Design Pics Inc/National Geographic Creative Image ID 1236337

Space Weather Situational Awareness and Its Effects upon a Joint, Interagency, Domestic, and Arctic Environment

by Patrick Perron

Major Patrick Perron, CD, PhD, *is a Signals officer currently employed as a military faculty member in the Department of Physics at the Royal Military College of Canada. His research interests lie in the field of space physics and space weather. The author acknowledges contributions and interesting discussions with Dr. Pierre Langlois (CSA), Major (ret'd) K. Rodzinyak (DND), Dr. K. Kabin (RMCC), Dr. D. Boteler (NRCan), Dr. L. Trichtchenko (NRCan), Mr. A. Cushley (RMCC), and Dr. E. Donovan (U of C).*

Introduction

The recent launch of Canada's first dedicated operational military satellite, *Sapphire*, into the space environment coincides with the fact that the Sun's activity is undergoing its peak portion as part of the 11-year solar cycle. Despite the fact that the current solar cycle is modest in intensity, an increasing number of space weather events are expected to occur, such as violent explosions on the surface of the Sun that can release enormous amounts of electromagnetic radiation and energetic particles. These phenomena can be extremely harmful to satellites and other technologies essential to joint military operations.

Space weather awareness aims at monitoring and predicting adverse conditions on the Sun and in the near-Earth space environment that can degrade and disrupt the performance of technological systems. In fact, space weather can negatively affect satellites, long-distance and satellite communications, radars, navigation systems, electrical power grids, and it can endanger human life. Canada's Arctic region is the most vulnerable to space weather effects, owing to its direct connection with Sun-Earth dynamics. This vulnerability takes on great importance since exercising sovereignty in the Arctic is a core objective of the federal government, as laid out in the Canada First Defence Strategy. This susceptibility to space weather will keep growing with time along with our dependency upon technologies for both civilian and defence purposes. This is particularly true from a defence perspective since space-based systems are now considered by senior officers to be critical enablers of military operations.[1] Space weather situational awareness (SA) is critical for the purpose of protecting our national space assets from the harsh space environment, and to achieve synchronized joint space effects in support of military operations.

In this article, it is suggested that the Canadian Armed Forces (CAF) and the Department of National Defence (DND) leverage Canada's world-class expertise in space weather in order to develop a unique Canadian space weather SA capability, which would enable successful operations in domestic, joint and inter-agency situations, and consequently, maintain Canada's sovereignty in the Arctic. To support the previous statement, space weather will be first introduced, along with its adverse impacts. Then, the space weather SA concept, as part of the overall space situational awareness (SSA), will be described, based upon Allied doctrinal frameworks. Finally, the latter concept will be discussed in the context of producing joint space effects in Canada's Arctic region.

What is space weather?

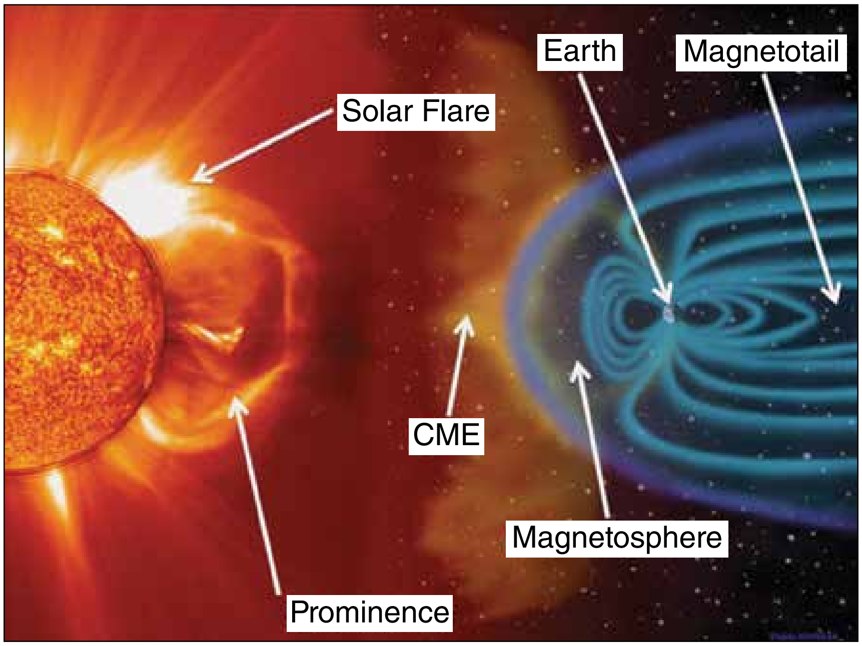
Space weather first began to affect human life in the 19th Century, altering the functioning of telegraph lines.[2] Space weather encompasses several components of the Sun-Earth system, such as the variable solar wind, sunspots, solar flares, coronal mass ejections (CME), interactions with the Earth's magnetosphere and ionosphere, and the production of the aurora. The prime source of space weather is the dynamic Sun. The Sun continuously releases streams of charged particles, named 'solar wind.' The solar wind travels in the interplanetary space at speeds of several hundred kilometres per second (km/s). Depending upon the Sun's activity, it may take 2-3 days for solar wind particles to reach Earth.

Besides the solar wind, dark regions often appear on the surface of the Sun, called sunspots, whose number is well-correlated with the approximate 11-year solar cycle. Sunspots are associated with magnetically active regions of the Sun's surface. At times, short-lived explosions can occur near these active regions, discharging radiation across the electromagnetic spectrum, as well as and high-energy particles. These bursts are called 'solar flares.' They are important because they have a direct effect upon the properties of the Earth's upper atmosphere.

In addition to solar flares, strong magnetic field loops, called prominences, often extend outside the surface of the Sun. At times, these features break apart, releasing formidable amounts of charged matter at speeds that can be much larger than the solar wind. This phenomenon is called 'Coronal Mass Ejection,' or CME. When a CME is directed toward the Earth, it can trigger a geomagnetic storm.[3]

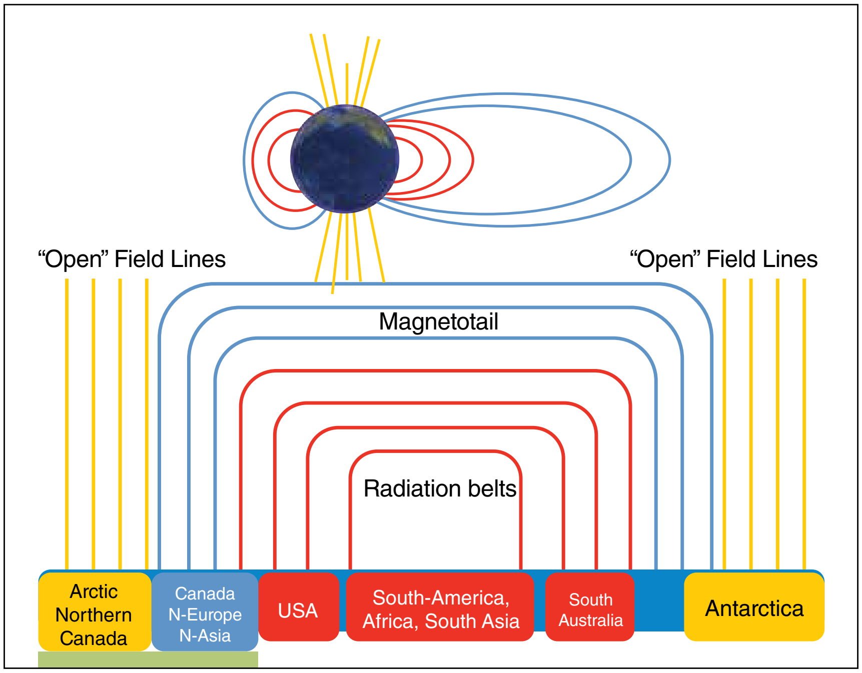
Besides the outflow of highly energetic particles, the Sun continuously emits electromagnetic radiation. Propagating at the speed of light, this radiation reaches our planet in slightly less than eight minutes. The extreme UV and X-ray parts of the spectrum are responsible for ionizing (breaking an atom or molecule into positively and negatively charged particles) the upper part of the atmosphere between approximately 60-1000 kilometres of altitude. The ionized part of the Earth's atmosphere is the ionosphere. Its free charges are capable of influencing radio propagation and GPS signals. The ionosphere's properties are highly variable with days, seasons, and solar cycles.

Fortunately, the Earth possesses a magnetic field that acts as a shield and deflects the majority of the solar wind. The region dominated by the Earth's magnetic field is called the 'magnetosphere.' On the day side, the Earth's magnetosphere is compressed, due to the solar wind's pressure, and on the night side, it is stretched into a long 'magnetotail' that resembles a windsock, as represented in Figure 1.



SOHO (ESA & NASA)

Figure 1 ~ Several components of the Sun-Earth relationship.



Dr. Pierre Langlois/CSA

Figure 2 ~ Features of the Earth's magnetic field topology and their relation to different near-Earth regions.

A large prominence and a solar flare are also depicted. Nevertheless, the Earth's magnetic field is not a perfect shield, particularly near the poles, where solar wind particles can penetrate into the atmosphere, guided by the nearly-vertical magnetic field lines.

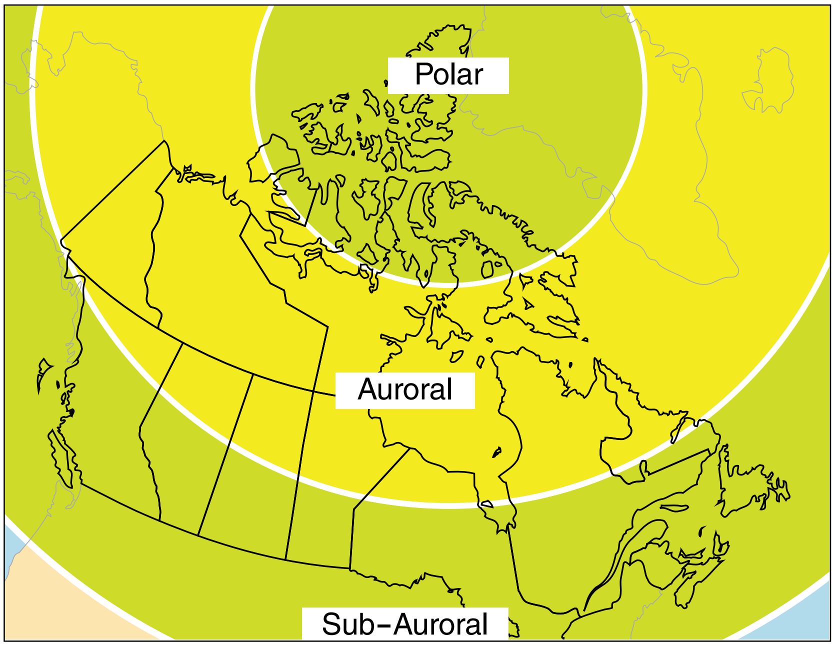


Figure 3 ~ Topside view of the polar, auroral and sub-auroral zones superimposed over Canada. Adapted from an example of geomagnetic activity conditions issued by Space Weather Canada.

For ideal solar wind-magnetosphere 'connection' conditions, the Earth's magnetic field typically comprises three types of lines, as illustrated in Figure 2. These magnetic field lines map into different near-space regions of the Earth. The yellow lines correspond to 'open' magnetic field lines that have 'one foot on the Earth,' and the other connected to the IMF. These yellow lines, which provide a direct path to the solar wind particles, map down to the polar cap (Arctic) region.

Magnetic field lines colored in blue are stretched into a long magnetotail. Generally speaking, the field lines colored in blue map into the auroral zone. In the auroral zone, the interaction of energetic particles with those of the upper atmosphere emits green, red, and sometimes violet light, a phenomenon commonly called 'Northern Lights.' On global scales, the aurora takes the form of ovals centered on the Earth's magnetic poles. Since the geomagnetic pole is shifted toward the Yukon from the geographical pole, "…eighty-to-ninety percent of the accessible land under the auroral oval lies in Canada."[4] The auroral oval makes Canada extremely vulnerable to space weather adverse effects. Closer to the Earth, the red lines encompass the Van Allen radiation belts, which consist of layers of energetic and charged particles around the Earth. They connect to the sub-auroral zone. The polar, auroral, and sub-auroral zones are evident in Figure 3.

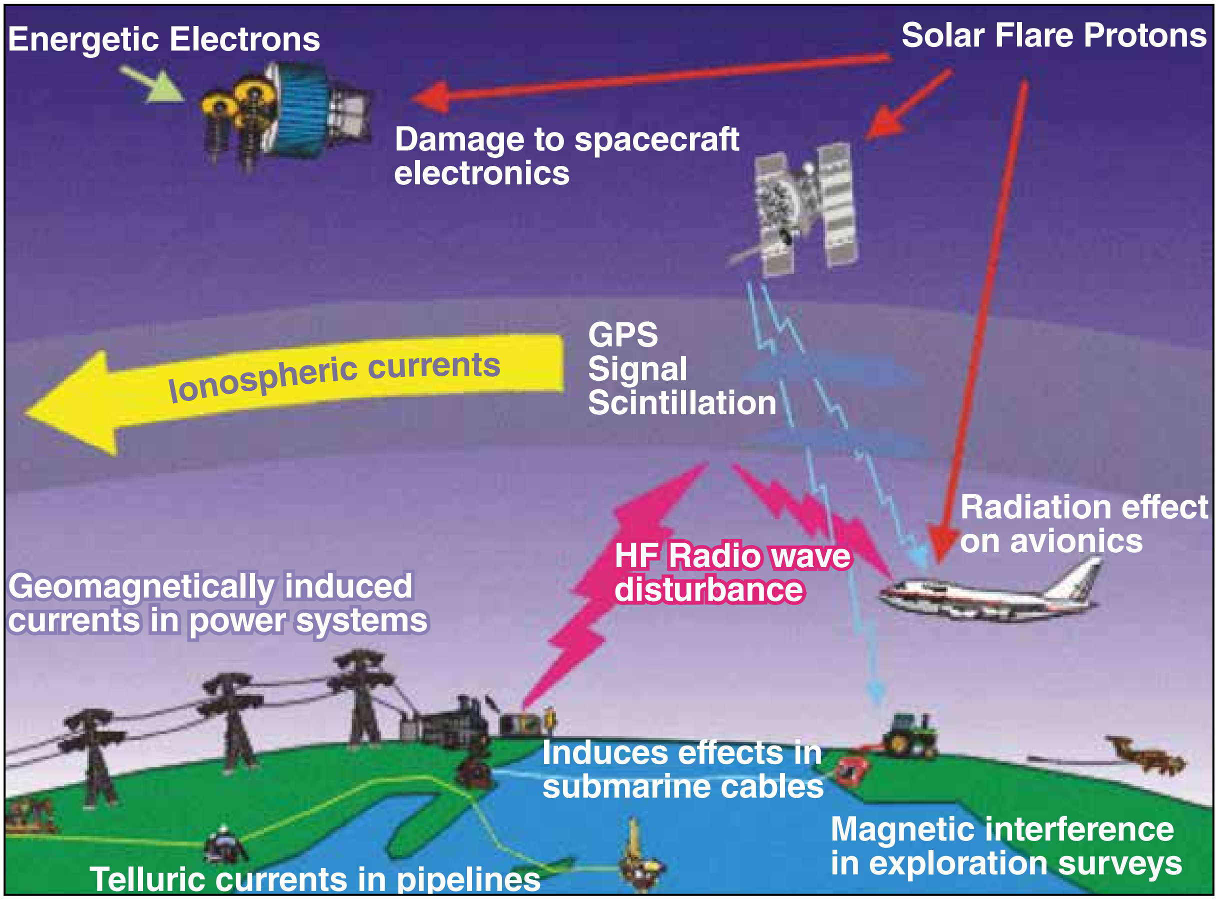


Figure 4 ~ Space weather adverse effects on technologies.

Reproduced with permission from Space Weather Canada/Natural Resources Canada at http://www.spaceweather.ca

Impacts of Space Weather

Space weather events can lead to detrimental consequences for both humans and technology, as shown in Figure 4. It can impair satellite hardware and solar cells, de-orbit satellites, and put the health of space and aircrews in jeopardy. Moreover, it can disrupt radio transmission and GPS signals and it can render entire power and communication networks inoperative. Military systems not hardened from space weather can also be adversely affected.

Energetic particles can damage spacecraft electronics, especially when travelling through the Van Allen radiation belts. Energetic particles can cause temporary operational anomalies, or can even disable an entire platform. In 1994, Canadian telecommunication satellites *Anik* E1 and E2 suffered important outages due to an increase in solar activity. *Anik* E1 failed for more than eight hours and *Anik* E2 was not restored for five months, depriving Canada's population of television and data services for hours and remote northern communities of telephone services.[5] In 1997, it is believed that a CME caused the loss of AT&T's *Telstar* 401 satellite.[6]

> **"The health of space crews can be harmed from space weather radiation exposure. In addition to astronauts, travelers in aircraft making use of polar routes are also exposed."**

In addition to deterioration caused by energetic particles, solar UV radiation can lead to material degradation. This effect is particularly important for solar panels. Furthermore, radiation from enhanced solar activity heats the Earth's upper neutral atmosphere. Consequently, it expands and causes satellites in low Earth orbit (LEO), below approximately 1000 kilometres, to experience increased drag (due to enhanced air density). Drag causes satellites to lose altitude and change orbital parameters. For example, the great geomagnetic storm of 1989 caused thousands of space objects, including hundreds of operational satellites, to lose many kilometres of altitude.[7]

The health of space crews can be harmed from space weather radiation exposure. In addition to astronauts, travelers in aircraft making use of polar routes are also exposed. Routes across the northern Polar region have been increasingly used for fuel and time savings since the beginning of the 21st Century. Unfortunately, since the Polar region can be directly connected to solar wind, humans are susceptible to absorbing significant radiation doses.

Power grids are also sensitive to space weather. In fact, the chain of events resulting from enhanced solar activity causes strong electrical currents to flow in the ionosphere, especially at high latitudes and within the auroral oval. These ionospheric currents in turn induce currents in the ground, which travel through least resistance paths, often power transmission lines, oil or gas pipelines, telecommunication cables, or railway circuits. These geomagnetically induced currents (GIC) have the capability to overload and knock out electrical components. Also, they can reduce the lifetime of ground infrastructure by enhancing corrosion and aging of transformers. A notable example of GIC event is the 1989 Hydro-Québec power grids blackout resulting from a CME-driven geomagnetic storm. The entire province electrical power system collapsed in 90 seconds, and US distribution grids were also affected. It lasted for nine hours and caused economic losses in excess of two billion US dollars.[8]

Extreme space weather occurrences can have extensive socio-economic consequences. On 23 July 2012, the most powerful CME ever recorded narrowly missed the Earth by approximately one week. Had it been directed toward the Earth, scientists believe that it would certainly have triggered a geomagnetic storm comparable to the largest events of the 20th Century[9] This recent event demonstrates that extreme space weather conditions can happen even during a modest solar activity cycle such as the one presently underway. Such extreme space weather events have the potential to cause long duration outages to power grids with catastrophic consequences.

In addition to power grids, space weather can seriously perturb communication, timing, and navigation systems by modifying the density distribution of the ionosphere. These irregularities cause scintillations, or fading, of radio signals travelling through the ionosphere. Also, it gives rise to GPS ranging and timing errors that can be considerable. Furthermore, long-range radio communications at high-frequency (HF) are sometimes completely blacked out, due to accrued absorption of radio signals, especially in auroral and polar zones. In this case, trans-polar airlines, which rely upon HF communications, must be re-routed to lower latitudes at great expenses. A notable example of communication failure occurred in 2003 when aviation communications were disrupted for 18 consecutive days.[10]

The occurrence of space weather adverse effects upon military systems is not new. In fact, during the Second World War, British radar operators reported periodic 'jamming' of the country's radar defence system. An investigation found that the interference was not caused by the Germans but by electromagnetic signals from the Sun, which was undergoing strong activity.[11] As far as CAF joint operations are concerned, demands on space-based assets for communications, weather, navigation and intelligence, surveillance, target acquisition, and reconnaissance (ISTAR) purposes will continue to increase with time. Therefore, space weather cascading effects on these systems should be forecasted or at least, monitored and understood. This will be even more challenging when deployed in the vicinity of the auroral and polar regions, which are more variable and affected.

Space Weather Situational Awareness and Joint Space Effects

Armed forces in many countries have realized the criticality to develop a space weather SA picture, as part of the overall SSA. Developing SSA is essential to the success of space operations, analogously to land, air, or maritime SA. According to US joint doctrine, space operations comprise four mission areas: space force enhancement, space support, space control, and space force application.[12] SSA, a sub-mission area of space control, underpins all four mission areas. By definition, "SSA involves characterizing, as completely as necessary, the space capabilities operating within the terrestrial environment and the space domain. It includes components of

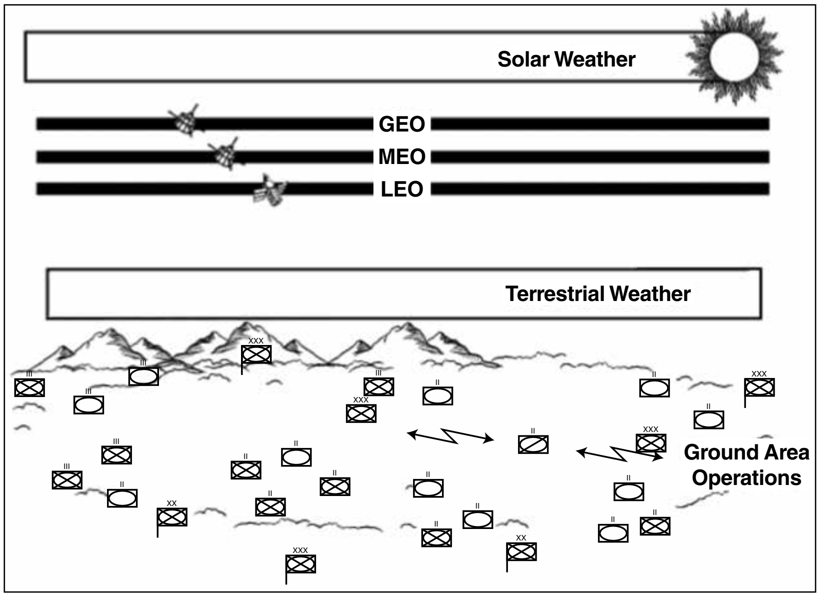


Figure 5 ~ Space AOI. Space (solar) weather needs to be considered as part of the space IPB input because of the effects on joint operations within the AOI. LEO signifies Low Earth Orbit, MEO is Medium Earth Orbit, and GEO is Geostationary Earth Orbit.

Reproduced from US Army Field Manual FD 3-14, *Space Support to Army Operations.*

Intelligence Surveillance Reconnaissance (ISR); environmental monitoring, analysis, and reporting; and warning functions."[13] The environmental monitoring component can be further described as including "the characterization, analysis, and prediction of space weather, terrestrial weather near important ground nodes, and natural phenomena in space."[14] Other authors used the expression 'Environmental SSA' instead of 'Space Weather SA,' whose given definition is "…the requisite knowledge of current and predicted environmental conditions and the effects of those conditions on space events, threats, activities and space systems to enable commanders, decision makers, planners and operators to gain and maintain space superiority across the spectrum of conflict."[15]

According to the US Army Field Manual FD 3-14, "Space Support to Army Operations," a space input is required to the Intelligence Preparation of the Battlefield (IPB). The purpose of space input to the IPB is "…to provide the G2 with a highly detailed analysis of the space medium and its capabilities and effects within the battlespace."[16] The first step consists of defining the environment and its effects. Indeed, space weather is considered to be part of the space IPB input because of its important effects on joint space operations within the Area Of Interest (AOI). An example of space AOI is provided in Figure 5. Then, as part of the space estimate process, space weather battlefield effects should be identified and linked to specific joint space capabilities.

Similarly, the United Kingdom (UK) recognizes that space weather is an essential component of SSA. In fact, the UK Future Air and Space Operating Concept stipulates: "Space situational awareness is necessary to prevent collisions, mitigate space weather effects and assist in anomaly resolution, including radio frequency interference."[17] Another document produced by the UK's Development, Concepts, and Doctrine Centre states that SSA involves, not only cataloguing space objects' orbital characteristics, but also the "collection of space weather information to provide advance warning."[18]

North Atlantic Treaty Organization (NATO) doctrinal terminology being somewhat different than the US counterpart, the 'space weather component' of SSA is named: 'Space Environment Operations.' The NATO Research and Technology Organization (RTO) defines SSA as "the knowledge and the understanding of military and non-military events, activities, circumstances and conditions within and associated with the space environment or space related systems that are relevant for current and future NATO interest, operations and exercises."[19] Space weather being an important component of SSA, NATO-RTO recently mandated the Systems Concept and Integration Panel 229 Task Group to provide Space Environment Support to NATO SSA.[20]

Developing space weather SA is crucial for the successful conduct of joint operations since the adverse effects of space weather impact joint space capabilities. Table 1 presents examples of linkages between space mission and sub-mission areas, space weather events and effects upon technology and joint space capabilities.[21] According to US Army doctrine, these linkages are part of the space estimate. The last column of Table 1 contains examples of current (in blue) and planned future (in red) Canadian joint space capabilities that could be adversely altered by space weather events. Note that this table mostly includes adverse effects on joint space capabilities. As alluded previously, space weather can also negatively impact ground or air based technologies critical to military operations, such as electrical power grids or HF over-the-horizon radar systems.

It is the effects of space weather on joint capabilities that are of concern to our commanders. Analogously to any other physical domain, monitoring and predicting environmental effects should be synchronized with commanders' courses of actions. For example, based upon the prediction of an imminent solar storm, a commander could decide to delay an operation, or to carry it forward, knowing that the adversary's communication, navigation, or targeting systems would be degraded. Also, operators must have the capability to discriminate among effects of natural origin and intentional enemy disruptions, such as jamming. In order for a commander to apply knowledge and to make sound decisions, the space weather SA data must be fused, to become relevant information, into a space Common Operating Picture (COP). The desired end state of space weather SA is the "effective application of space weather SA information," in other words, "to mitigate negative impacts on and improve performance of our space systems, and exploit potential space environment impacts on enemy systems."[22] However, this desired end state should not be restricted solely to space systems, but to any ground or space-based systems that could be negatively affected by space weather. Space weather products could be displayed as COP overlays highlighting the regions within the area of operation where operational capabilities are affected, for instance, UHF satellite communication scintillation maps, GPS receiver error maps, HF illumination maps or radar auroral clutter maps. These products would assist commanders and staff in mitigating space weather effects on their systems by synchronizing operations differently, by planning for alternate means, or by exploiting enemy space weather susceptibilities for possible advantage.

Space Mission Areas	Sub-Mission Areas	Joint Space Capability Examples	Space Weather Events	Effects on Technology	Impacts on Joint Space Capability	Examples of current (Blue) or planned future (Red) Canadian capability impacted
Space Force enhancement	ISR	Intelligence	Solar flares, Ionospheric storm, Aurora clutter	Radio frequency (RF) interference, Range uncertainty, Loss of target discrimination, Spectral distortions, Degraded system performance, Reduction in resolution of SAR images	Inaccurate enemy position data, Loss/Degradation of intelligence data	Joint Space Support Project (JSSP)
		Space IMINT				Polar Epsilon (RADARSAT)
		Space RADAR				
	SATCOM and Long-range comms	Strategic comms (Wideband)	Solar flares, Polar Cap Absorption (PCA), Ionospheric storm, Auroral Absorption	RF interference, Scintillation, Comms blackouts	Inability for Comds to exercice C2, Decreased ability to tie sensors to shooter, Inability to send MEDEVAC, Life of small teams at risk	MERCURY GLOBAL, MILSATCOM
		SATCOM on the move				Land Command Support System (LCSS) Life Extension Project
		Tactical comms (Narrowband)				Polar Comms and Weather (PCW)
		HF Arctic comms				Tactical narrowband SATCOM
	Environmental monitoring	Meteorology and Oceanography	Solar flares, Ionospheric storm, Aurora clutter	RF interference, Scintillation, Reduction in resolution of multispectral and hyperspectral imagery	Impacts on joint intelligence preparation of the battlefield (JIPB), Decreased ability to perform BDA	PCW, RADARSAT
	Positioning, navigation and timing	Precision Engagement	Solar flares, Ionospheric storm	GPS signals scintillation, Ranging errors, Degraded positioning accuracy, Time errors, Impacts on timing	Precision guided munition miss target, Increased collateral damage, Risk of friendly fire	Excalibur artillery projectile, PLGR, IRIS (TCCCS) System
		GNSS/ NAVWAR			Loss of navigation and maneuvering accuracy, Decreased ability to synchronize ops with precision timing, Decreased COMSEC	
		Precision Timing				
	C2	Friendly Force Tracking		GPS scintillation, Ranging errors	Loss of Blue PA	No known Canadian space-based Blue PA capability
	Personal Recovery Ops	Friendly Force Tracking		Scintillation, Positioning errors	Decreased probability of saving lives	Low/Medium Earth Orbit search and rescue satellite repeaters (LEOSAR, MEOSAR)

continued on next page

Space Mission Areas	Sub-Mission Areas	Joint Space Capability Examples	Space Weather Events	Effects on Technology	Impacts on Joint Space Capability	Examples of current (Blue) or planned future (Red) Canadian capability impacted
Space Support	Satellite/Payload Ops	Telemetry, tracking, and commanding	Energetic particles, Geomagnetic storms, Radiation Belts	Satellite electronics anomalies or permanent failures, Satellite Drag	Decreased operational payload utility, Decreased ability to control satellites	Surveillance of Space Satellite – SAPPHIRE, NEOSat, RADARSAT, PCW
Space Control	SSA	SST	Solar flares, Ionospheric storm, Aurora clutter	RF /RADAR interference, Scintillation	Risk of collisions, Loss of satellite tracking	SAPPHIRE, NEOSat

Table 1: Relations between space mission areas, space weather events, effects on technology and joint space capabilities. Examples of current (in blue) or planned future (in red) Canadian joint space capability that could be adversely impacted are also presented.

Canadian Context

The DND and the CAF acknowledge space as a separate and unique joint domain within the strategic environment that should be considered in all levels of operations.[23] The DND/CAF integrated capstone concept publication states that space-based assets are critical mission enablers "in support of achieving Canadian strategic goals, such as exercising sovereignty in the Arctic." It emphasizes that the CAF "will need to expand its role in space to protect and exploit vital information and communication sources."[24] Although the document indicates that "space is extremely hostile to human habitation," and that "space vehicles must be designed to endure the harsh conditions of space,"[25] space weather adversarial effects on the conduct of joint operations are not specifically discussed therein.

The DND and the CAF have had a space policy since 1992. The most recent official version, dating from 1998, identifies space as a foundation of military operations.[26] Additional guidance is provided to capability developers, such that opportunities for collaboration with OGDs and international partners should be sought in order to carry out defence-related space activities in the most efficient manner. Significant progress has been made since the release of this policy by the organization responsible for space related capability development within the Chief of Force Development structure, namely, DG Space. There now exists a Defence Space Program in place addressing several capability gaps, for example, global communications, maritime and global domain awareness, SSA, Search and Rescue, and navigation warfare (NAVWAR). A National Defence Space Policy and Strategy have been drafted to support the six core mission areas identified in the Canada First Defence Strategy. That new defence space policy "reflects the strategic importance of space to the DND/CAF and reinforces the fact that assured access to space capabilities are essential for the CAF to successfully conduct operations."[27] Since it would be financially impossible for DND to develop an independent military space program, this policy document emphasizes the requirement for Canada to establish a whole-of-government (WoG) and comprehensive approach, as well as seeking cooperative opportunities with key allies, in order to deliver space effects. In addition, it specifies three overarching objectives that are to deliver and sustain space effects, to integrate space effects, and to assure freedom of space operations.[28] The third objective contains an important sub-goal, which is to deliver indigenous space domain awareness. This sub-objective indicates that DND will "create a space domain awareness road map that will address sensors (both ground and space based); agreements for space weather/solar events data; and agreements and mechanisms to obtain system status and state-of-health."[29] It further states that DND "will develop an indigenous orbital analysis capability to effectively contribute to the characterization of the environment, quickly differentiate man-made from environmental effects and forecast system degradations."[30] Clearly, DND has recognized the importance to understand the space environment, to protect our systems from natural threats in order to ensure the continuity of operations.

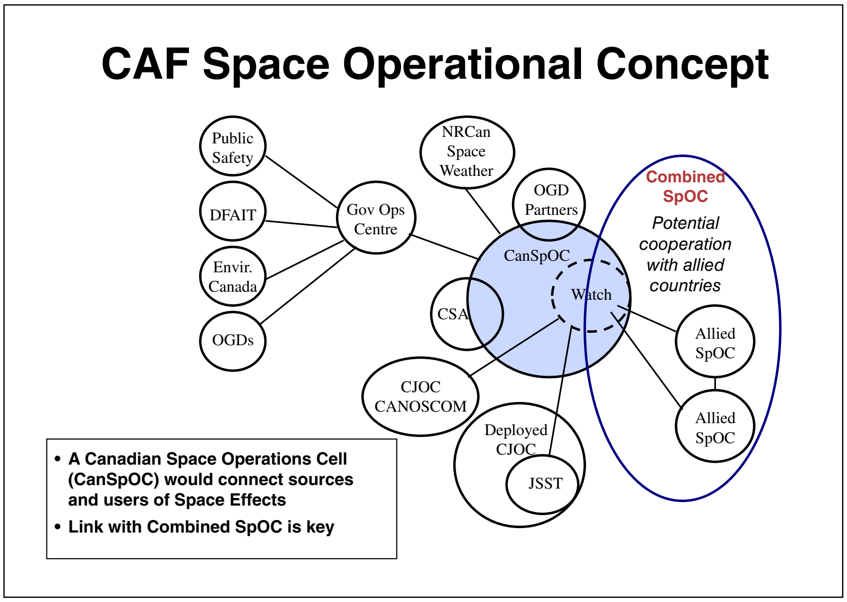


Figure 6 ~ CAF Space Operational Concept

Adapted from Major K. Rodzinyak's presentation, DG Space Strategic Plans and Readiness ~ Scott Jones

Ralph Lee Hopkins/ National Geographic Creative Image ID 1052290

The DND/CAF recently created the Canadian Space Operations Centre (CanSpOC), as part of the Canadian Joint Operations Command (CJOC), the purpose of which is to connect sources and users of space effects, in addition to providing SSA to CJOC commander and staff. A schematic of the CF Space Operational Concept, linking the CanSpOC, OGDs, Allied SpOC and users is shown in Figure 6.

At this point, one might ask who the space weather stakeholders in Canada are, and which organization should be leveraged by DND/CAF?

Canada has a long history of accomplishments in space weather R&D owing to its strategic geographical position. For example, Natural Resources Canada (NRCan) has monitored the geomagnetic field for more than 150 years, using a vast network of government-owned ground-based magnetometers. NRCan has also operated the Canadian Space Weather Forecast Centre since 1974.[31] It monitors, analyzes, and forecasts space weather, and dispatches warnings and alerts across Canada.

The Geospace Observatory (GO) Canada program is the largest and most powerful ground-based network of sensors and instruments in the world, aimed at observing the space environment.[32] The deployed ground-based instrumentation consists of radar systems, optical imagers, ionosondes, magnetometers, radio receivers and GPS ionospheric scintillation monitors, to name a few. The Canadian Space Agency (CSA), which is the federal government organization leading the GO Canada science program, works in close relationship with several space science research groups embedded in Canadian universities, international partners, and NRCan, to understand and improve the prediction of space weather events. Although optical instruments would not allow continuous monitoring of space weather events, due to clouds and terrestrial weather phenomena, other types of sensors, based upon radio waves, have the capability to continually observe the space environment. For instance, NRCan operates a deployed network of Relative Ionospheric Opacity Meters (RIOMETERs) that are used for continuous measurement of ionosphere absorption.[33] RIOMETER measurements can be directly linked to HF signal degradation.[34] Hence, this example shows that existing space weather sensors could be used to estimate the level of attenuation that long-distance communication HF radios would undergo in an Arctic environment.

Other federal government organizations also share important stakes in space weather forecasting and research. In particular, National Research Council (NRC) is responsible for the F10.7 solar radio-monitoring program. This has been running since 1947, and, after sunspot numbering, it is the most widely used index of solar activity.[35] Some OGDs are especially concerned with extreme space weather events for the purpose of protecting Canada's critical infrastructure, for instance, Public Safety Canada (PSC) and the Royal Canadian Mounted Police (RCMP).

Relevance of Space Weather SA for Canada to Achieve Effects in a Joint, Interagency, Domestic, and Arctic Environment

Space environment SA takes on extreme importance in the Arctic region, due to its enhanced vulnerability to space weather. In this section, it is argued that, notwithstanding the sharing and collaboration with Allied countries, the DND/CAF should develop its own space weather ground-based monitoring and forecasting capability by leveraging the existing expertise of Canada's OGD, academia, and industry in this field, as well as the unique, ground-based network of sensors. The reasons are threefold. First, this type of capability would mitigate space weather adverse effects upon Canadian space-based assets, or any other satellites used for the successful planning and conduct of joint operations in the Arctic. Secondly, Canada because it is the most vulnerable country in terms of space weather, a tailored and leveraging Canadian monitoring capability would better suit its defence requirements. Lastly, since Canada has the best observing geography, and the most robust ground-based space weather network of sensors in the world, leveraging this existing technology and infrastructure would be the most cost-effective option for DND.

Exercising sovereignty in the Arctic region is a top priority of Canada's foreign Arctic policy.[36] In support of achieving Canadian strategic goals, the DND/CAF will continue to play a crucial role in developing, generating, and employing joint task forces capable of producing effects in this northern region. The immensity of Canada's arctic territory, combined with the harsh climatic conditions, make it difficult for the CAF to maintain a permanent military presence in the majority of the area. Instead, Canada must develop the capability to rapidly project task-tailored forces in dispersed areas as needed. To achieve this capability, developing and maintaining SA is fundamental. This SA requirement makes space-based surveillance assets critical mission enablers. For example, the Canadian RADARSAT series continues to provide a vital capability for Arctic and maritime surveillance, since it can collect images during darkness or cloudy conditions. And yet, 284 space weather events were recorded when RADARSAT was travelling through the South Atlantic anomaly,[37] a region where the Van Allen radiation belts come closest to the Earth's surface, and where higher levels of radiation are present. Furthermore, six events, possibly related to space weather, caused a 'reboot' of the satellite as it was passing over the poles.[38]

Moreover, the establishment of communication links in this vast territory must often rely upon SATCOM resources. To this end, CSA, in partnership with DND and other federal departments, is developing the Polar Communication and Weather (PCW) mission aimed at providing weather and communication services to the arctic region. We can expect PCW to experience disruptions and anomalies when placed into orbit, since it will spend a large portion of its orbiting time in a high-radiation environment. Perfect radiation hardening engineering solutions are impossible, and trade-offs between cost, weight, and space must be considered. One way to mitigate space weather adverse events is to enhance awareness and to properly account for these effects in the joint operational planning cycle.

As mentioned before, a WoG approach is key to achieving the objectives of Canada's foreign Arctic policy. This is especially relevant for the CAF Space program to remain flexible, agile, reliable, and affordable in the future Arctic security environment. Space weather related capabilities would also need to be leveraging and collaborative. Canada is already the home of the most robust and extensive network of ground-based sensors observing space weather. Also, a vast amount of space weather expertise already resides within numerous groups and OGDs. It would be in Canada's utmost interest to leverage this existing specialized knowledge, which requires decades to build up, in order to develop a Canadian space weather capability that would better suit its current and future defence requirements. Indeed, the CanSpOC cannot just integrate space weather products from Allied countries in the planning and conduct of domestic operations, due to Canada's unique location with respect to space weather phenomena. The geospace processes above Canada are much different than those observed at mid-and-low latitudes. What is more, the ionosphere dynamics are more intense in Canada than in Scandinavian countries, because of the presence of the geomagnetic pole within Canada. Hence, integrating other countries' space weather products would be equivalent to applying terrestrial weather forecasts to the wrong area of interest. The recent lack of access to Allied space weather reports, due to the US government partial shutdown of Autumn 2013, constitutes another compelling argument in favor of developing a Canadian space weather SA solution.

Finally, Canada has the best geography to observe space weather phenomena. Using ground-based sensors is an option significantly cheaper than building and launching satellites into orbit. For example, the cost for a single RIOMETER instrument is on the order of a few thousand dollars. Yet, this instrument can provide valuable insight into the status of the ionosphere and the level of absorption that radio waves would undergo. Therefore, leveraging the existing ground-based infrastructure would be the most affordable joint capability development option. This course of action would also be in line with the spirit of DND space policy and Canada's foreign Arctic policy documents.

Conclusion

Space weather features originating from the Sun can lead to disruption of satellite and polar aviation operations, and degradation of SATCOM, radar, and/or navigation systems. These adverse effects are directly linked to equivalent joint military capability impacts. For this reason, several modern Allied militaries have acknowledged the requirement to develop an environmental SSA in order to achieve joint space effects.

Space weather effects should be adequately integrated into the planning and execution of domestic, joint, and interagency operations to ensure strategic success in Canada's Arctic region. The DND/CAF should leverage the already existing Canadian world-class expertise in space weather R&D in order to develop an inter-agency and affordable Canadian ground-based SSA capability, better suited to mitigate Canada's extreme and unique vulnerability to space weather.

Space is essential to joint military operations, especially in the Arctic, and operational dependencies and vulnerabilities must be understood. Canada's space weather vulnerability cannot be neglected in terms of joint capability development simply because it will grow exponentially with time, along with the CAF's critical reliance upon infrastructure and technologies. By developing situational awareness of space weather effects, we can better execute the command, sense, act, and shield functions of our defences, and deliver them more effectively. Hence, capability developers should carefully compare each of these functions in the space domain against each of the six core missions of Canada's Defence Strategy in order to deduce the exact future requirements.

Brian J. Skerry/National Geographic Creative Image ID 699233

NOTES

1. At least, it was the opinion of Colonel F. Malo, Director Space Development in: F. Malo, "Canada's Defence Space Program," in *Frontline Defence*, No.6, 2008.
2. Committee on the Societal and Economic Impacts of Severe Space Weather Events: A Workshop, National Research Council, National Academy of Sciences, *Severe Space Weather Events – Understanding Societal and Economic Impacts*, Workshop Report (The National Academy Press, 2008), p.13.
3. A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere due to space weather events that can last from a few hours to several days. Classical magnetic storms are described in R. D. Hunsucker and J.K. Hargreaves, *The High-Latitude Ionosphere and its Effects on Radio Propagation,* Cambridge Atmospheric and Space Science Series, (Cambridge, MA: Cambridge University Press, 2003).
4. P. McMahon, "Sun struck," in *Canadian Geographic*, Vol. 133, No.1, 2013, p. 36. The original quote is from Dr. E. Donovan.
5. H.L. Lam, D.H. Boteler, B. Burlton and J. Evans, "Anik-E1 and E2 Satellite Failures of January 1994 Revisited," in *Space Weather*, Vol. 10, Issue 10, 2012.
6. J. Wilkinson, *New Eyes on the Sun*, (Springer, 2012), p. 186.
7. M. Moldwin, *An Introduction to Space Weather*, (Cambridge, MA: Cambridge University Press, 2008), p. 82.
8. Report from AON Benfield, "Geomagnetic storms," Empower Results, January 2013, p. 5, at <http:thoughtleadership.aonbenfield.com/Documents/201301_geomagnetic_storms,pdf>, accessed 26 March 2013.
9. D.N. Baker, X. Li, A. Pulkkinen, C. M. Ngwira, M. L. Mays, A. B. Galvin and K. D. C. Simunac, "A major solar eruptive event in July 2012: Defining extreme space weather scenarios," in Space Weather, Vol. 11, pp. 585–591, 2013.
10. AON Benfield, "Geomagnetic storms," p. 5.
11. As reported by Dr. L. Lanzoretti during the keynote address, "Space Weather: Affecting Life and Technologies on Earth and in Space," Inaugural International Critical Infrastructure Protection (CIP) & Space Weather Workshop, Ottawa, 28-29 March 2012.
12. US Joint Publication 3-14, "Space Operations," 6 January 2009, p. II-1.
13. *Ibid.,* p. II-7.
14. *Ibid.*
15. Lieutenant Colonel K. Hand and Colonel M. France, "Weather Situational Awareness and Joint Space Effects," in *High Frontiers, The Journal For Space and Missile Professionals*, US Air Force Space Command, Vol. 2, No. 1, pp. 51-55.
16. US Army Field Manual 3-14, "Space Support to Army Operations," 2005, p. A-3
17. Joint Concept Note 3/12, Future Air and Space Operating Concept, Ministry of Defence, United Kingdom, September 2012.
18. "Space: Dependencies, Vulnerabilities and threats," Multinational Experiment 7, The Development, Concepts, and Doctrine Centre, Ministry of Defence, United Kingdom, 2012.
19. Space Environment Support to NATO Space Situational Awareness (SCI-229) at http://www.cso.nato.int/Activity_Meta.asp?Act=2069, accessed 6 May 2014.
20. *Ibid.*
21. Elements of this table were adapted from US and NATO references: Lieutenant Colonel Hand and Colonel France, "Weather SA and Joint Space Effects," pp. 51-55; US JP 3-14, "Space Operations," p. II-1; and Lieutenant Colonel Single, "NATO Space Ops Assessment."
22. As defined by Lieutenant Colonel Hand and Colonel France, "Weather SA and Joint Space Effects," pp. 51-55.
23. A-FD-005-002/AF-001, Integrated Capstone Concept, Chief of Force Development, 17 Wing Winnipeg Publishing Office, 20 October 2009, p. 29.
24. *Ibid.*
25. *Ibid.,* p. 74 (Note 25).
26. Department of National Defence, Space Policy, Ottawa, Canada, 1998.
27. Draft National Defence Space Strategy, Version 4.3, p. 2.
28. *Ibid.,* p. 5.
29. *Ibid.,* p. 8.
30. *Ibid.*
31. H.L. Lam, "From Early Exploration to Space Weather Forecasts: Canada's Geomagnetic Odyssey," in *Space Weather,* Vol. 9, S05004, 2011.
32. "Canadian Space Environment Community LTSP Roadmap," prepared by the Space Environment Advisory Subcommittee with Community Consultation, 17 November 2009.
33. This deployed array is complemented by University of Calgary's NORSTAR RIOMETERs, forming the joint Canadian RIOMETERs network.
34. A description of the riometer technique is provided in Hunsucker and Hargreaves, *The High-Latitude Ionosphere and its Effects on Radio Propagation.*
35. K. F. Tapping, "The 10.7 cm solar radio flux (F10.7)," in *Space Weather*, Vol. 10, Issue 3, 2013.
36. Statement on Canada's Arctic Foreign Policy, "Exercising Sovereignty and Promoting Canada's Northern Strategy Abroad," at http://www.international.gc.ca/arctic-arctique/arctic_policy-canada-politique_arctique.aspx?lang=eng, Last modified 3 June 2013.
37. As reported by Dr. P. Langlois during the address, "Space Weather-Related Activities at the Canadian Space Agency," Inaugural International Critical Infrastructure Protection (CIP) & Space Weather Workshop, Ottawa, Canada, 28-29 March 2012.
38. *Ibid.*