch a 50 kg satellite into low earth orbit.

[5] Rimfaxe is a Swedish ”Pegasus light”. A study still in progress at LUTAB.

The American Pegasus that is released from a bomber (B-52), as in figure 3, serves as a model for Rimfaxe.

2.4 Swedish satellites

Sweden has built satellites and instruments on its own and in cooperation with other countries for the past 20 years. As a result, it has the competence to build satellites independently for its own needs, see table 3. Five of the satellites listed in table 3 are for research. Costs shown indicate the entire project costs, including the cost of launch.

Table 3
The purpose of Swedish satellites, their weight and cost (not including payload) in 1995[6]

Satellite	Application	Weight (kg)	Cost	Year
TeleX	Communication	1100	2 000 million Swedish crowns	1989
Viking	Northern lights research	286	$40 M	1986
Freja	Northern lights research	214	$19 M	1992
Astrid 1	Northern lights research	27	$1,2 M	1995
Astrid 2	Northern lights research	30	$2,5 M[a]	1998
Odin	Astronomy- and atmosphere research	240	$35 M[b]	2001

[a] including a new ground station
[b] including payload (a radio telescope)

2.5 Fighting systems and deterrence systems

To combat a ballistic missile in its trajectory is difficult. The missile will continue in its ballistic trajectory whether or not it is attacked. The risk of a large-scale attack with hundreds of missiles is basically non-existent but the risk of a terror attack with occasional missiles is increasing considerably.

[6] The information is taken from the report "Technical, managerial and financial aspects of a possible future Swedish satellite programme, Swedish Space Corporation SSB490-4, October 2000. The TeleX data is provided by Sven Grahn, Swedish Space Corporation.

Information technology as well as methods for signal processing and control engineering have been developed to a state where it might be of interest to develop space based systems to be able to counter occasional terror missiles from space.

As the civil and military sectors become more dependent on space-based systems, their value from a military perspective increases. It is becoming increasingly vital to protect those assets. It has become so important that the US research organisation RAND[7] has argued that part of the national objectives for US engagement in space issues are “Ensuring continued freedom of, access to, and use of space” and “Deterring threats to U.S. interests in space and defeating aggression if deterrence fails”, see Johnson (1998). Even if it is not exactly stated how these objectives are to be achieved, it is difficult to see how this can be done without placing weapons in space.

As more and more countries gain access to increasing numbers of space-based systems, any future opponents will be vulnerable to attacks on such systems. The military potential of neutralizing an opponent’s command systems by preventing their use of satellites is simply too large to be ignored. Overall, current trends speak for a more militarised space in the next twenty years.

The question of weapons in space can be seen from three perspectives: space-to-space, space-to-ground, and ground-to-space, according to Handberg (2000). Regarding a Swedish space strategy, the most relevant threat is obviously the threat against systems in use—our own, commercial, or coalition partners—and the effect such a threat has on the development of space strategy, military doctrine, and command systems. Threats against our own systems can be broken down into four categories (Oberg 1999):

- Threats to the spacecraft/satellite
- Threats to the communication linkage
- Threats to ground-stations
- Threats known as ‘mission attack’ (political and diplomatic)

In this study, we will focus on ‘ground-to-space’ threats, in which we include airborne and other threats to satellites.

[7] RAND www.rand.org

2.6 Affecting space from earth

The ionosphere consists of plasma, which is a gas where the atoms and the molecules have decayed to free positively charged ions and negatively charged electrons. Different molecules ionize at different altitudes and special mechanisms contribute to the ionization. This leads to a division of the ionosphere into different layers called D, E, F_1 and F_2 with D closest to the surface of the earth and F_2 at the top, see figure 1.

A measure of the ionization in the ionosphere is the electron density at different altitudes. The electron density is at its maximum at the altitude of about 250 km. A characteristic of the plasma in the ionosphere is that it reflects radio waves and that the reflection is such that a certain frequency reflects at a certain electron density. The higher the frequency transmitted, the higher the electron density demanded for reflection.

UV-radiation from the sun is the most important source of ionization in the top layers (F_1 and F_2). This leads to the electron density in these layers varying from day to night, with the greatest difference for the F_1 layer (at about 140-200 km altitude) where in principle the electron density disappears at night to reappear at sunrise.

This mechanism explains why the reception of long wave transmission is best at night. The ionosphere then has better characteristics to mediate long wave transmissions over long ranges (Fälthammar 1990).

Some areas can be changed locally by affecting the ionosphere from earth. Influences can, for instance, occur by transmitting microwaves towards the ionosphere which will contribute to the ionization of the plasma. The great advantage of such technology is to have control over the ionization in an area and thereby its ability to reflect radio waves.

Radio transmissions over long distances or radar that looks over the horizon (OTH) are normally dependent on natural ionization and thereby sensitive to random variations but they can become more or less independent of the natural variations. This technique is called ‘Artificial Ionosphere Mirror’ (AIM) and is based on irradiation of a certain area in space from a transmitter on earth, see figure 4 also in line with House et al. (1996).

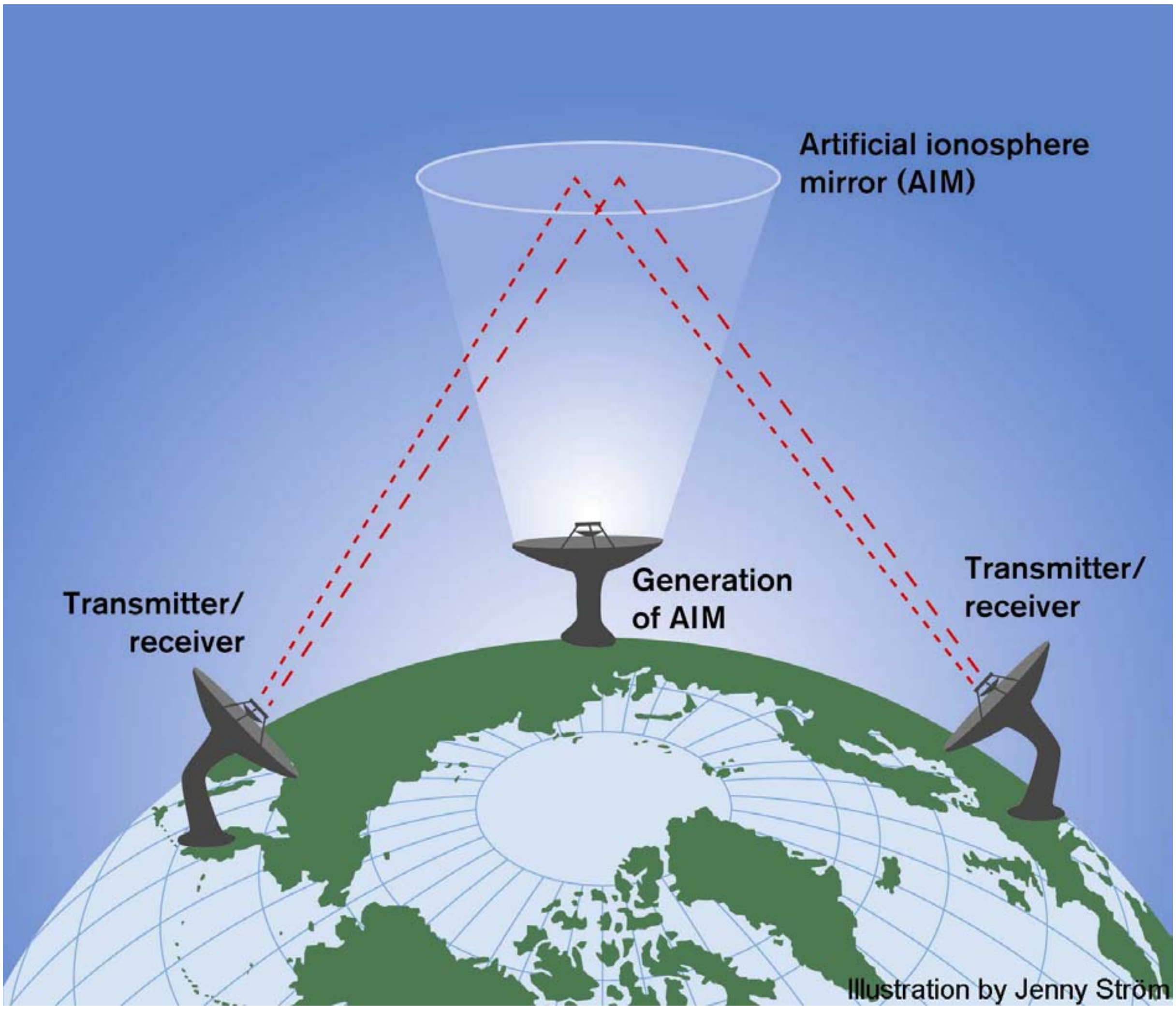

Figure 4 - The principle for AIM

2.7 Space and Network Centric Warfare

The Swedish Armed Forces have commenced a transition towards a new defence posture. This new focus—"Network Centric Warfare (NCW)"—refers to a conscious usage of information technology to increase the effectiveness of the armed forces. NCW is based on a functional division of sensors and command and action functions to ensure that tailored combinations can be fused for each task while all components in the system have access to needed information. Internationally, this is known as Network Centric Warfare[8] (Alberts et al. 1999).

[8] The official Swedish term used is Network Based Defence, in Swedish NBF for short.

One of the foundation stones of NCW is the use of a network of sensors connected to an information-infrastructure to ensure what is commonly referred to as Dominant Battlespace Awareness—a detailed and accurate picture of the chain of events in real time. Satellites are essential in such a system, providing platforms for sensor and communication capabilities. Within FOI, studies concerning NCW have been collected under what is known as FoRMA, see André et al. (2001) and Söderqvist et al. (2001).

2.8 Laws in space

Early in the 1960s the importance of regulating the use of space were realized. This led to the Outer Space Treaty in 1967 that forbids weapons of mass destruction in space and military activities directed towards celestial bodies. Nuclear weapon tests in space had already been forbidden in 1963 in the so-called Partial Test Ban Treaty. After that, a number of treaties were signed up until 1979 such as the Rescue Agreement, Liability Convention, Registration Convention and the Moon Agreement, see table 4 in appendix A. In addition to these international space treaties directed by the UN there are some bilateral agreements between the USA and the Soviet Union/Russia concerning space.

3 Strategies for engagements in space issues

The Gulf War in 1990-1991 is sometimes referred to as the first “space war”. The operative concepts used in the Gulf War are often regarded as the precursors to concepts outlined in Joint Vision 2010. Joint Vision is the basis for what often is equated with Network Centric Warfare.

A succinct summary of the use of space-based systems during the Gulf War is as follows: “Space was no longer a luxury or an item nice to have, rather it became a vital force” referenced to Handberg (2000). Functions identified as important in relation to space-based systems during the Gulf War were intelligence gathering, weather monitoring, missile warnings, navigation and communication. The majority of these functions are of interest to the Swedish Armed Forces as it reorients itself towards NCW - increasing its focus on information and command systems.

The military is becoming increasingly dependent on the commercial sector due to its development of space technology. As an example, 45% of the communications between the Middle East and the US during the Gulf War were routed through non-military satellites. According to American estimates, about 60% of military satellite communications and 25% of reconnaissance pictures will come from commercial satellites by 2010, Cynamon (1999).

If Sweden wants to follow the international trend and take advantage of the capabilities offered by space-based systems and what they can offer to the Armed Forces, several strategic questions need to be answered. In the short term, it is likely that the best means of gaining access to space based systems is to purchase services from commercial satellite operators. One disadvantage with such a set-up is that commercial services are not optimised for military use. By the same token, these assets cannot be controlled: we risk being disconnected from image access during a crisis due to another actor’s involvement.

One strategy to alleviate this weakness within the framework of a Swedish national space strategy is to weigh up military, civilian, and commercial interests and allocate assets accordingly in order to gradually meet defence-related needs in a Swedish space program. This is a considerably more ambitious approach than simply buying commercial services. Another way to satisfy military requirements is to become part of an international military cooperation process in the field of space issues. It is likely that such a partner would be found in Europe rather than the US. To date, military space cooperation has taken place within the framework of the Western European

Union (WEU) where Sweden is not currently a full participant according to McLean et al. (1997).

Several countries that took part in the coalition against Iraq during the Gulf War are the ones that are expected to lead future coalitions where Sweden and the Swedish Armed Forces will participate. It implies that we will work together with troops who base their tactics on the existence of space-based systems and are trained to perform missions with the support of space-based systems. If we do not have the same ability, we risk taking part in these operations on other inferior conditions or not taking part at all.

Examples of different military strategies for space issues are outlined in the American study “Space: Emerging Options for National Power”, written by Johnson (1998), where three different military strategies for the US are presented: *Minimalist*: minimal military engagement with the largest use of commercial systems; *Enhanced*: military space based systems that are strongly integrated with the other fighting services; and *Aerospace Force:* military systems in and for space form their own fighting service.

Even if our goals and possibilities are not similar to those of the US, we can use an analogous manner to identify different strategies at both a national and military level. These strategies should be identified and assessed to outline a relevant space strategy for Sweden.

4 Military functions for and in space

4.1 Satellite related functions

Satellites are used today in a series of functions, both civilian and military. The satellite in itself is only a platform. The payload determines the function of the satellite. The orbit of the satellite is chosen based on its field of application and the kind of payload it carries. Typical functions for satellites are reconnaissance, communication and navigation/location.

The most important payloads are supposedly different kinds of sensors for reconnaissance, surveillance or targeting. There are active sensors as well as passive sensors. The active sensors are for instance radar and synthetic aperture radar (SAR), passive sensors are signal intelligence (SIGINT), infrared reconnaissance (IR) and optical reconnaissance.

Different sensors have different capabilities and are suitable for different types of targets. Photo-reconnaissance has been used for the detection of airplanes, missiles or tanks and SIGINT has been used to locate ships at sea. IR can be used for the detection of flames from rocket engines and SAR has a certain capability to penetrate vegetation and can be used for the detection of vehicles that are hidden under trees. Different types of sensors can also gather information about the environment.

The sensor systems on satellites are mainly radar and infrared sensors. Infrared sensors are passive and they take multi-spectral pictures that give information about terrain/water. Laser systems on satellites are not common. The USA is probably in the front position of developing laser systems for space applications but how often they are used from satellites is unknown. At the moment there are operational, ground-based laser systems that track and identify satellites. The systems are among other things used for military purposes.

4.1.1 Remote sensing and weather satellites

The concept of gathering and processing data from a distance is referred to as remote sensing. There are several different platforms for sensors, for instance airplane or weather balloons, but it is the space-borne system that provides a continuous coverage in both time and space.

Within the framework of NCW, information superiority is an important component. In the quest for such superiority, the use of remote sensing functions is critical according to Ekblad (2001). An important function is to obtain the data in the form of—for example—radar, satellite photos or SIGINT data over areas that are not covered by other sensor systems due to territorial boundaries. This includes the capacity to obtain information on remote areas of operations prior to entry into that area by Swedish personnel.

A great benefit for the armed forces is to integrate the remote sensing functions into the command support system. By collecting data and feeding it into weather or oceanographic models, weather and water quality predictions can be provided in areas of operations, around ships, and other nearby areas. This knowledge can then be used to predict ranges of sonar, radar, and laser systems. Command support systems with this capacity improve the possibility to plan operations, minimize the risk of discovery, or optimise search patterns with available assets with respect to the prevailing conditions. The benefit of this command system occurs at all levels, with the focus on real time usage at the tactical level—for example at tactical headquarters.

4.1.2 Defence against ballistic missiles

Discussions have been held on the feasibility of creating a operational defence against ballistic missiles ever since a ballistic missile was used for the first time in the autumn of 1944. One of the challenges associated with countering such missiles is that they “do not fly”; they fall freely in the gravitational field and continue in a trajectory even after being hit by a surface-to-air missile. In two wars where ballistic missiles were used —WWII (V2 missiles) and the Gulf War (Scud missiles)—, the defensive manoeuvre was to seek out and counter the launch pad. The defence systems against strategic missiles in place by the US and the Soviets during the Cold War were based on nuclear “antimissile” missiles, Handberg (2000) and Rydqvist (2001). A description of the missile threat against Sweden is given in the report “Missile Threats Against Sweden”, Axberg et al. (2001).

Ballistic missiles have different ranges, from short ranges that reach hundreds of kilometres in about five minutes called Theatre Ballistic Missiles (TBM) to the Inter-Continental Ballistic Missiles (ICBMs) with ranges of up to thousands of kilometres with a trajectory of around 30 minutes. The longer the range, the higher the missile reaches at the highest point of its trajectory. A missile with a reach of 100 km does not go any higher than 40 km above the surface while a missile with the target at 3000 km reaches heights of around 600 km see Ekblad et al. (1995).

Due to the trajectory of ballistics missiles they are hard to detect with ordinary surveillance radar. In “normal cases”, ground based surveillance radar aiming to detect aircraft and cruise missiles have an altitude range of 30 km (in a best-case scenario). In its first phase, a ballistic missile passes this altitude in a few seconds and may at most give out a few echoes on the radar. Nonetheless, with IR and other heat sensitive techniques, it is easy to discover the missile in its boost phase. This means that the boost phase (when the engine is burning) is the part of the trajectory in which the missile is easiest to lock on to.

The problem with radar surveillance also occurs at the terminal phase when the missile is on its way down through the area of radar coverage. At this point, there is no rocket engine to provide an IR signature. On top of this, if the missile is detected at this stage, there are only a few seconds left until impact, which allows too little time for countermeasures. As such, countering in the first and final phase respectively does not share similar characteristics. An additional factor as regards the challenge of defending oneself against ballistic missiles is their significant speed, especially on their way down - making a hit even more difficult.

To attain the longest warning time possible and thus the greatest potential for counter attacks, detection of the missile is needed during the start phase (initial phase). Since the launch can take place in a geographically remote area, there is a need for reconnaissance systems with a long range. To predict missiles’ trajectories and impact points—thereby supporting the countermeasures—it is desirable to follow the missile in its path, even at high altitudes. It is therefore natural to exploit satellite-based reconnaissance systems.

Experiences from the Gulf War show that even for TBM with Scud characteristics (short air time, low “highest point”) satellite-based systems were useful, both for warning against incoming attacks, assistance to Patriot missile batteries and to locate launch positions.

The sensors used on satellites to detect ballistic missiles are radar/SAR, optical/IR and signal intelligence (SIGINT). Radar surveillance can, together with SAR, be used to locate launch ramps. The same applies to optical reconnaissance. It was optical flight reconnaissance that discovered the Soviet missile ramps in Cuba 1962. Signal intelligence is expected to give a warning in the form of a transmission pattern change in conjunction with a launch. IR can be used during the initial phase to detect the flames from the missile motor and radar to follow the missile during its trajectory.

Common to all these systems is that if they are to be used as a warning against medium and long-range ballistic missiles aimed against Sweden, they cannot be ground-based or airborne since the necessary ranges cannot be reached. There will probably be a need for satellite-based systems. This is certainly an area for international cooperation, especially within Europe.

A capacity for early warning of an impending attack is a key contribution made by satellite-based systems. If the system can locate the point of origin of a missile, there is always the possibility to take out the launch pad.

In the short term, these capabilities are of greatest value for Swedish troops involved in international operations where the threat will most likely be in the form of TBM. Since Swedish troops will most likely be involved in international operations in coalition with others the capability for cooperation with potential coalition partners in the field of early warning is crucial.

In comparison to ground-based or airborne systems, satellites have the advantage of long ranges and can in many instances cover potential tension areas—e.g. the Balkans. Such capability probably shortens the time limit for going from a political decision to actual troop deployment into the area of operations with complete protection.

A great deal of research and development around sensors, signal processing, data fusion, and communications systems is necessary to build a satellite-based system that provides sufficient information at the right time for an accurate early warning. Methods and routines to integrate the information into the command systems is an obvious requirement. Of importance, yet difficult, is the capacity to process information from early warning sources (e.g. of an impending ballistic missile attack against Sweden) and use this information in a constructive manner for civilian society.

To gain strategic and tactical advantage from an early warning system, one or more of three capabilities are needed: the capacity to neutralize an incoming missile; the capability to evacuate the target area; or the ability to neutralize the missile's launch pad after it hits its target. If these capabilities are not available, the information from the early warning system will fulfil the somewhat limited function (at best) of pointing out the guilty party after the attack. It is worth noting that the American efforts for a "high-altitude" defence against TBM, THAAD (Theatre High Altitude Area Defence) have encountered a number of technical problems. Needless to say, much research and development is needed for the development of missile countermeasures.

4.1.3 Communication

Communication can go via a satellite in a so-called geostationary orbit. The advantage is that one single geostationary satellite can cover about 40% of the earth's surface. With three geostationary satellites, the entire earth—except for the polar areas—can be covered. The disadvantage of this system is the long distances. With a satellite in a low orbit, contact can only take place for a few short moments a couple of times per day. To overcome this, there are systems with many satellites.

a) Radio communication

Nations and organizations that have their own military satellite communications capability (transponder and satellite) include NATO, the US, the U.K., France, Italy, Spain, and Russia. The US uses commercial satellite systems for non-sensitive military communication.

With satellite communication, the Armed Forces can obtain lines of communication to and from Sweden with troops serving in international operations. In addition, communication can be established in areas lacking terrestrial telecom systems. During international operations, communications can be maintained between reconnaissance platforms (UAVs, aircraft, etc.) and units that cannot be reached due to the terrain, for example the mountains in former Yugoslavia.

The future will probably lead to closer cooperation between nations' armed forces. Using satellite communications represents one way of ensuring that communications between units of different nations are interoperable.

There is a need for satellite communication for troops out on international operations, aircraft, ships and army units. In principle they all need it for transmission of data, communication over long ranges and communication within or to and from areas with a bad infrastructure.

To understand the possibilities and risks involved in satellite communication it is necessary to understand how a satellite's orbit affects its purpose. In the case of communications, you also have to be familiar with antennas and antenna systems. In addition, you need to know about jamming techniques and counter jamming methodologies. It is also vital to know different types of stealth techniques, such as choice of frequency, code selection, power control and beam pointing. Knowledge in all these areas is necessary to efficiently use satellite communication both strategically and tactically. To purchase/build and integrate such systems, there is also a need to know about satellite platform techniques and control mechanisms and steering mechanisms. Within the private space industry, Ericsson (with Saab Ericsson Space and EMW) has knowledge of how antennas are built.

b) Optical communication

Demonstration of free space laser communication, both in the atmosphere and in space, has been carried out since the invention of laser technology in the 1960s. The most surprising demonstration perhaps took place in December 1992 when NASA via JPL communicated from the ground to the spaceship Galileo using a green laser. The distance was over 6 million kilometres.

Free space laser communication has received increasing attention due to the following factors:

- High transmission capacity compared to RF-links, potentially tens of Gbits/second for long distances with wavelength multiplexed proportionally to the number of wavelengths.
- Smaller, easier and cheaper links in comparison to an RF-link.
- Directional selection; transmitting and receiving lobes on fractions of milliradians and antenna dimensions in centimetres. This allows good reception while complicating jamming and triangulation.
- By using already existing fibre optic networks one can connect directly to a system with high capacity.
- No need for frequency-choice planning.

In 1991, the US Navy demonstrated that it is possible to communicate between an aircraft and a submerged submarine. The final goal was to place a laser in low satellite orbit for this type of communication with strategic submarines. Tactical links have been demonstrated but due to questions of cost and availability, this technology has not been further developed.

Data from remote sensing satellites are linkable to communication satellites in GEO or LEO for the purpose of downloading data in real time when there is not direct contact with the ground station. Contact between a laser satellite and a ground station can be hampered due to cloud cover. The problem can be solved through a network of multiple ground stations appropriately spaced from each other.

Some projects in this area include:

- BMDO (Ballistic Missile Defence Organization) and DARO (Defence Air Reconnaissance Office) that carry out laser communication projects, including links between satellites/aircraft and ground stations.

- Astro Terra (US) works with JPL and has demonstrated a 32-channel laser link from the ground to satellite with a capacity of one Gbit/second.

- Matra (France) has built a 50Mb/s laser link between SPOT 4 and a GEO satellite.

- ESA's (European Space Agency) SILEX program represents the first operative satellite that uses laser to send earth-resource satellite data to a relay satellite.

- Japan has a test satellite with laser-based communication. The goal is 10 Gb/s and adaptive optics are deemed necessary.

In Sweden, the armed forces have practical experience of satellite communication for international operations in the former Yugoslavia. The FMV (Swedish Defence Materiel Administration) has knowledge of current systems and their use in international operations. FOI is currently carrying out research in free space laser communication, see Bolander et al. (1999).

4.1.4 Navigation

Satellite navigation was introduced in the early 60s with the American system Transit or NNSS (Navy Navigation Satellite System). This marked a new era in positioning systems. Satellite navigation techniques have continued their development and are increasingly space-based.

The satellites in the American Global Positioning System (GPS) have a circular orbit at an altitude of 20000 km and the time for one revolution is 12 hours. The satellites use passive measuring for distances and the system is based on using precise clocks in the transmitter and the receiver for measuring the time it takes for a pulse to be transmitted from at least four satellites to the receiver. This will determine the position, the height, the time and the speed.

The positioning error is today of approximate size 5-10 m military and 10-20 m civilian. The error in time in the receiver's clock is reduced to less than 0.1 microseconds.

For many years, there has been a program for a European counterpart to the American GPS system. The system, known as Galileo, will be similar to the future (versions of) GPS. It will be independent of the GPS system but compatible with it. Galileo is open for international cooperation. The EU and ESA are responsible for R&D. The system is planned to be operational around 2008.

"Without GPS no wars can be won" was a spontaneous comment from Western senior military commanders in conjunction with the successes during the Gulf-War. Today, there is a more tempered view, especially given GPS's sensitivity to jamming which has led to increased consideration of methods to improve reception protection.

The military requirements for a navigation system are that they fulfil the needs of being autonomous, jam-secure, global, precise, accessible, and cost effective. Due to its sensitivity to jamming, the GNSS (Global Navigation Satellite System) can only partially meet military requirements.

Future "tele-threats" to satellites will increase as the military expands its use and dependency on space based navigation technology. Due to the low signal strength at the surface of the earth, satellite signals are very vulnerable to local jamming using airborne or fixed noise generators. Through integration, "stiff"-navigation, terrain navigation, and jam-reducing software algorithms, the possibility to deliberately jam a satellite navigation system should be reduced.

For precision bombing, a variety of methods have been developed to support GPS-based positioning that greatly increase precision, especially for missile use. Use in cruise missiles turns out to be a very cost-effective method. A bonus effect of the significant time precision in GPS is that it can be used as time-reference in multi-static radar. As the precision of the navigation and positioning system improves, it is necessary to similarly maintain precise mapping functions. Another requirement for the use of precision weapons, such as missiles used against fixed objectives using differential GPS, is that the objectives are correctly entered into the missile navigator's individual reference system. This is most easily done by placing a receiver close to the objective during peacetime and reading the position off directly (or indirectly) with a laser distance reader. Alternatively, one can use triangulation via photos from satellite reconnaissance.

Knowledge of and information regarding "satellite based radio navigation" exists within a handful of Swedish entities, companies, and civilian enterprises. Examples are Armed Forces HQ, FMV, FHS, FOI, Saab Ericsson Space, Technical universities, and SGIC (Scandinavian GPS Industry Council).

4.1.5 Nuclear, Biological and Chemical Indication

Traditional indication methodologies for nuclear, biological and chemical weapons are based largely on indication instruments close to production areas. The exception is nuclear identification, as nuclear tests, which since 1963 have been monitored by satellite based systems. Today, these are integrated onto GPS satellites and the sensors are used to detect x-rays, visible light, and EMP.[9]

The work is carried out by the US Department of Energy and is part of the cooperation for overseeing the Comprehensive Nuclear Test Ban Treaty (CTBT). Sweden and FOI are part of this cooperation.

In recent years, a variety of systems have been developed to remotely identify substances within the chemical sector. The United States leads the research and development phase, much of which has come about due to the increased attention to nuclear, biological and chemical (NBC) weapons for terrorist acts.

The systems that are commercially available today, either currently on sale or still in the production phase, are not sufficiently sensitive to allow for a space-based detection of NBC-weapons use, except nuclear explosions. Current efforts are focusing on detection levels and increasing specificity while integrating the systems into ground and air based platforms (e.g. UAVs) in accordance to Dunn et al. (2000).

Much research is being done today, primarily in the US, to integrate BC-sensors on space-based platforms. It is at present difficult to evaluate the possible development of system capability during the next 20 years. Tests with ground-based remote sensing systems used to identify chemical weapons have been carried out at FOI, see Fällman et al. (2000). An example of such is shown in figure 5.

[9] Monitoring Nuclear Treaties and Agreement www.nn.doe.gov/monitor.shtml 2001-05-17

Figure 5 - Remote Air Pollution Infrared Detector (RAPID)

The current weather conditions in an area of operations often determine the efficiency of NBC weapons. The availability of satellite based weather maps and the possibility to predict weather situations is therefore vital to be able to foresee the consequences of NBC weapons.

An important part of the progress being made in the survey of possession, proliferation and reduction of weapons of mass destruction are the different forms of information gathering carried out with the help of space-based systems. Several successful surveys of nations that hold hidden nuclear and chemical weapons have been done with the help of space-based photo and radar information. Even commercially available information has been used successfully in line with Albright et al.[10] [11]

The industrial infrastructure that is needed to create weapons of mass destruction varies according to their characteristics. Nuclear weapons probably require the most complex infrastructure and are therefore difficult to camouflage from space-based surveillance systems.[12] Even chemical weapons requiring large-scale production, maintenance, and testing can be discovered through

[10] www.isis-online.org
[11] Viewing Syria's strategic missile infrastructure from space, Jane's Int. Rev., 1998, (10)4, 24-25.
[12] www.fas.org/spp/military/program /masint/caliope.htm 2001-04-17

space-based agents. Biological weapons, on the other hand, do not require a complex infrastructure and are therefore believed to be able to avoid detection from space-based systems.

4.1.6 Signal Intelligence

Signal intelligence is picking up radio signals at short or long distances. The strength (power) of the signal received decreases with the distance squared. Since the geostationary orbit lies 50 times further away than orbits close to earth it is more difficult to detect signals from a geostationary orbit. This can be overcome by using very large antennas.

Signal intelligence from a satellite is primarily of interest on frequencies where the ionosphere does not limit the propagation of signals from the earth's surface to a satellite. Roughly speaking, this means short-wave frequencies and higher, i.e. over 30 MHz.

Naval Ocean Surveillance System (NOSS), sometimes called *Whitecloud*, is probably the most advanced satellite signal intelligence system in the United States. Reconnaissance is mainly targeted to ship-based radar to establish a ship's position. NOSS consists of a mother (main) satellite and three "slave satellites" in a constellation (cluster) with an orbit height of 1,100 km and an orbit time of 107 minutes. The slave satellites are positioned 50-100 km apart from each other. They have antenna and receiver equipment. Measurement data is transferred to the mother satellite on frequencies around 1430 MHz. The information is probably customized at the mother satellite before it is sent to the ground. The mother satellite is approximately 200 km ahead of the slave satellites. The system establishes the position of an object using a combination of TDOA (Time Difference of Arrival), i.e. measuring the arrival time of individual radar pulsations to the three slave satellites, and interferometry. The accuracy is estimated to some kilometres.

Russian satellites are believed to be able to precision-position radar stations with an accuracy of roughly 10 km. The Russian satellites named EORSAT (ELINT Ocean Reconnaissance Satellite; ELINT= ELectronic INTelligence) are estimated to be able to position with an accuracy of 2 km.

USA and Russia are said to have signal intelligence satellites for monitoring communication. Their performance is unknown. Some of them are supposed to be in the geostationary orbit. Some examples of SIGINT satellites, in addition to the ones mentioned above, which have been in existence for several years, are:

- *Rhyolite*, American geostationary SIGINT-satellite
- *Argus*, American geostationary SIGINT-satellite
- *Chalet*, American geostationary SIGINT-satellite
- *Magnum*, American geostationary SIGINT-satellite
- *Zircon*, British radio SIGINT-satellite
- *Jumpseat*, American geostationary SIGINT-satellite
- *Cerise*, French satellite
- *Clémentine*, French satellite similar to Cerise with several frequencies
- *Zénon*, French SIGINT-satellite for radio- and radar-SIGINT with frequencies between 1 and 20 GHz, which is to be launched at the earliest in 2004

Signal intelligence from land, sea and air is today important from a strategic and tactical point of view when it comes to intelligence purposes. By complementing such signal intelligence with reconnaissance from space one could offer additional sources of information that can be used to verify information that has been gathered in traditional fashions. A continuous SIGINT function with good range also has an important role to play when it comes to the development of a threat library.

On the Swedish side, SIGINT satellite data would be analyzed by the Military Intelligence organization, after which the information would be provided to relevant stakeholders using regular channels. SIGINT represents an additional information layer that can be included into the information structure (which is an indispensable foundation for network centric warfare).

Those who want to protect themselves against signal intelligence should understand the various reconnaissance threats which currently include SIGINT from satellites. The possibilities and risks involved in the use of SIGINT satellites should be categorized according to SIGINT from geostationary satellites versus LEO satellites. Among other things, this serves to analyse the effects of distance on the capabilities of SIGINT satellites.

Within the framework of international operations, it would be of interest for the commander on the ground to have access to SIGINT data from other nations' SIGINT resources. This requires well-established international contacts and agreements on the harmonization of techniques used in command systems so that data from other sources can be incorporated into the overall system.

In Sweden there currently exists substantial knowledge within FRA and FOI regarding signal intelligence from both tactical and technical aspects. Satellite knowledge can be found, among other places, within the Swedish Space Corporation. To piece together these SIGINT competencies is more a question of technical construction and development than research. The challenge lies more on the plane of international cooperation—having access to data from countries that today operate satellite based SIGINT systems.

4.1.7 Using satellites for strategic and tactical reconnaissance

One of the first practical uses for military space technology was strategic photo reconnaissance. The capability to use satellites for reconnaissance missions has gradually been developed to include several types of sensors and usage areas.

According to an American study, McCall et al. (1995), the vision for the immediate future for a satellite-based military system for continual global surveillance and object reconnaissance consists of (among other things):

- Continual (limited by weather conditions) multi-spectral surveillance with 10-meter resolution and 2-3 meter accuracy for positioning.

- Continual positioning of radio transmitters with 10-meter accuracy.[13]

- Hourly pictures from synthetic aperture radar (SAR) with a resolution of 1 meter.

- Fusion pictures once a day from multi-spectral optical sensors and SAR with better than one meter resolution.

The continual surveillance described above is boosted through optical sensors providing 10 cm resolution for detail-oriented reconnaissance. Other documents[14] discuss an American system of reconnaissance satellites with SAR that should be capable of providing 1-meter resolution in GPS coordinates and have a 2-minute delay in sensor-to-shooter connections.

Commercial remote sensing satellites currently have sufficiently good resolution to be interesting in military situations. Nevertheless, commercial systems pose

[13] We do not take a position on whether this accuracy is viable.
[14] For instance Technology for Future Precision Strike Missile Systems, NATO RTO-EN-13AC/323(SCI)TP/25, September 2000.

several disadvantages, see Ekblad (2001). Even if they can have the same capabilities, civilian systems are not optimised for military needs. For example, passes over the Swedish territorial proximity occur during a limited part of the day, effectively limiting military applicability.

The quality demands on the sensor information vary substantially depending on the application. When limiting the demands to the needs in combat, the parameters are described according to table 5.

According to Ekblad (2001), it is doubtful that the performance of a commercial satellite would be adequate for fire control of weapons in accordance with table 5. The exception is fixed ground targets that could be localised with sufficient precision. Satellites should be used though for detection and localisation as a means for pointing out targets for other sensor and weapon systems.

Table 5
Performance requirements for space-borne reconnaissance systems to be able to fight targets

	Fixed ground targets	Mobile ground targets	Sea targets	Air targets
Resolution	1 m	0,1 m	10 m	10 m
Accuracy	100 m with homing device 2-3 m with navigation missile	100 m depending on target seeker	1000 m with anti-ship missile	100 m
Time delay	No specific demands	Seconds-minutes	Minutes	<1 second
Continuity	Not demanded	Demanded during combat	Demanded during combat	Demanded during combat

Currently, only the US—and to a certain degree Russia—have extensive systems for satellite reconnaissance. Nevertheless, the commercial sector is growing and is of use even to military customers. Nonetheless, for the next few decades, the American military systems will have a tactical advantage in their capacity for sensor-to-shooter connection. A Swedish strategy for satellite reconnaissance in the near future can be based on the purchase of services from commercial satellite system operators. The commercial services can be complemented by a limited military system—for example for signal intelligence.

4.1.8 Receiving and analysis of data

Today there is one ground station (Esrange) in Kiruna, Sweden that receives satellite data. If this function is considered to be crucial for times of crisis and war then redundancy could be created with more than one ground station, and there could also be a development of mobile stations for international operations.

To transform data, received by the ground stations, to useful information there is a need for advanced signal processing and/or image processing. The methods and algorithms used have to be adapted to the need of the user and to the characteristics of the gathered data. This will demand extensive research and development in signal and image processing. If the capability to gather information through space-based systems increases then the ability to analyse all gathered information has to increase to the same extent. This is an overall problem, and not limited to space-based systems.

4.2 Countering satellites and sensor jamming

The development of our knowledge of the systems employed to prevent or complicate the use of satellite-based systems is probably one of the more important steps for evaluating the threats to our own systems, also in Ekblad (2000). As has been mentioned previously, threats to satellite systems can be grouped into four categories: threats to the satellite and its sensors; threats to the communications link; threats to the ground station; and “mission attack”, i.e. political or diplomatic threats to the system as a whole. Political or diplomatic activities lie outside the scope of this report. Threats to the ground component of satellite systems are likely to be similar to threats to other ground-based installations. Therefore, in this report we limit ourselves primarily to threats against the satellite and sensor. We also take a limited look at threats to the communications link.

4.2.1 Direct confrontation of satellite from ground or air

By ground or air based confrontation we mean all systems that are ground-based or are launched from the ground, sea (ship), or air (aircraft). We can differentiate between two different types of weapons, *material* weapons using a detonation or kinetic energy and *beam* weapons using some form of electromagnetic radiation.

Early forms of *material* weapons were the anti-satellite systems developed by the US and the Soviet Union in 1960s and 70s. In the US, research was done in the 1980s with anti-satellite missiles launched from aircraft. According to sources, the development of the system was closed down before it became operational.

Sounding (probe) rockets could perhaps be developed to have a capability to combat satellites, since these rockets can reach the altitude at which satellites operate. These rockets could be equipped with anti-satellite weapons and operate from Swedish territory. The same goes for the airborne systems that place satellites in orbit—similar to the US Pegasus system.

To provide an example of the use of laser as a weapon, the US and Israel have a cooperative effort that uses ground-based laser to destroy missiles. The system either neutralizes the electronics or affects the navigation system. No particularly sophisticated laser is needed to damage the optics of a satellite. A common semiconductor laser mounted on a satellite can damage the optics of another satellite.

As regards *beam* weapons, lasers from the ground directed towards satellites have been tested in the US. Significant amounts of energy are required to neutralize a satellite from the ground. Even if such a system does not exist today, we believe it lies within our present technological reach. It is possible to have ground-based laser systems for combating satellites operational within ten years.

A special form of *beam* weapon is the High Power Microwave (HPM).[15] HPM could be used to neutralize the electronic system of a satellite. The radiation can be produced with some form of hardware that is shot at the satellite, either from another satellite or with the help of a missile from the ground.

It is important to establish whether there currently exist any operational anti-satellite systems that can be used against the satellites, needed by Sweden and those of our coalition partners, during international operations. The important question to ask is whether a potential enemy or some power allied to the enemy has an anti-satellite capacity of this type and if it represents a threat to the satellites we use.

It should be noted that each form of weapon confrontation with a satellite leads to the disintegration of the satellite into pieces that increase the amount of space

[15] Taken from FOI orienterar om elektromagnetiska vapen och skydd, 2001.

debris. This is a danger to all satellites, our own and those of others.[16] It is therefore reasonable to assume that those who create an anti-satellite system and at the same time are themselves dependent on satellite systems will focus on a system that minimizes the amount of space debris.

4.2.2 Communication and sensor jamming

Jamming can occur both against sensors onboard satellites, communication between satellite and ground, and between satellites themselves. In addition to intentional jamming, there is also jamming due to natural phenomena, from example solar wind, powerful magnetic fields or northern lights. This jamming due to natural phenomena can sometimes be difficult to differentiate from intentional jamming.

There are both electro-magnetic and electro-optical methods that can be used to jam satellite sensors. For example, a laser can be used to blind optical sensors. Electromagnetic jamming can be aimed at radar and SIS as well as communication to and from the satellite. In these cases, the communication with the receivers is jammed—i.e. it usually affects the ground station rather than the satellite.

The possibility to jam GPS-receivers should be emphasised, both on the ground and on the satellites. Given the navigation system's central role in today's armed forces, this is already being studied at FOI, see Boberg (2000).

Another form of jamming is mechanical influence, for instance spreading particles or water droplets around an object to cut it off from communication. There is also the possibility to spread dust and paint around the satellite to jam both sensors and solar panels.

4.2.3 Electromagnetic pulse

A potential electromagnetic threat against satellites is an electromagnetic pulse originating from a nuclear detonation in space. With the conditions outside the atmosphere, the majority of the energy from a nuclear explosion will be released as x-rays. These x-rays, as well as gamma rays from fission reactions, can affect satellites through a generated electromagnetic pulse. Electromagnetic pulse as a threat to a satellite is generated with direct interaction between the satellite and

[16] A satellite that disintegrates doesn't crash like an airplane. The satellite debris will continue in orbit until it re-enters the atmosphere.

primarily x-ray; effects generally depend on the design of the satellite. As a result, no standard protection is used against this type of threat; instead, every individual system design that needs to be protected is considered at an individual level. It should be noted that outside the atmosphere, the attenuation of x-ray and gamma radiation in principle is negligible as the radiation only decreases with the square of the distance.

4.2.4 Unauthorized use and take-over

Just as unauthorized entry is possible in computer systems on the ground, it is possible to hack into a satellite's computer system to jam it or plant a virus. A more sophisticated way to use this method is to affect the information that the satellite sends to the receiver. This requires in-depth knowledge of the satellite system to be attacked. There is also the possibility of unauthorized use of satellites to advance a nation's own interests, for example by using someone else's communication satellite without permission. Such unauthorized use has already happened.

A physical takeover using space shuttles or the equivalent to bring down others' satellites is possible. The US has shown the feasibility of this by taking down its own satellites for repairs.

4.2.5 Satellites as a platform for weapons

Most weapons that can be used against satellites can also be placed on satellites. Satellites can be equipped with different types of projectiles and beam weapons. An advantage of placing beam weapons on satellites is that they require less energy than their counterparts on the ground as there is no attenuating atmosphere. On the other hand, one can experience problems with energy supplies due to difficulties in generating and storing energy in the satellite. Beam weapons based on explosive materials could possibly overcome this problem. An example of space based beam weapons is the planned American Space-Based Laser.[17]

The satellite itself can be used as a weapon component/space mine that can be placed in orbit and be brought to detonate close to its objective. Another method of attack is to simply collide with the object.

[17] For instance Ballistic Missile Defence Organisation, US DoD, www.acq.osd.mil/bmdo, 2001-05-17.

Again, attention should be paid to potential space debris and its consequences. All debris will continue into another orbit and will in the end burn up in the atmosphere. Before this occurs there is a risk of a domino effect, debris from one satellite collides with another satellite and debris from that satellite continues to destroy a third satellite and so on.

4.2.6 The satellite's shielding

Satellites as well as mechanical systems are vulnerable and are therefore possible to neutralize. Furthermore, they have predictable orbits and the fact that satellites are falling instead of flying makes it difficult to take evasive action. This implies that it could be useful to equip satellites with various types of shielding.

Signature adjustment of satellites, so called stealth satellites, is a good way to complicate the tracking of a satellite and prevent prediction of its orbit. This adjustment includes changes in the satellite's configuration, for instance folding in the solar arrays when they are not needed, in fact, anything to reduce the radar signature of the satellite.

Sensors and optics on the satellite can be protected against beam weapons by using a mechanical or electro-optical lens protector in front of the optics and in a similar manner protect the radar by intelligently blocking the signal.

Laser radiation intended for mechanical destruction of the satellite or for heating up the electronics is countered by various kinds of protective surface structures and reflecting or ablating material.

4.3 Modification of the ionosphere

The satellite systems that observe the earth and then communicate with a ground station need to pass through the ionosphere with both its sensor system and its communications channels. As such, a satellite's reconnaissance and communications capability could be blocked through manipulation of the ionosphere. A more speculative thought would be to equip a satellite with energy—and thus extend its lifetime—by charging the ionosphere around the satellite.

From a military perspective, influencing the ionosphere from the ground is interesting for a variety of reasons. Among other things, it can function as a support to ground operations and affect the capabilities of satellite systems. Ground support mainly takes the form of control over the properties that make radio waves bounce against the ionosphere and thus attain long reach.

At present, there is extensive research concerning the ionosphere being done at HAARP in Alaska. This effort is partially supported by U.S. Department of Defence.[18] The technology is not yet mature, but the interest shown in some military circles in (among others) the US and the UK shows that there are great expectations.

In Sweden, research on ionosphere physics is being carried out at places such as the Department of Astronomy and Space Physics (Uppsala University), the Alfvén Laboratory (KTH) and the Swedish Institute for Space Physics (IRF, Kiruna). In Kiruna there also exists a receiver station for EISCAT (European Incoherent Scatter) that is a Swedish-Finnish-Norwegian institute for ionosphere research. Some smaller projects aiming to analyse the technical feasibility is being carried out at FOI. Research or studies concerning its military uses are not yet in progress.

4.3.1 Reconnaissance

A by-product with military applications arising from the possibility to influence the ionosphere may be a large-scale reconnaissance system. Using radio waves from earth to “heat up” the circular streams around the north and south poles in the ionosphere (electro jet), it is possible to generate low frequency (ELV, VLF) radiation from the ionosphere. This in turn induces currents in structures on and under the earth’s surface. The technique can have both military and civilian applications. If the technique is developed so that it becomes both strategically and tactically useful, it would open the possibility for localizing large structures under the earth and water surface. The effect has been tested, for example, tunnels have been mapped in the Silver-fox mine in Alaska. One of the mapped tunnels was 3 meters wide, located 23 meters under the surface.

Such a system could represent one of several components in a surveillance system aiming to achieve information superiority in a specific area. Since fixed installations are needed, the system could be vulnerable in the event of a large

[18] For instance Summary of March 1999 HAARP/HIPAS Research Campaign, April 1999.

organized attack on Swedish territory. Nonetheless, it would be possible to spread the transmitting units and hide them in/around other structures.

It is important to remember that this technique is still at the research and experimental stage. More basic research on both the ionosphere and the effects that can be utilized is needed to transform the technique into a useful method.

It is important, along with both civil and military research about the fundamental technology, to make a cost, effect and risk analysis from a military point of view. The knowledge about military applications of the technology that exists today is probably greatest within the US Navy and the US Air Force.

4.3.2 Long range radar

The technique of creating ionosphere mirrors (AIM-Artificial Ionosphere Mirror) was suggested for the first time by a Soviet researcher in the mid 1970s. The technique potentially allows control over the spread of (reflections, bounces) radio waves in the ionosphere. Using the technique, long-range communication could be made less sensitive to random variations in the ionosphere.

Today's "Over The Horizon" radar (OTH), is based on reflections against the natural, unaffected ionosphere. It gives a number of "set" ranges that represent different numbers of bounces against the ionosphere—with blind zones in between. By letting the radar's signals bounce against an AIM from the right distance and height, the range can be controlled and blind zones could be avoided.

Such radar techniques would provide early warning of incoming cruise missiles; they would also provide longer range to surveillance systems. Theoretically, an AIM can reflect radio waves up to 2 GHz according to House (1996), which is roughly 100 times higher than what the natural ionosphere allows. Thus, one would have greater opportunities to choose the radio wave lengths that are used for the detection of certain objects rather than relying on the radio waves "allowed" by the ionosphere.

In a future scenario where the armed forces are network oriented, the information from such a system could be integrated with other intelligence to create an information network facilitating both strategic and tactical uses.

4.3.3 Jamming

Changing the characteristics of the ionosphere, the same techniques that are used to enhance our own systems, could also be used for degrade an opponent's system. Natural variations in the ionosphere lead to interruptions in our systems that use ELF/VLF. A capability to fabricate such interruptions has obvious military applications. Carried out well, these interruptions would probably be very difficult to distinguish from variations occurring naturally in the ionosphere.

Of special relevance is the possibility to jam communication between an opponent's satellites and the ground—as well as disturbing/jamming sensors onboard the satellite—by modifying the ionosphere.

4.3.4 Transmission

Finally, it is possible to use the ionosphere as a transmitter of VLF and ELF. By "exciting" the ionosphere with HF-radio waves that are modulated by VLF/ELF, the ionosphere can send waves back to the ground with the modulated frequency. If this technique were used, a communication that is "caught" would be seen as stemming from space. It would not be possible to determine its origins.

The frequency area of interest for transmission is 1 mHz to 7 kHz since it can reach underwater receivers. There is a military potential for such a technique.

5 Conclusions and future work

This primary study shows that there is much knowledge on both satellite systems and sensors in Sweden; however, knowledge and experience vis-à-vis the combinational functions of satellite and sensor in relation to military applicability is often lacking. Knowledge of the military significance for Sweden of space based systems is also limited.

The rapid international development, both civilian and military, motivates further study in the area. This becomes especially relevant as we are likely to face threats connected to other actor's capabilities with space-based systems within the framework of international operations.

This study demonstrates that the Swedish Armed Forces could benefit greatly from the capabilities or the services that a space-related system would offer. Within the four main tasks of the Swedish Armed Forces, a space system would be useful in many different ways. International experience has shown that space-based systems have an important role to play in Network Centric Warfare.

The opportunity that satellite-related functions could provide in international operations is especially emphasized here. An example of such an opportunity is the analysis of the environment in the area of operation before the arrival of the forces and the ability to establish communication in an area without good infrastructure.

Most nations that can be expected to be leading coalitions in which we eventually may participate have access to or operate satellite-related systems. This means that we should develop a similar capability to participate on "equal terms". Our own unique capabilities (developed in anticipation of cooperation) can also be valuable to provide a Swedish contribution.

Cooperation with other countries concerning space-related functions could occur through joint organizations or through cooperative projects. Nevertheless, the fastest way to access satellite functions will be to purchase services from commercial satellites.

The cost for an engagement in a satellite system is not estimated to be unreasonable. However, there is no detailed analysis of the cost for obtaining a satellite system and therefore no figures are presented here.

5.1 Conclusions of functions

The different aspects that are of military interest in this report are the following:

Remote sensing

Remote sensing from satellites will increase the range of sensors. The reach and the greater area coverage are useful in international operations. By integrating data from remote sensing into models for command and control support systems, the basis for those involved in an operation at different levels is considerably improved. The new or improved abilities that are possible due to satellite remote sensing should be defined and analyzed.

Defence against ballistic missiles

Defence against ballistic missiles is an area where it is natural to seek cooperation with other nations. As a short-term solution, it is possible to create systems for detection and early warning but not to fight incoming missiles. Satellite-based systems could be necessary to put an early warning system into practice. The reconnaissance should occur with different types of sensors with different kind of wavebands. To make reconnaissance and early warning useful they have to be combined with one or more of the three following capabilities: to evacuate the target area, fight the missile in its orbit or have the ability to neutralize the launch site.

Communication

Communication is an important part of Network Centric Warfare. Secure communication over long ranges is essential to keep in contact with Swedish troops out on international operations. The capability to rapidly establish an infrastructure for communication in a new area is also of importance. Both these functions are supported by satellite communication. Satellite communication provides the opportunity for increased bandwidth and therefore a possibility to transfer a larger amount of data at a higher speed and increasing ranges.

Navigation

To benefit from Global Navigation Satellite System (GNSS) systems with great accuracy it is necessary to have a mapping with sufficient quality. To be able to use GNSS for precision engagement there is a demand for a small positioning error of targets. The best mapping is achieved by positioning targets during peacetime. An alternative is to position targets through satellite reconnaissance with such accuracy that precision engagement is possible.

NBC

The ability to detect nuclear, biological and chemical (NBC) weapon activity is an important area that should play a major part in present studies. It would enable remote detection of accidents, discharge and the use of NBC weapons. In particular, in international operations, the environment could be examined for traces of NBC prior to our troops landing there.

Signal Intelligence

Signal intelligence from satellites would provide a more extended range than traditional SIGINT. This could be valuable both in terms of remote sensing systems and as a way to build a threat library. SIGINT could be used toward the ground as well as toward other satellites.

SIGINT is probably an area where it could be hard to access other nation's information or to form a part of a working international cooperation. The access to commercial services is non-existent and a SIGINT satellite could be a good function to evaluate for an estimation of the feasibility and the value of having our own satellite system.

Strategic and tactical satellite reconnaissance

In the short run, it is possible to access information from commercial satellite services. In the long run, these systems are limited because they are not optimised for the Swedish Armed Forces and they are out of our control. In the future consideration should be given to providing custom-made systems either a system of our own or a system in cooperation with other nations.

There are many possible applications, from strategic surveillance of missiles and mass destruction weapons to tactical troop movements.

Combating satellite systems

There are a number of different ways to fight satellites. No anti-satellite weapon systems are at present operational. The risk of interference of sensors and communication channels is probably greater than the threat against the satellite. This should be taken into consideration if Sweden intends to involve itself in space issues. This study has shown that the knowledge in Sweden about the threat against satellites is limited and the area should be studied further.

Modification of the ionosphere

To affect the ionosphere gives rise to many interesting applications that could provide the Swedish Armed Forces with new powers. This area is still unexplored and further research is needed. One way of handling it is to make a preliminary study about the threats and possibilities that are connected to modification of the ionosphere.

5.2 Capabilities

During this study, it has been found that there are a number of capabilities that are considered to be critical if Sweden wishes to continue exploring the military applications of space issues. In addition to the obvious qualifications such as knowledge about launching of satellites and satellite orbits it is first and foremost a matter of signal processing, image processing, communication, data fusion and antenna techniques.

5.3 Suggestions for future work

The working team has found during this project that there are a number of areas that need to be dealt with specifically.

Military space strategy

Looking at military as well as civil and commercial commitments to space-related systems and their importance internationally and to the importance of space related systems in the Network Centric Warfare, a Swedish military strategy should be developed. The first step in such a strategy is to increase our knowledge about the military applications of space systems. Consideration should be given to collaboration between military and civil actors.

International operations

The benefits regarding the tactical-operational perspectives of space related systems in international operations should be studied. Particular attention should be paid to an investigation of those abilities that Swedish troops in international operations could benefit from if there is access to information from space-based sensors that belong to nations which Sweden is collaborating with.

Signal intelligence satellites

If there is a commitment towards a satellite for military applications, a SIGINT satellite could have the potential to supply the best capabilities to the Swedish Armed Forces, a capability that is not possible to buy from commercial satellites. A feasibility study regarding SIGINT satellites should be carried out with the purpose of establishing whether it is realistic for Sweden to produce its own satellites for military use or not.

Capacity to launch

This study has come to the conclusion that Sweden could have its own capacity to place small satellites in LEO. Launch capacity is one of the most difficult topics when it comes to Sweden's commitment to space issues. It is doubtful whether Sweden needs to develop such a capacity as long as our main interest is military applications. To find out how to secure the need for launch capability there should be a study of different options for launching satellites from the ground or air according to the space strategy.

The benefits of modification of the ionosphere

The military potential when it comes to systems for modification of the ionosphere should be investigated and evaluated. The result of such an evaluation should provide guidelines for basic research for military applications.

Appendix A

Table 4
International treaties, agreements, and conventions regulating the use of space

Treaty, Agreement, or Convention	**Year**	**Stipulates (in selection)**	**No. of arti cles**
(**PTBT**, Partial Test Ban Treaty) Treaty banning nuclear weapon tests in the atmosphere, in outer space and under water	1963	*Article I:* *1. Each of the Parties to this Treaty undertakes to prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control:* *(a) in the atmosphere; beyond its limits, including outer space; or under water, including territorial waters or high seas.*	5
(**Outer Space Treaty**) Treaty on principles governing the activities of states in the exploration and use of outer space, including the moon and other celestial bodies	1967	*Article IV:* *States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.* *The moon and other celestial bodies shall be used by all States Parties to the Treaty exclusively for peaceful purposes. The establishment of military bases, installations and fortifications, the testing of any type of weapons and the conduct of military manoeuvres on celestial bodies shall be forbidden. The use of military personnel for scientific research or for any other peaceful purposes shall not be prohibited. The use of any equipment or facility necessary for peaceful exploration of the moon and other celestial bodies shall also not be prohibited.*	17
(**Rescue Agreement**) Agreement on the rescue of astronauts, the return of astronauts and the return of objects launched into outer space	1968	*Article 1 regulates the handling of information on accidents, distresses, emergency or unintended landings.* *Article 2 states the obligation to give rescue and rendering assistance.*	10
(**Liability Convention**) Convention on international	1972	*Article II:* *A launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the earth or to aircraft in flight.*	28

Treaty, Agreement, or Convention	**Year**	**Stipulates (in selection)**	**No. of articles**
liability for damage caused by space objects		*Article VII:* *The provisions of this Convention shall not apply to damage caused by a space object of a launching State to:* *(a) Nationals of that launching state.*	
(**Registration Convention**) Convention on registration of objects launched into outer space	1975	*Article II:* *1. When a space object is launched into orbit or beyond, the launching State shall register the space object by means of an entry in an appropriate registry which it shall maintain. Each launching State shall inform the Secretary-General of the United Nations of the establishment of such a registry.* *Article IV:* *1. Each State of registry shall furnish the Secretary-General of the United Nations, as soon as practicable, the following information concerning each object carried on its registry:* *(a) Name of launching State or States;* *(b) An appropriate designator of the space object or its registration number;* *(c) Date and the territory or location of launch;* *(d) Basic orbital parameters, including:* *(i) Nodal period,* *(ii) Inclination,* *(iii) Apogee,* *(iv) Perigee.* *(e) General function of the space object.*	12
(**Moon Agreement**) Agreement governing the activities of states on the moon and other celestial bodies	1979	*Article 3:* *1. The moon shall be used by all States Parties exclusively for peaceful purposes.* *3. States Parties shall not place in orbit around or other trajectory to or around the moon objects carrying nuclear weapons or any other kinds of weapons of mass destruction or place such weapons on or in the moon.* *4. The establishment of military bases, installations and fortifications, the testing of any type of weapons and the conduct of military manoeuvres on the moon shall be forbidden. The use of military personnel for scientific research or for any other peaceful purposes shall not be prohibited. The use of any equipment or facility necessary for peaceful exploration and use of the moon shall also not be prohibited.*	21

In parenthesis are given the popular names of the treaties. In italic are given brief accounts of some of the contents in the treaties. The table is found in Bruce

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Space and defence

Abstract (not more than 200 words)

The importance of space assets has increased for civilian as well as military applications. As the technology matures the number of applications has increased and most people use on a daily basis systems that in one way or another rely on space assets.

With the aim of doing an inventory of functions and problems related to space assets that are of interest to the Armed Forces , FOI has carried out a study entitled Space and Defence. The study has shown that space assets can be of use to the Swedish Armed Forces for a number of different functions. Three areas of special interest are: Satellite-related functions, anti-satellite systems and ionosperic modification.

Due to the expected value of space assets to the Swedish Armed Forces and the interest shown by other nations in space-related systems, the study suggests that a process for gathering knowledge and information about military applications of space assets should be initiated. With a start in the Armed Forces requirements a Swedish Armed Forces space policy should be developed where both military, civilian and commercial space assets are taken into consideration. The possibilies associated with space assets supporting Swedish Armed Forces involved in peace support operations should be studied independently.

Keywords

Space, satellite, ionosphere, remote sensing, ballistic missile, communication, navigation, NBC, surveillance, reconnaissance, signals intelligence

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Rymd och försvar

Sammanfattning (högst 200 ord)

För såväl civila som militära tillämpningar ökar betydelsen av rymdbaserade system. I och med att teknik och metoder mognat har tillämpningarna blivit fler och de flesta av oss nyttjar dagligen tjänster som på ett eller annat sätt är beroende av rymdbaserade system.

I syfte att inventera vilka frågeställningar och funktioner som är relevanta för Försvarsmakten har FOI under våren 2001 bedrivit en förstudie under rubriken Rymd och Försvar. Studien har visat att rymdbaserade system kan vara till nytta för Försvarsmakten på flera olika punkter. Studien identifierar tre områden av intresse för militära applikationer. De tre områdena är satellitrelaterade funktioner, bekämpning av satelliter och modifiering av jonosfären.

Mot bakgrund av den förväntade nyttan av rymdrelaterade system och andra nationers engagemang i rymdfrågor föreslår studien att en process för kunskapsuppbyggnad kring militära applikationer av rymdteknik tas fram inom Försvarsmakten, FMV och FOI. Mot bakgrund av Försvarsmaktens behov bör en militär strategi avseende rymdfrågor tas fram där samverkan med civila och kommersiella intressen beaktas. Specifikt bör studeras hur rymdbaserade system kan användas för att stödja svensk personal vid internationella operationer.

Nyckelord

Rymden, satellit, jonosfär, fjärranalys, ballistiska missiler, kommunikation, navigering, NBC, signalspaning, spaning

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