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IR[3] FEATURE ARTICLES

Editorial Corner

Dr. Robyn Fiori

About the Editor

Dr. Robyn Fiori is a research scientist for the Canadian Hazards Information Service of Natural Resources Canada specializing in space weather. Her research is applied to the development and improvement of space weather tools and forecasts to be used by operators of critical infrastructures and technologies in Canada. Dr. Fiori's research has been published in numerous peer reviewed scientific journals, including the Journal of Geophysical Research, the Journal of Atmospheric and Solar-Terrestrial Physics, and Space Weather. Dr. Fiori received her B.Sc., M.Sc., and Ph.D., from the University of Saskatchewan, Department of Physics and Engineering Physics while studying in the Institute of Space and Atmospheric Studies. She can be reached at robyn.fiori@canada.ca.

This Issue

The ninth issue of IR^3 describes infrastructure resilience with articles related to Global Navigation Satellite Systems (GNSS), nuclear reactors, aviation, and airborne threat detection.

Issue 9 opens with a special tribute to Martin Rudner, Ph.D., Distinguished Research Professor Emeritus, at Norman Paterson School of International Affairs, Carleton University, by **Felix Kwamena**.

Michela Menting's article about the vulnerabilities and threats to the ever expanding and increasingly important GNSS network provides a description of jamming and spoofing with an extensive list of known events followed by a discussion of defense mechanisms for protecting GNSS signals.

Kristina Gillin discusses a sustainability-based approach to nuclear decommissioning and waste management. Her article provides a summary of the current state of nuclear reactors worldwide, and a discussion of the benefits and challenges of a sustainable decommissioning approach through back-end management.

The IRRR closes with a series of articles related to the Earth's ionosphere in terms of infrastructure resilience and security. The International Civil Aviation Organization (ICAO) has identified space weather as a risk to aviation with impacts to high frequency radio communication, satellite communication, and Global Navigation Satellite System (GNSS) accuracy. **Larry Burch** provides a high-level overview of the ICAO space weather advisory service. Following this is an article by **Robyn Fiori and David Boteler** that describes the space weather impacts to aviation, including the phenomenon monitored by the ICAO space weather advisory service and the event frequency. **Ryan Riddols** closes this Issue with a description of the role of the ionosphere and over-the-horizon radar (OTHR) for early warning of airborne threats to Canada. The article describes the general theory of OTHR, performance issues, and a historical and current state of OTHR in the U.S. and Canada.

Next Issue:

Issue 10 will feature articles from speakers at the November 27, 2019 Infrastructure Resilience Research Group Armchair Discussion (The Environment: Economic Security, Resilience - Select Industry Response) and Dean's Lecture (The Environment: Past, Present and Future - Sustainability Challenges and Strategies). We invite authors to contribute additional articles for Issue 10 relating to their experience in the field of infrastructure resilience. Draft articles of 2500-4000 words are requested by February 21, 2020. You may not have much time or experience in writing 'academic' articles, but IR^3's editorial board can provide guidance and help. Your experience is valuable and IR^3 provides an ideal environment for sharing it.

A TRUBUTE TO

MARTIN RUDNER, Ph.D.
(1942 – 2019)

Distinguished Research Professor Emeritus
Norman Paterson School of International Affairs, Carleton University

Dr. Martin Rudner passed away on Saturday, December 14th 2019, at the Ottawa General Hospital Cancer unit.

The only son of Moses Rudner and Esther Hockenstein of Montreal, he will be sadly missed by his partner Angela; sister Bonnie (Alex Spira); daughter, Aliza (Jeremy Goldstein); four nephews Brian, Avi, Danny and Shalom Spira; and numerous friends and colleagues in Canada and abroad.

An internationally recognized Canadian scholar, inspired teacher, and a tireless pioneer for interdisciplinary research, promoter of knowledge and understanding who authored over 100 articles and books.

He was educated at Hebrew Academy and McGill University, Montreal (B.A and M.A. 1965), Linacre College Oxford (M.Litt., 1969) and Hebrew University of Jerusalem (PhD 1974). Martin started his academic career as a Senior Research Fellow, Department of Economics, Research School of Pacific Studies at Australian National University (1975), then as an Academic Assistant to the Vice-Chancellor (1980-1982).

He returned to Canada in 1982 to work with the Canadian International Development Agency, and as a Visiting Associate Professor at The Norman Paterson School of International Affairs (NPSIA), Carleton University, where he became a Professor in 1988, and subsequently appointed Director of the NPSIA's Canadian Centre of Intelligence and Security Studies (CCISS).

I first met Martin in 2002, at a security workshop at the old Ottawa Convention Centre. After listening patiently to my lament of a lack of theoretical framework to help address the emerging threats to critical Canadian energy infrastructure and the "silo approached" being used by stakeholders, he suggested we meet for coffee. Coffee meetings led to lunches, dinners and countless hours brainstorming in his home sunroom, garden, or walking through his neighborhood while debating practical solutions to security and resilience issues post 9/11. These discussions led us to conclude that what was lacking was a multidisciplinary approach to breaking the "entrenched professional and academic silos".

To encourage multidisciplinary research, Martin "recruited" professors from the Norman Paterson School of International Affairs (NPSIA), and Faculty of Engineering and Design (FED) to redirect their research expertise to addressing energy security and resilience issues. Under the auspices of CCISS and with funding from Natural Resources Canada, he directed and published 18 commissioned studies. These studies, served as foundational research, included the following topics:

- The Legal Imperative To protect Critical Energy Infrastructure;
- Insurance and Critical Infrastructure: Is There a Connection In An Environment of Terrorism;
- Utilization of Advanced Engineering Technologies To Enhance The Protection of Critical Energy Infrastructure In the Gulf Region;
- Assessing Trinidad's Energy Security Vulnerability: Threats and Responses;
- Oil Platform Security: Is Canada Doing All it Should?;
- Who Does What? Critical Energy Infrastructure in the Canadian Government.

Martin was not a person to rest on his laurels. Under his leadership, he convinced the late Professor Abd El Halim, then Chair of the Department of Civil and Environmental Engineering, and me to sponsor the establishment of an interdisciplinary graduate program to train the next generation of analysts and engineers. Under the Championship of Professor Rafik Goubran, then Dean Faculty of Engineering and Design, and after almost 4 years of approvals, the Master of Infrastructure Protection and International Security (MIPIS) Program became a reality. Although the initial enrollment was projected to be 10, the current annual enrollment of over 30 and the continuing success of the MIPIS program, which Martin referred to as "the first of its kind in the world" where social scientists study engineering, and engineers took policy and security courses; is a further testimony of his vision and tenacity.

Recognizing the need to foster critical interdisciplinary thinking among public and private sector security practitioners, Martin accepted my invitation to co-found the Infrastructure Resilience Research Group, (IR^2G) with me under the Office of the Dean, FED, in 2013. He served as an Editorial Board member of IRRG's Online Journal, *Infrastructure Resilience Risk Reporter (IR^3)*. Until 2017, Martin was also the Moderator for the IR^2G's hosted Dean's Annual Lecture Series, another important interdisciplinary learning forum for the public, private and diplomatic community.

In addition to his academic engagements, Martin was a founding member of the Energy and Utilities Sector Network and served as the first Chair of its Research and Training Working Group. He was also a frequent speaker at the International Pipeline Security Forum, (co-hosted by Natural Resources Canada and the U.S. Department of Homeland Security, Transportation Security Administration), and IR^2G hosted security and resilience symposiums and workshops. His commitment to recruiting other international speakers is another clear demonstration of his dedication to proactive information sharing.

Martin was a good man, gentleman, and scholar. I have lost a great friend and a collaborator. I will miss him greatly. May the Lord continue to bless his soul.

Felix Kwamena, Ph.D.

Vulnerabilities and Threats to Global Navigation Satellite Systems

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I. GNSS ON THE RISE

Global Navigation Satellite Systems (GNSS) are a constellation of satellite systems that transmit positioning, navigation, and timing (PNT) data signals from space around the globe. GNSS is a main component of various essential communication, navigation, and surveillance (CNS) systems.

Testament to the growing importance of satellite systems today, new constellations will become operational in the near future. The U.S. Global Positioning System (GPS), and Russia's GLONASS, are the two primary systems currently in operation, but several others will reach full operational capacity soon, including the European Galileo and China's BeiDou. Interestingly, Galileo's primary focus is on civilian usage, a departure from the traditional military history of GPS and GLONASS. Although today, most satellite constellations are dual-purposed, serving both military and civilian use. In addition to GNSS, there are various regional constellations and satellite-based augmentations in operation, such as Korea's Multi-Purpose Satellite, Japan's Quasi Zenith Satellite System, and the Indian Regional Navigation Satellite System (NavIC), fueled by demand in satellite-based connectivity on a global scale.

This is primarily because GNSS has become a key technology in modern societies, used across a broad number of sectors, including military, transportation (automotive and other road transport, aviation, and maritime), telecommunications, emergency services, law enforcement, energy, finance, agriculture, and forestry, environmental protection, highway and construction, surveying, weather, and manufacturing, among others. With the growth of the Internet of Things (IoT), GNSS will increasingly be leveraged alongside cellular and other connectivity technologies. In large part, this is because GNSS is a reliable technology, underpinned by four critical characteristics. These are:

1) Accuracy in terms of position, speed or time;
2) Integrity, by providing confidence in GNSS performance and providing an alert if confidence dips below a certain level;
3) Continuity of service: it is able to function without interruption; and
4) Availability, notably the percentage of time a signal takes to meet the stated accuracy, integrity and continuity criteria.

As such, GNSS provides a common time reference used to synchronize systems, communication networks, operations, and supports a wide range of applications, be it in autonomous driving, fleet management, asset tracking, synchronization of power levels by SCADA systems, etc.

Certainly, the value of GNSS will increase significantly as new and varied IoT applications emerge, which means that threats to it will grow in parallel. As such, the preservation of its key characteristics (i.e., accuracy, integrity, continuity, and availability) will become evermore important.

II. VULNERABILITIES & THREATS

Unfortunately, there are numerous traits in GNSS technology that makes it vulnerable today: weak signal at the receiver antenna (in part due to the long distance the signal must travel from satellite to ground); single frequency band (common among various constellations); limited number of satellites; natural and artificial impediments; low and fixed power level (making it difficult to cope with obstructions and poor radio environments).

These weaknesses mean that threats to GNSS can easily degrade or disrupt the signal. Broadly speaking, GNSS threats can be classed in two broad categories: unintentional or intentional.

Unintentional threats are primarily the result of natural and manmade elements, such as atmospheric conditions, solar radiation, electromagnetic interference (power lines), physical obstacles (valley, mountain range, urban canyons, or underground spaces), very high frequency communications, television signals, certain RADARs, mobile satellite communications, military systems, microwave links, and GNSS repeaters. Until recently, they have been the primary issues that stakeholders in the field have been attempting to manage.

A newer, and perhaps more worrying, phenomenon is the emergence of intentional threats, at least beyond classic military usage. These threats are the result of the modern strategic value of satellite PNT data, and its widespread use across various industries. This makes it a target for malicious attack, notably through jamming and spoofing.

Jamming is the intentional interference with GNSS signals. This is done through the deliberate radiation of electromagnetic signals at GNSS frequencies in order to overpower legitimate GNSS signals so they cannot be acquired or tracked by GNSS receivers. Jammers are often used in the military, but, recently, the rise of Personal Privacy Devices (PPDs, also known as civil jammers) has been recognized as a major cause of interference to GNSS. PPDs are marketed as devices aimed at protecting a user’s privacy by hiding their location (by jamming the GNSS signal) to limit tracking or monitoring of the user. However, they have the unfortunate effect of also jamming all GNSS signals in a radius of a few kilometers and therefore tend to effect devices unrelated to the user with the PPD.

Jammers are illegal in many countries, but this has not stopped their commercial proliferation, especially as most are generally low-cost and affordable to the average user.

The other intentional threat, and probably the more dangerous of the two, is spoofing. Spoofing involves the broadcast of false PNT information and convincing a receiver to accept it as legitimate. Another spoofing method involves rebroadcasting GNSS signals recorded at another place or time (meaconing). Spoofed signals are generally high-powered so they can more easily overwhelm the legitimate lower-powered GNSS signal.

While spoofing is a more complex threat than jamming, it is becoming more readily accessible (and affordable) through the availability of software-defined radios (SDR). GPS simulators, in 2009, cost on average EUR 6,000. Today, a USB3 to VGA adapter that can replay a GNSS signal costs only EUR 5.

Interestingly, a market for SDR spoofers emerged with the popularity of the Pokémon Go game in 2016. Some players used SDR spoofers to catch elusive Pokémon while remaining stationary. The gaming industry is just one example of a popular application driving a parallel underground movement to cheat the system. For most threat actors, it is the popularity of a platform that drives interest in subverting or interfering with it, often for financial gain.

It is becoming increasingly clear that spoofing will likely be able to defeat any number of legitimate uses in technologies using GNSS, such as geo-fencing, tracking in pay-as-you-go driving, toll fee collection, advanced diver assisted systems, V2V/V2X, automated insurance calculation, intelligent transportation systems, telematics, fleet management, ship and aircraft navigation systems, among many other IoT and M2M applications.

The table on the next page provides a snapshot of some high-profile cases where jamming and spoofing were directed against GNSS.

Sector	Description
Automotive	In June 2019, Regulus Cyber demonstrated how a spoofing attack on the Tesla (Model S and Model 3) GNSS receiver could easily be carried out wirelessly and remotely, exploiting security vulnerabilities in mission-critical telematics, sensor fusion, and navigation capabilities.
General	Between 2016 and 2019, the European STRIKE3 project monitored stations in 23 countries around the globe, capturing and analyzing more than 450,000 GNSS-L1/E1 interference signals.
Maritime	In 2017, the U.S. Maritime Administration issued an alert to respond to the reports of GPS disruptions and interference from multiple vessels between the Cyprus and Egypt port.
Maritime	In 2017, a GPS spoofing attack involved over 20 vessels in the Black Sea with the vessels reporting their location at an airport.
Maritime	North Korea used GPS jamming against South Korean ships, fishing vessels and equipment on land and sea in 2010 and 2016. The jamming campaign in March 2016 affected the signal reception of more than 700 ships.
Surveillance	In 2015, the first criminal GPS spoofing of a border surveillance drone was reported on the border of the U.S. and Mexico.
Aviation	In 2014, researcher Ruben Santamarta proved that it was possible to interfere with satellite communications, with flight navigation systems, using the in-flight entertainment system accessible through Wi-Fi.
Maritime	In 2014, researchers from the University of Texas demonstrated how to change a ship's direction and trick the onboard navigation system by faking a GPS signal.
Maritime	In 2014, Trend Micro showed that an attacker with a US$100 VHF radio could exploit weaknesses in Automatic Identification Systems of ships and tamper with data, impersonate a port authority's communications with a ship, or effectively shut down communications between ships and with ports.
Maritime	In 2014, the NCC Group found flaws in one vendor's Electronic Chart Display and Information System software that would allow an attacker to access and modify files, including charts.
Maritime	In 2014, the GPS signals of USS Donald Cook, a 4th generation guided missile destroyer, were completely jammed by a Russian Sukhoi Su-24 in the Black Sea using electronic warfare devices.
Maritime	In 2014, a GPS jamming experiment was performed by the U.K. and Irish General Lighthouse Authority on a vessel called Pole Star.
Maritime	In 2013, a research team from the University of Texas used electronic equipment worth $3000 to take control of an 80 million dollar 210-foot yacht in the Mediterranean Sea.
General	In 2012, North Korea used lorry-mounted devices to block GPS signals in South Korea for 16 days, causing 1,016 aircraft and 254 ships to report disruption.
Aviation	In 2012, researcher Brad Haines presented on the weaknesses of Automatic Dependent Surveillance-Broadcast (ADS-B).
Aviation	In 2012, Andrei Costin also presented on ADS-B (in) security and techniques of how potential attackers could play with generated/injected air traffic, opening new attack surfaces onto the air-traffic control system.

While the majority of threats seem to stem from the maritime sector, in large part due to the high reliance of the industry on GNSS while out at sea (and lack of alternative connectivity technologies), it is also clear that other sectors can be affected, with more recent threats in the automotive and aviation space.

III. Defenses

There are some basic protection mechanisms that can be used to protect GNSS signals, both from intentional and unintentional interference.

One of the primary efforts, at least for unintentional interference, is to ensure allocation frequency separation of stations from different services, as well as coordination between administrations to guarantee interference-free operations conditions. The latter is done primarily through the International Telecommunication Union (ITU), which allocates global radio spectrum and satellite orbits. The various ITU regulations and conventions govern frequency allocation, and the ITU provides a forum for States to discuss interference issues.

Proper installation of protective elements for GNSS systems, such as shielding, antenna separation and out-of-band filtering can go a long way in minimizing interference. Further, a legal framework can help various efforts in this field and uphold common standards by regulating effective spectrum management and governing the use and commercialization of tools, such as GNSS repeaters, pseudo-satellite transmitters (pseudolites), spoofers and jammers.

From a technical perspective, various methods of protection are available. A first step is testing for interference. Detectors, for example, provide an effective way to test for intentional interference. They can record and analyze artificial interference, such as profiles of jammers and spoofers, enabling tracing of the source.

A second step is to try to detect spoofing. Various spoofing detection techniques aim to determine whether a signal is legitimate or not, by trying to detect anomalous harmonics in the spectrum. These can include a high-powered signal for example that might indicate that it is trying to overpower a legitimate signal).

Other efforts look to use dual-polarized antennas to mitigate multipath propagation, as well as multi-constellation GNSS to allow the receiver to track more satellites. These would help boost received capabilities and limit disruption and interference. Further dual-frequency GNSS devices would help to minimize risk of intentional interference, as a malicious actor would have to spoof or jam two signals. The higher the barrier for causing harm, the more this will dissuade malicious actors.

A third step is to implement security mechanisms, such as authentication and encryption. Except in specific military use cases, security is not generally implemented in civilian use of GNSS. Few options exist, but with the growing threat of intentional interference, a few efforts have emerged as likely candidates for widespread adoption.

For example, Galileo’s Open Service Navigation Message Authentication (OS-NMA) enables authentication of the navigation data on Galileo and GPS satellites using asymmetric cryptography. The data carries information about satellite location and, if altered, will result in wrong receiver positioning computation. OS-NMA is currently in development, and plans are to make it publicly available in 2020. A number of receiver manufacturers are already prototyping OS-NMA (such as Septentrio).

The U.S. GPS is also testing satellite based anti-spoofing solutions for civil users with the Chimera authentication system. Chimera would add encrypted steganographic watermarks to the signal by the satellite. The key is sent to the receiver after a slight delay. This would let users know when a signal is being spoofed as the received key would not match to a spoofed signal (which may not even have a watermark). Chimera also enables users to verify their location to other parties, providing authentication from one party to another.

Another security technique that can be implemented is a firewall between the antennas and the GNSS, which can serve to block untrusted signals. For example, BlueSky offers a GNSS Firewall that uses a decision engine to analyze signals to determine legitimacy. There is no doubt that as machine learning and analytics move to the edge, these can be increasingly leveraged to undertake intensive computations, such as behavioral analysis that are popular in the cybersecurity industry.

Finally, the Center for Spatial Information Science at the University of Tokyo has been developing anti-spoofing solutions based on QZSS (Japanese GPS) to authenticate QZSS, GPS, GALILEO, and BEIDOU signals. They have already started conducting pilot projects with interested universities, industries, and organizations.

Most of these security techniques are still relatively new, but certainly authentication mechanisms are the most likely candidates to hit the market first in terms of GNSS protection. However, they will need to contend with latency expectations as well, and specifically in markets where delay can be an issue (in automotive, for instance).

IV. International Forums

In addition to technical means, there are a number of international organizations pushing for better cooperation in securing GNSS. The objective of most countries is to ensure both compatibility and achieve interoperability between the various constellations to minimize interference and provide better coverage and availability for users. Of real concern is intentional interference in terms of jamming and spoofing, and the focus of many forums today is on how to thwart these. The following section looks at these various efforts.

The International Committee on Global Navigation Satellite Systems (ICG), created in 2005, is an international forum focused on promoting GNSS use. One of its core areas of focus is GNSS interference and spectrum protection. Specifically, their subgroup on compatibility and spectrum protection is investigating methods of implementing interference detection and mitigation capabilities through permanent network-based solutions and through crowdsourcing techniques. An Interference Detection and Mitigation (IDM) Taskforce was created in 2017 to undertake this work. The ICG recently ran a seminar in June 2019 on GNSS Spectrum Protection and Interference Detection and Mitigation to educate participants on the importance of GNSS spectrum protection at the national level and explain how to reap the benefits of GNSS.

In 2016, the International Civil Aviation Organization (ICAO) developed a GNSS RFI mitigation plan as a part of their GNSS Manual (ICAO Doc 9849). The mitigation plan describes a list of preventive and reactive measures aimed at mitigating the interference risk as far as practicable. Already in 2012, ICAO had recommended that States provide effective spectrum management and protection of GNSS frequencies to reduce the likelihood of unintentional interference or degradation of GNSS performance. The ICAO Navigation System Panel (NSP) is currently developing a standard for the new generation of dual-frequency, multi-constellation (DFMC) GNSS.

The Alliance for Telecommunications Industry Standards (ATIS) sent a letter to government officials in 2018 to various U.S. departments (Transportation, Defense, Commerce, and Homeland Security) as a result of a workshop it hosted with the Resilient Navigation and Timing Foundation. The letter asked officials to "…mitigate the impacts of GPS vulnerability to the public" and offered a series of recommendations to this effect, including establishing an assured PNT program for civilian infrastructure, monitoring for GPS/GNSS disruptions and impact, publishing GPS disruption reports and the government's analysis, and taking enforcement action against spectrum violations.

The Regional Aviation Safety Group for the Middle East Region (RASG-MID) issued a Safety Advisory in April 2019 concerning GNSS vulnerabilities that also provides guidance material to mitigate the safety and operational impact of GNSS service disruption.

The International Federation of Air Traffic Controllers' Association (IFATCA), the International Federation of Air Line Pilots' Associations (IFALPA) and the International Air Transport Association (IATA) have worked together to present a Call to Action at a technical commission of the International Telecommunication Union in August 2019. The working paper A40-WP/188 on “An Urgent Need to Address Harmful Interferences to GNSS” invites States to adopt and implement measures to manage and reduce the operational impact from harmful interference to GNSS.

The European Union is also highly focused on GNSS protection. The European Commission has been aware of GNSS vulnerabilities, and in particular, interference with tolling fees. In 2015, it contracted with Nottingham Scientific Ltd. in the U.K. to lead a multi-nation team and assess the extent of the problem through the STRIKE3 project. STRIKE3 operated between February 2016 and January 2019, sampling and classifying interference events in 23 different countries. During the timeframe, it detected almost half a million interference events, with about 73,000 classified as having a major impact on GNSS. The project further identified 59,000 of these as jammer signals. The project has been a success and has placed the EU at the forefront of GNSS threat detection, reporting and mitigation strategies.

More recently, the Official Journal of the European Union is set to publish a funding opportunity for a GNSS Advanced Interference Detection and Robustness Capabilities System. A prior information notice was published in August 2019, which highlighted the purpose of the tender to “establish a new mechanism to detect interference at receiver and antenna level based on crowdsourcing and sharing information coming from any user (individuals or associated ones) and run the service for a period of 2 years”.

Other projects have similarly sought to provide information and these can be found in the following the SENTINEL Report, US Coastguard Problem Reports, and UK Ofcom Reports.

V. Future Considerations

Next-generation GNSS (multi-band multi-constellation) will offer new levels of precision timing for ultra-precise UTC synchronization. There is no doubt that next-generation GNSS developments will lead to more and more capable applications in the IoT and M2M space. This will be especially attractive in upcoming 5G settings where IoT and M2M connectivity is set to explode, of which many applications will rely on GNSS, and notably in the domain of real-time tracking.

Consequently, it is critical that the security of GNSS signals be addressed as soon as possible. The obvious growth in intentional interference from a civilian perspective (let alone from a military one) will only increase exponentially as IoT usage becomes widespread.

Security solutions (such as authentication, encryption, and firewalls) coupled with modular multi-band multi-constellation GNSS receivers can provide better assurance that accuracy, integrity, continuity and availability are protected.

About the Author

***Michela Menting**, Research Director at ABI Research, delivers analyses and forecasts focusing on digital security. Through this service, she studies the latest solutions in cybersecurity technologies, blockchain, IoT and critical infrastructure protection, risk management and strategies, and opportunities for growth. She then delivers end-to-end security research, from the silicon to cyber-based applications, closely analyzing technology trends and industry-specific implementations.*

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A Sustainability-Based Approach to Nuclear Decommissioning and Waste Management

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Abstract

With the list of permanently shut down reactors growing ever longer, efforts required for nuclear decommissioning and waste management are increasing worldwide. At the same time, it has become clear that projects associated with nuclear back-end management rarely go as planned, when viewed over the long term. Especially with regard to implementing facilities for disposal of radioactive waste or used fuel, for which significant delays have become the norm and complete stops are not uncommon. Therefore, it can only be concluded that current practices are unsustainable. Which makes one wonder: Why? What would a sustainable decommissioning paradigm look like? And how do we get there?

In this paper, these questions are explored by applying resilience thinking, which has emerged as a leading concept within sustainability research. The case is made that nuclear back-end management is a typical complex adaptive system and that the associated challenges ought to be approached as a sustainability problem.

I. INTRODUCTION

Given the age distribution of the world's nuclear power reactors, a significant increase is anticipated in the rate of units being shut down and requiring decommissioning. It is therefore more important than ever to reflect on the experiences gained to date and incorporate lessons learned into future decommissioning -related endeavors. In doing so, it is vital to consider not only key aspects – such as technical, regulatory, organizational or financial – but the paradigm for nuclear back-end management as a whole.

The scope of this paper is the latter, i.e., to reflect on the overall paradigm for nuclear back-end management and whether it is conducive for meeting the needs of current and future generations. For purposes of this paper, nuclear back-end management is defined as all processes related to the shutting down, decommissioning, waste management and site revitalization associated with a nuclear facility.

The approach selected is to view nuclear back-end management through a sustainability lens. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1].

The reason for selecting a sustainability lens to reflect on nuclear back-end management is four-fold:

- Sustainable development (or sustainability) deals naturally with long timelines and major uncertainties – both of which are prominent features of nuclear back-end management.
- Social, economic and environmental factors are inherent in sustainability – all of which are impacts (whether real or perceived) of nuclear back-end management.
- Sustainability has become pervasive in much of today's society, but application of it in the nuclear industry is, so far, limited (mostly just used in the context of building new reactors or continuing to operate existing ones, in light of climate change).
- The sustainability of the current paradigm is questioned in this paper.

A key concept within sustainable development is resilience, and it is deemed to be particularly relevant and useful for the scope of this paper; consequently, nuclear back-end management is herein reflected upon using resilience thinking. Resilience is the capacity to deal with change and continue to develop[1] and is a means to understand complex adaptive systems (described in Section 3). As such, resilience thinking is an approach that embraces human and natural systems as complex systems that continually adapt through cycles of change [2]. Examples of attributes that typically enhance resilience include: diversity, social capital, innovation and overlap in governance [2].

The scope of this paper is limited to nuclear power reactors, but it is worth noting that the situation described and conclusions drawn would be similar for much of the world's research reactors and non-reactor nuclear facilities.

II. CURRENT STATUS AND EXPERIENCE

When stepping back and reflecting on the current status and experience to date, it is clear that:

- **The number of reactors in shut down mode and undergoing or awaiting dismantling is large and increasing.** The majority of the nuclear power reactors in the world were built in the 1970s and 80s. Of the 625 reactors that have been completed to date, 477 (76%) were built before 1990, see Figure 1. Although life extension measures are taking place at many of these, the list of reactors that have been taken out of service and require decommissioning continues to grow. At present, 173 reactors have been permanently shut down. Of these, the vast majority have yet to be dismantled and the associated sites released from regulatory control.
- **When viewed over the long term, projects rarely go as planned.** Many of the key aspects of nuclear back-end management are associated with great uncertainties: Scheduled shutdown dates often change – either by occurring earlier than anticipated or by being postponed. Facilities for waste storage or disposal are commonly not available as assumed. The entity owning or managing the site may change as part of transitioning to decommissioning or during decommissioning. Even the regulatory landscape and requirements tend to change during planning or implementation, given the long timelines.
- **The landscape is fragmented.** Key areas of expertise related to nuclear back-end management are often approached separately, e.g., aging management, decommissioning, site remediation and waste management. Examples of where this is manifested include organizational structures, staff training courses, and regulatory documents and standards. The distinct roles and responsibilities of key stakeholder groups further enhance the fragmentation, as the current paradigm promotes separation of positions rather than collaboration to achieve what is best for future generations.

Since there is no indication that these realities are about to change, it can only be concluded that the current paradigm is unsustainable; in particular, given the unprecedented scale of decommissioning related activities that is anticipated in the coming decades. This raises the questions: Why? What would a sustainable decommissioning paradigm look like? How do we get there?

III. COMPLEX ADAPTIVE SYSTEMS

It is vital to recognize that decommissioning and managing the resulting wastes of a nuclear power plant are part of a bigger picture: The shutting down of an industrial asset. Like the shutting down of any industrial facility, this has disruptive consequences for surrounding communities. People will be worried about jobs, property values and the impact on the local economy. The identity and source of pride of local communities might be at stake. There may also be concerns of noise, dust and other environmental impacts of decommissioning and waste handling.

[1] Source: https://stockholmresilience.org/research/resilience-dictionary.html, July 6, 2019.

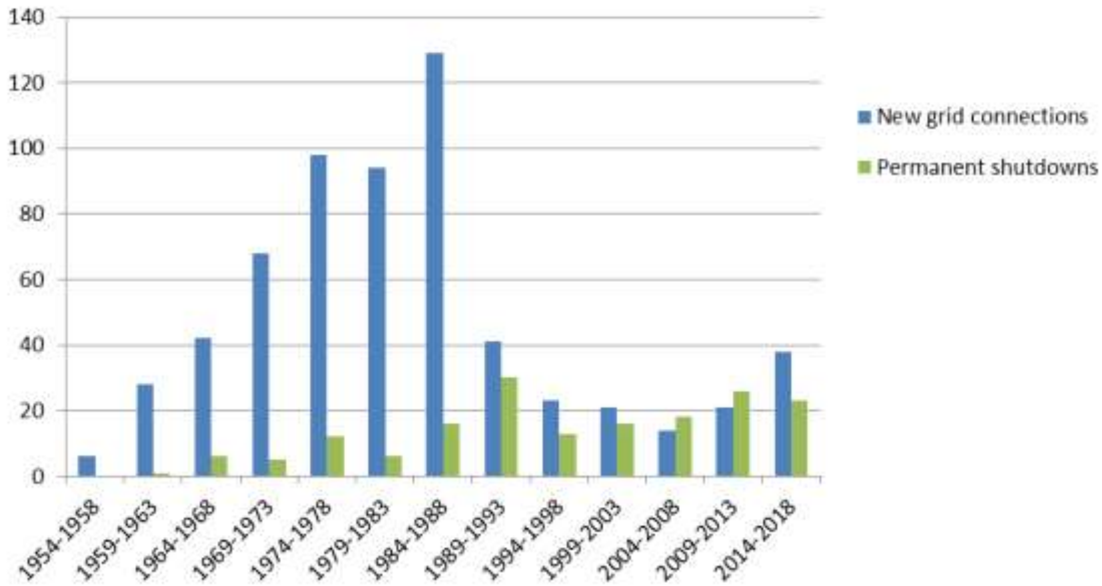

Figure 1: New nuclear reactor grid connections and permanent shutdowns in the world.
Source: IAEA Power Reactor Information System (PRIS), https://www.iaea.org/pris/, May 20, 2019.

These concerns are social, economic and environmental in nature, not technical. Consequently, this confirms that it is logical to view nuclear back-end management from a sustainability perspective – as a complement to seeking solutions to the technical challenges.

Within sustainable development, systems thinking is paramount. Unlike engineering, which deals with systems that are predictable and controllable, sustainable development involves complex adaptive systems.

Complex adaptive systems are self-organizing and constantly changing. They are characterized by feedback loops, tipping points and emergent properties. Their future is impacted by their past, and surprise is inevitable. Examples of complex adaptive systems include farms, forests, cities, companies and our immune systems. The key to managing such systems is to understand and attempt to influence their resilience.

A useful tool in resilience thinking is the adaptive cycle, which encompasses both the accumulation of resources in a given system (the fore loop) and the freeing up of them once the system collapses (the back loop), see Figure 2 [2]. The back loop is the part of the cycle during which there is most uncertainty, but equally, the most potential for influencing the future system. This is the time for leveraging creativity, and the time when being open to and exploring new connections will pay off the most for the future.

The adaptive cycle further confirms the relevance of viewing nuclear decommissioning, waste management and related fields as a sustainability problem, since the back loop perfectly coincides with nuclear back-end management.

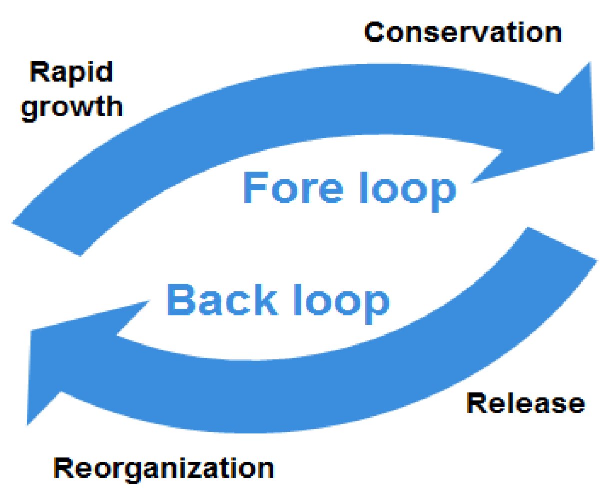

Figure 1: The adaptive cycle (adapted from [2]).

IV. A Sustainable Decommissioning Approach

Once recognized that decommissioning and waste management are part of a bigger picture – the shutting down of an industrial facility, with impacts on surrounding communities – it becomes clear that nuclear back-end management at the overarching level needs to be approached as a sustainability problem. By taking an integrated view of nuclear back-end management and sustainable development, a different approach than what generally is applied in the current paradigm emerges – an approach referred to as sustainable decommissioning in this paper.

In the following subsections, the cornerstones, benefits and challenges associated with such an approach are outlined.

Cornerstones

By viewing nuclear back-end management as the back loop of the adaptive cycle (Figure 2), it becomes evident that a holistic approach is essential to success. Since complex adaptive systems constantly change, another key characteristic of sustainable decommissioning is being adaptive.

When translating these two characteristics into useful principles, the following emerge as cornerstones of a sustainable decommissioning approach:

- **Inclusive** – enabling the public and other external stakeholders to actively participate in the decision making. This goes well beyond just sharing information or asking for input; it means making room at the table for those who will be impacted by the difficult decisions that need to be made. A benefit of this is that a broader spectrum of perspectives, knowledge, ideas and passions will be tapped into compared with decisions that are made behind closed doors.
- **Asset-focused** – considering every part of the system as being of value as a potential building block in a future use, either on or off the site. This includes people, buildings, systems, components, demolished materials, surrounding infrastructure and important habitats. Repurposing of the whole site ought to be considered as well. It has already been demonstrated that this can be done successfully on nuclear sites (e.g., in Stockholm, Sweden, and Greifswald, Germany). While it is recognized that not everything may be reusable, the point is to have a mindset at the onset that all system parts are potential assets, not liabilities.
- **Integrated** – exploring the range of fundamental questions pertaining to shut down, decommissioning, waste management, etc., in concert, as the answers are highly interdependent. This includes how to replace the power and jobs lost; how to mitigate impacts on surrounding communities; what the site will be used for in the future; which structures and materials can be reused; and, for those structures and materials that cannot be reused, how the waste will be managed.
- **Vision-based** – determining what the site will be used for post-decommissioning prior to commencing the planning. That is, rather than viewing the end point as an open-ended release from regulatory control, it should be placed later – beyond decommissioning – and coincide with the point in time when new uses and reuses are fully operational on the site. This way, a shared vision is created, towards which both internal and external stakeholders can strive. Consequently, planning for decommissioning becomes planning for site transformation – that is, the complete process of transforming a site from current to future uses.

Benefits

Compared with current practices, a sustainable decommissioning approach offers a range of valuable benefits. With a higher degree of reuse, less waste is created. And by collaborating and inviting external stakeholders into the decision making, trust, resilience and adaptive capacity are built. The timeline between productive uses on a site is shortened, and the risk of major delays or dead ends is reduced.

A sustainable decommissioning approach has potential to significantly reduce the financial impacts of facility shut down and decommissioning, not only for site owners and operators, but for surrounding communities and society at large. Furthermore, safety is increased long term due to reduced risk that sites, at some point, end up having to be abandoned prior to release from regulatory control.

Challenges

While there are tremendous benefits associated with a sustainable decommissioning approach, major challenges lie ahead if adoption is to occur in practice. For example:

- The nuclear industry is a mature industry in which traditional linear thinking tends to be the norm (in the adaptive cycle in Figure 2, it is high up in the conservation stage). While uncertainty is embraced, it is often dealt with quantitatively (such as in the case of probabilistic safety assessment). The pace of change is slow and governance is strongly top down. Adopting resilience thinking, therefore, will be a challenge, as it largely has the opposite characteristics.
- Among the supply chain, decommissioning is viewed as a growth area; hence, many organizations within the industry are likely to resist changes that lead to overall cost reductions.
- Although the level of public and stakeholder engagement generally has become relatively high, there is often a lack of trust between nuclear industry representatives and some external stakeholder groups. Transforming to a collaborative approach will therefore be a stretch for both sides.
- Current project management practices are poorly equipped to deal with the non-linear nature of complex adaptive systems. As such, alternative ways of working will need to be developed, to enable management of projects in a manner that is holistic, embraces uncertainty and values adaptive capacity.

V. CONCLUSION

Given the unprecedented level of effort needed for nuclear decommissioning and waste management during the coming decades, it is time to acknowledge that the current paradigm is not working as intended and is unsustainable. Instead, innovative approaches to nuclear back-end management need to be explored and tested.

A logical and promising approach is to view nuclear back-end management, at the overarching level, as a sustainability problem. Granted, a large portion of the world's reactors were designed and built before the concept of sustainable development even existed. Even so, by founding nuclear back-end management on sustainability principles, tremendous benefits can be gained – benefits for both internal and external stakeholders – both current and future generations. Aspects of what sustainable decommissioning entails have already been demonstrated to be successful, through projects, such as the revitalization of the Fernald site in the U.S., as well as the repurposing of the R1 reactor hall in Stockholm, Sweden and the Greifswald nuclear power plant site in Germany.

Despite the benefits, it is recognized that transformation to a sustainable decommissioning paradigm is anything but easy. Fundamental challenges exist and can only be overcome if key stakeholder groups come to the joint conclusion that it is better to act sooner than to continue to postpone and leave key issues to be resolved by future generations. A key prerequisite for transformation is that dialogue and collaboration occur between groups that traditionally have tended to oppose each other. Of particular importance in such dialogues is to engage people – especially the youth – living near existing nuclear reactor and waste storage sites, since it is those communities that will inherit the issues and continue to host various radiological inventories until such time that plans for long-term management have been implemented.

The anticipated increase in decommissioning related activities is not unique to the nuclear sector. A similar age distribution among assets, and a corresponding increase in efforts required for decommissioning and waste management, can be seen in oil & gas and other heavy industries. Since viewing the back-end management processes in those industries through a sustainability lens would be equally relevant, it is concluded that the same cornerstones, benefits and challenges derived in this paper are applicable in general to non-nuclear industries.

About the Author

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[1] World Commission on Environment and Development, "Our Common Future", United Nations, 1987.

[2] B. Walker and D. Salt, "Resilience Thinking: Sustaining Ecosystems and People in a Changing World", Island Press, 2006.

ICAO Space Weather Advisory

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Space Weather is used to designate processes occurring on the Sun or in the Earth's magnetosphere, ionosphere, and thermosphere that could have a potential impact to the near-Earth environment. Space weather phenomenon such as solar flares, radiation storms, and geomagnetic storms are some potential concerns for aviation.

The potential effects of space weather on the aircraft include communications and navigation systems, and radiation exposure to occupants and avionics.

The International Civil Aviation Organization (ICAO) implemented a space weather advisory program on November 7, 2019. Under this program, ICAO has initially designated three global space weather service providers:

- The ACFJ consortium, comprising of space weather agencies from Australia, Canada, France and Japan
- The PECASUS consortium, comprising of space weather agencies from Finland (Lead), Belgium, United Kingdom, Poland, Germany, Netherlands, Italy, Austria, Cyprus and South Africa
- The United States' space weather agency (SWPC)

The ACFJ, PECASUS, and SWPC serve as three global space weather centers that share the responsibility to issue global space weather advisories, on a rotating basis, when there are impacts to high frequency communications (HF COM), communications via satellite (SATCOM), satellite (GNSS) based navigation and surveillance systems, or when heightened radiation occurs above flight level (FL) 250. The operation of the three centers will consist of a primary, backup, and an alternate that will rotate on a two-week basis. The primary center will be responsible for issuing the ICAO space weather advisories with collaboration among the backup and alternate space weather centers.

A space weather advisory is issued whenever space weather conditions exceed pre-defined ICAO thresholds for both moderate impacts (MOD) and severe impacts (SEV) as given in the table on the next page.

SEV radiation is a rare event with only a few short-lived events occurring during an 11-year solar cycle.

The space weather advisory provides an observed or expected location for the impact and 6-, 12-, 18- and 24-hour forecasts. The advisory describes the affected part of the globe in one of three ways:

- Six pre-defined latitude bands of width 30° shown in the table (next page) (multiple bands may be given in one advisory), followed by a longitude range in 15° increments*; or
- the term DAYLIGHT SIDE, meaning the extent of the planet that is in daylight; or
- a polygon using latitude and longitude coordinates

**Note: E18000-W18000 (or E180-W180) is used when the entire band is affected.*

Effect	Sub-effect	Parameter used	Thresholds		Impact within advisory area	
			MOD	SEV	MOD	SEV
GNSS	Amplitude Scintillation	S4 (dimensionless)	0.5	0.8	Possible degraded service	Possible unreliable service
GNSS	Phase Scintillation	Sigma-phi (radians)	0.4	0.7		
GNSS	Vertical Total Electron Content (TEC)	TEC units	125	175		
RADIATION		Effective dose rate (micro-Sieverts/hour)*	30	80	Possible increased dose rates above normal levels.	
HF COM	Auroral Absorption (AA)	Kp index	8	9	Possible degraded service	Possible unreliable service
HF COM	Polar Cap Absorption (PCA)	dB from 30MHz riometer data	2	5		
HF COM	Shortwave Fadeout (SWF)	Solar X-rays (0.0-0.8 nm) ($W\text{-}m^{-2}$)	$1x10^{-4}$ (X1)	$1x10^{-3}$ (X10)		
HF COM	Post-Storm Depression	Maximum usable frequency (MUF)	30%	50%		
SATCOM	No threshold has been set for this effect				Possible degraded service	Possible unreliable service

** MOD advisories will only be issued when the MOD threshold is reached between FL250 and FL460.*

SEV advisories will be issued when the SEV threshold is reached at any FL above FL250.

For context, the background effective dose rate at FL370 at very high latitudes is approximately 9 micro-Sieverts / hour during solar minimum and 6 micro-Sieverts/hour during solar maximum. These rates decrease progressively toward the equatorial regions to values approximately one quarter of what is observed at very high latitudes.

Latitude bands used in space weather advisories	
High latitudes northern hemisphere (HNH)	N90 to N60
Middle latitudes northern hemisphere (MNH)	N60 to N30
Equatorial latitudes northern hemisphere (EQN)	N30 to equator
Equatorial latitudes southern hemisphere (EQS)	Equator to S30
Middle latitudes southern hemisphere (MSH)	S30 to S60
High latitudes southern hemisphere (HSH)	S60 to S90

It is recognized that the horizontal, vertical and temporal resolutions of the advisory are very coarse. The use of 30-degree latitude bands, 15-degree longitude increments, 3,000-foot vertical increments (for radiation), and 6-hour time intervals will at times result in over forecasting the affected airspace. In addition, while an entire latitude band may be forecast to have MOD or SEV space weather, there will often be times that the effect does not cover the entire width of the band or is intermittent or temporary. Users should refer to the remarks section of the advisory for additional information. Users can also go to the center's website where a graphical depiction of the space weather event may be provided along with additional information.

Format of the space weather advisory:

Format	Explanation	Examples
Communication header	Product's coded identification for the issuing centers. KWNP is SWPC, LFPW and YMMC are ACFJ, and EFKL is PECASUS.	FNXX01 KWNP FNXX01 LFPW FNXX01 YMMC FNXX01 EFKL
SWX ADVISORY	Space weather (SWX) advisory	SWX ADVISORY
STATUS:	Status indicator (optional) for Test or Exercise	TEST EXER
DTG:	Date and time of origin, in YYYYMMDD/HHMMZ	20190418/0100Z
SWXC:	Name of the Space Weather Advisory Center (SWXC)	ACFJ PECASUS SWPC
ADVISORY NR:	Advisory number (NR)	2019/9
NR RPLC:	Advisory number being replaced by this advisory (optional)	2019/8
SWX EFFECT:	Space weather effect	HF COM MOD HF COM SEV SATCOM MOD SATCOM SEV GNSS MOD GNSS SEV RADIATION MOD RADIATION SEV
OBS (or FCST) SWX:	Observed (OBS) or expected (FCST) space weather effect date/time, location and altitudes (altitudes are only used in the radiation advisory).	18/0100Z EQN W18000-W12000 18/0100Z HNH HSH E180-W180 ABV FL370 18/0100Z DAYLIGHT SIDE 18/0100Z NO SWX EXP
FCST SWX +6 HR:	6-hour forecast. Date/time, location and altitudes.	Same as above
FCST SWX +12 HR:	12-hour forecast. Date/time, location and altitudes.	Same as above
FCST SWX +18 HR:	18-hour forecast. Date/time, location and altitudes.	Same as above
FCST SWX +24 HR:	24-hour forecast. Date/time, location and altitudes.	Same as above
RMK:	Remarks (RMK)	Additional information
NXT ADVISORY:	Date/time when the next (NXT) scheduled advisory will be issued	2010418/0700Z

Example. Space weather advisory – GNSS

Note: GNSS is the acronym for Global Navigation Satellite System, the term for all the world's navigation satellites, which includes the US's Global Position Satellites (GPS).

FNXX01 KWNP 020100
SWX ADVISORY
DTG: 20190502/0100Z
SWXC: SWPC
ADVISORY NR: 2019/59
NR RPLC: 2019/58
SWX EFFECT: GNSS MOD
OBS SWX: 02/0100Z HNH HSH E18000-W18000
FCST SWX + 6 HR: 02/0700Z HNH HSH E18000-W18000
FCST SWX + 12 HR: 02/1300Z HNH HSH E18000-W18000
FCST SWX + 18 HR: 02/1900Z NO SWX EXP
FCST SWX + 24 HR: 03/0100Z NO SWX EXP
RMK: IONOSPHERIC STORM CONTINUES TO CAUSE LOSS-OF-LOCK
OF GNSS IN AURORA ZONE. THIS ACTIVITY IS
EXPECTED TO SUBSIDE IN THE FORECAST PERIOD
NXT ADVISORY: 20190502/0700Z=

Example. Space weather advisory – RADIATION

FNXX01 EFKL 190300
SWX ADVISORY
DTG: 20190219/0300Z
SWXC: PECASUS
ADVISORY NR: 2019/20
SWX EFFECT: RADIATION MOD
OBS SWX: 19/0300Z HNH HSH E18000-W18000 ABV FL370
FCST SWX + 6 HR: 19/0900Z NO SWX EXP
FCST SWX + 12 HR: 19/1500Z NO SWX EXP
FCST SWX + 18 HR: 19/2100Z NO SWX EXP
FCST SWX + 24 HR: 20/0300Z NO SWX EXP
RMK: RADIATION AT AIRCRAFT ALTITUDES ELEVATED
BY SMALL ENHANCEMENT JUST ABOVE PRESCRIBED
THRESHHOLD. DURATION TO BE SHORT-LIVED
NXT ADVISORY: NO FURTHER ADVISORIES=

Example. Space weather advisory – HF COM

FNXX01 YMMC 020100
SWX ADVISORY
DTG: 20190202/0100Z
SWXC: ACFJ
ADVISORY NR: 2019/10
SWX EFFECT: HF COM MOD
OBS SWX: 02/0100Z DAYLIGHT SIDE
FCST SWX + 6 HR: 02/0700Z DAYLIGHT SIDE
FCST SWX + 12 HR: 02/1300Z DAYLIGHT SIDE
FCST SWX + 18 HR: 02/1900Z NO SWX EXP
FCST SWX + 24 HR: 03/0100Z NO SWX EXP
RMK: LOW END OF BAND HF COM DEGRADED
ON SUNLIT ROUTES. NEXT 12 HOURS
MOST POSSIBLE, DECLINING THEREAFTER.
NXT ADVISORY: 20190202/0700Z=

Changes to the space weather advisory content and format are possible in the coming years as experience is gained with the use of this product.

Additional information is available in ICAO Annex 3 – *Metrological Service for International Air Navigation* and ICAO Doc 10100 – *Manual on Space Weather Information in Support of International Air Navigation*.

About the Author

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Space Weather Impacts to High Frequency Radio Communication Used by Aviation

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Abstract
High frequency (HF) radio communication, relied on by the aviation industry, is sensitive to space weather and would benefit from an operational service that warns the industry when impacts can be expected. Recognizing this need, the International Civil Aviation Organization (ICAO) initiated the development of a space weather advisory service that began operation on November 8, 2019. This article describes two space weather phenomena, absorption and post-storm maximum usable frequency (MUF) depression, which can severely degrade HF communication.

I. INTRODUCTION

Space weather describes a collection of physical processes beginning on the Sun and ultimately affecting human activities on Earth and in space (see www.spaceweather.ca). The Sun constantly emits energy, as electromagnetic radiation, and as energetic electrically charged particles that stream out from the Sun (as the solar wind) and are sometimes thrown out in spectacular explosions. The radiation and particles interact with the Earth's geomagnetic field and ionosphere[ii] in complex ways, causing concentrations of energetic particles to collect and electric currents to flow in regions of the ionosphere. The resulting magnetic storms and ionospheric disturbances, along with creating beautiful auroral displays, can pose a hazard for human activities by impacting a wide range of critical infrastructure and technology. Of particular relevance to aviation is space weather disturbances that affect HF radio communication and Global Navigation System Satellite (GNSS) positioning used by aircraft, and cause increased radiation exposure to aircraft passengers, crew and avionics.

The International Civil Aviation Organization (ICAO) has recognized that space weather is a hazard to aviation with impacts to HF communications and GNSS services and impacts due to radiation by initiating the development of an operational space weather services for aviation[iii]. ICAO has selected three (3) global warning centres:

1) Australia-Canada-France-Japan (ACFJ) consortium,
2) Pan-European consortium for aviation space weather user services (PECASUS), and
3) National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) (United States).

On November 8, 2019, these centres launched special space weather services to provide advisories when space weather impacts to aviation are expected.

This article describes the space weather phenomenon recognized as having the potential to impact HF communication.

[ii] The ionosphere is the upper layer of the Earth's atmosphere ionized by solar radiation and through the precipitation of energetic particles. See Section 2 for more information.

[iii] See the preceding article *ICAO Space Weather Advisory* by Larry Burch in this issue of IRRR.

II. HF Radio Communication and the Ionosphere

HF radio communication (3-30 MHz) is possible over long distances due to the reflection of radio signals between the Earth and the ionosphere, see Figure 1. The ionosphere is an ionized region extending upwards of ~70 km altitude forming the upper layer of the Earth's atmosphere ionized primarily by solar radiation (photoionization) and through the precipitation of energetic particles during space weather disturbances. Photoionization occurs when solar radiation excites electrons in neutral particles, causing them to split into ions and electrons. Ionization can also be produced by energetic particles precipitating into the Earth's upper atmosphere and colliding with neutral particles separating them into a positive ion and secondary electron. Ions and electrons composing the ionosphere can also recombine to create neutral particles. The rotation of the Earth and its ionosphere through the dayside and nightside and the recombination of ions and electrons leads to regular daily patterns of growth and loss of ionization.

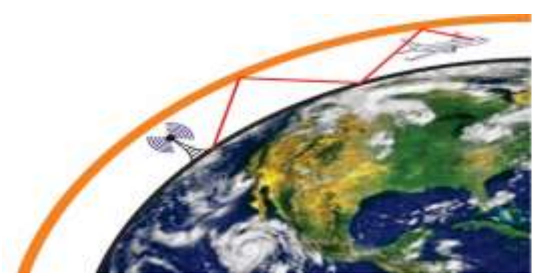

Figure 2: Illustration of a high frequency radio waves travelling large distances by reflecting between the ionosphere and the Earth.

The ionosphere is organized into several ionized layers separated by altitude and characterized by the vertical electron density profile. Due to the different density profiles of neutral particle species and recombination rates, there are characteristic peaks in the electron density with the ionosphere composed of three (3) regions: D, E and F, as shown in Figure 2. Electron density is a very important factor in HF radio communication as it determines whether a radio signal passing into the ionosphere will entirely reflect off the ionosphere; refract (bend) as it travels through the ionosphere; entirely transverse the ionosphere; or be absorbed (e.g., Figure 2). Radio signals refract through and reflect from the upper E and F regions of the ionosphere, but can be absorbed in the lower D-region of the ionosphere at ~70-90 km altitude. Absorption is caused by the interaction of radio signals with charged particles in the ionosphere. Collisions with D-region particles cause the energy of the radio wave to be dispersed (absorbed) as heat, reducing the strength of the radio signal.

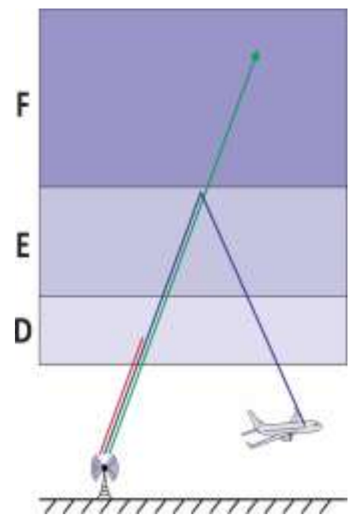

Figure 3: Illustration of an HF transmission of different frequencies interacting with the ionosphere. Frequencies below the lowest useable frequency (LUF) (red line) are absorbed in the D-region of the ionosphere. Frequencies between the LUF and maximum useable frequency (MUF) (blue line) reflect from the ionosphere back toward the ground. Frequencies above the MUF (green line) penetrate the ionosphere and are suitable for satellite communication (SATCOM).

Large atmospheric densities in the D-region ionosphere lead to high recombination rates and often cause the D-region ionization to disappear at night leading to a significant reduction in absorption. The F-region of the ionosphere is the highest in altitude, with an electron density peak at ~300 km altitude. The low atmospheric density at these heights leads to lower recombination rates and a persistence of the ionization throughout the night. The night-time combination of a high-altitude reflecting layer (F-region) and the disappearance of the absorbing D-region provides the best conditions for long distance HF radio communication. This is why distant radio stations can often be heard on the shortwave band at night.

The behaviour of a radio signal passing into the ionosphere is also dependent on the frequency of the signal itself, influencing how much a refracting / reflecting signal will bend and how likely the signal is to be absorbed (e.g., Figure 2). At the right frequencies, the radio signal travels up through the D-region and is refracted by the E- or F-region to return back through the D-region to be received on the ground or by an aircraft, allowing HF radio communication. Frequencies that are too high will not bend at all in the ionosphere and travel out into space. These high frequencies are used for satellite communication (SATCOM), but are not useful for HF communication. Low frequency radio signals are partially or entirely absorbed in the D-region, severely degrading, or event preventing HF radio communication.

There is a window of operating frequencies, the "Goldilocks band", in the HF frequency band that are high enough to penetrate the D-region, but low enough not to penetrate the entire ionosphere, thereby allowing HF communication. The lower and upper limit to the transmission windows are referred to as the lowest useable frequency (LUF) and maximum useable frequency (MUF), respectively. The LUF and MUF vary based on the level of ionization. Photoionization due to regular solar radiation produces predictable daily and seasonal variations in the D, E, and F layers of the ionosphere, and therefore in the frequencies used for HF radio communication (Figure 3). As a general rule, the higher the Sun is in the sky, the higher the LUF and MUF.

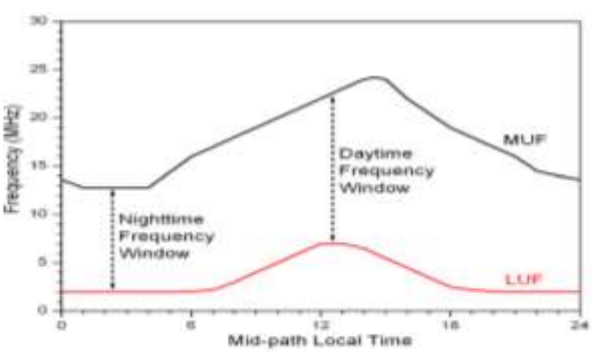

Figure 4: Variation of the LUF and MUF over the course of a day. Frequencies between the LUF and MUF are suitable for HF radio communication.

Space weather disturbances narrow the HF transmission window by either increasing the D-region absorption, which raises the LUF, or decreasing the electron density, which reduces the MUF. Differentiating between these impacts determines whether the frequency of the impacted HF transmission needs to be raised or lowered to fall within the transmission window. Severe space weather disturbances, causing multiple effects, can cause the HF transmission window to shrink to zero, making HF communication impossible at any frequency: a condition referred to as "radio blackout".

III. Space Weather Phenomenon Impacting Aviation

Understanding the space weather impacts to HF radio wave propagation used by aviation requires an understanding of two phenomena: absorption and post-storm MUF depression (PSD). This section describes the three primary types of absorption (shortwave fadeout, auroral absorption, and polar cap absorption), and PSD.

Shortwave Fadeout (SWF)

Shortwave fadeout (SWF) is a relatively short-lived (typically <2 hours) phenomenon caused by solar X-ray flares. A solar flare is a sudden release of energy at the surface of the sun causing a visible brightening of the photosphere. The electromagnetic radiation emitted during a solar flare, most notably in X-ray and EUV bands, travels at the speed of light, reaching the Earth in ~8 minutes. This radiation increases ionization in the dayside ionosphere, predominantly near the equator, falling off toward the nightside (Figure 4). Enhanced dayside ionization leads to increased absorption in the impacted region that typically affects shortwave radio signals by reducing their signal strength, sometimes entirely.

The level of absorption expected during a SWF event is related to the strength of the solar X-ray flare, which is classified as A, B, C, M, or X-class flares based on their peak intensity. Categories A-X have subdivisions 1-9 which are scaled in such a way that an M2 X-ray flare, for example, is twice as powerful as an M1 flare, and an M3 X-ray flare is three times as powerful as an M1 flare. The X-class flare category does not have an upper limit and >X9 flares are possible. M, and especially X, class solar X-ray flares have the strongest signatures in ground based observations and the most notable impacts to HF radio wave propagation.

The duration of a solar X-ray flare, and the duration of shortwave fadeout, is related to the flare intensity. Empirically derived statistical average flare durations for M1, M5, X1, and X5 solar X-ray flares are 25, 40, 60, and 120 minutes, respectively[iv].

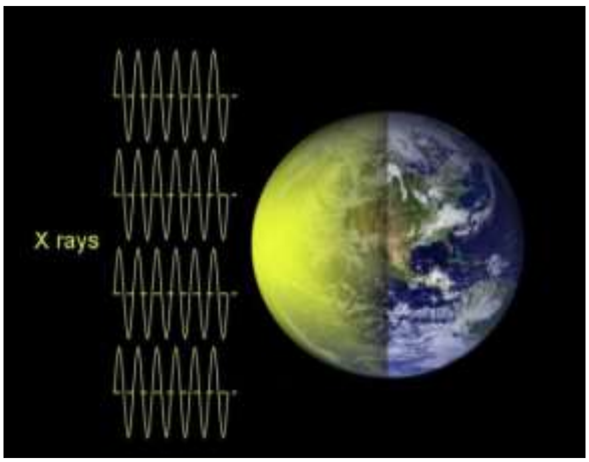

Figure 5: Illustration of solar X-rays travelling toward the Earth following a solar X-ray flare. Photoionization is strongest near the equator on the dayside and falls off toward the nightside.

Auroral Absorption (AA)

Ionospheric ionization is also caused by the precipitation of high-energy energetic electrons into the ionosphere. The interaction between the solar wind and the interplanetary magnetic field with the Earth's geomagnetic field leads to a constant streaming of particles into the Earth's ionosphere causing ionization at auroral latitudes that span the central latitude region of Canada (see Figure 5). This ionization can be intensified during space weather events leading to increased absorption in the auroral zones, referred to as auroral absorption (AA). Absorption peaks in the pre-noon and midnight ionosphere, and enhanced ionization in these local time zones typically lasts for 1-2 days. The impacted region of the Earth is more localized for AA than SWF being limited to the auroral zone for a period of 1-3 hours as the Earth's rotation carries the region through the most active regions of the auroral zone ionosphere. Events leading to increased electron precipitation include high speed streams from coronal holes, and coronal mass ejections[v].

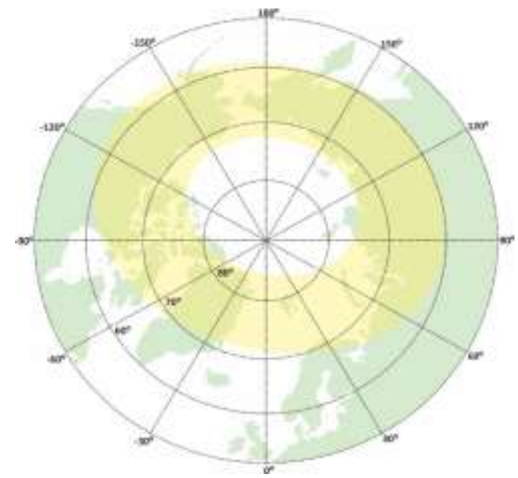

Figure 6: Yellow shading shows the typical location of the auroral oval. The oval expands to lower latitudes when geomagnetic activity increases.

The magnitude of AA is related to the amount of energetic electron precipitation, which is typically characterized by solar wind parameters or the overall level of geomagnetic activity characterized by the Kp index (e.g., https://www.gfz-potsdam.de/en/kp-index/). During periods of high geomagnetic activity, the auroral oval expands to reach lower latitudes extending the region affected by auroral absorption.

[iv] Estimates of the total solar X-ray flare duration can be found in documentation available from NOAA SWPC (https://www.swpc.noaa.gov/content/global-d-region-absorption-prediction-documentation).

[v] Various solar phenomenon, including coronal mass ejections, are described in *An overview of space weather - a Canadian perspective*, in Issue 3 of the IRRR (https://carleton.ca/irrg/wp-content/uploads/Vol-1-Issue-3-Final.pdf).

Polar Cap Absorption (PCA)

Precipitating energetic protons can also cause enhanced ionization and absorption in the ionosphere. The Sun sometimes expels energetic protons, for example, following a solar flare, often in association with a coronal mass ejection (CME). The energetic protons are accelerated to near relativistic speeds, reaching the Earth after a few hours where they penetrate deep into the high-latitude D-region causing polar cap absorption (PCA) across the entire high-latitude region. The low-latitude cutoff of increased ionization and absorption is tied to the strength of the geomagnetic field and the energy of the precipitating particles. PCA is more strongly felt in the sunlit ionosphere, but can also impact HF communications on the nightside (see Figure 6). Rotation of the Earth therefore leads to regularly changing levels of increased absorption for HF radio users at a particular location.

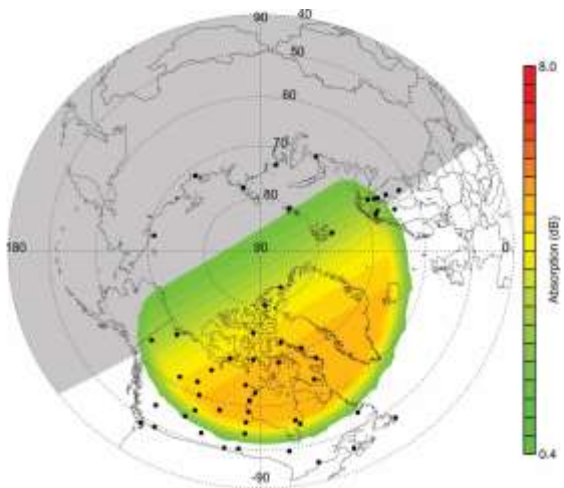

Figure 7: Example of absorption modeled during a polar cap absorption (PCA) event. Dark shading represents the nightside of the Earth. Black filled circles indicate the location of riometers. Absorption is highest on the dayside and absorption contours are roughly aligned with the day/night boundary line.

PCA is a more complicated phenomenon to characterize than SWF or AA as it depends on multiple parameters. Rather than characterizing PCA by a single parameter, it is more practical to model absorption across the high-latitude region and characterize the strength of the event by the strength of the modelled absorption. Currently, the most widely used model for predicting absorption due to PCA is the D-Region Absorption Prediction (D-RAP) model, developed by the Space Weather Prediction Center (SWPC) of the National Oceanic and Atmospheric Administration (NOAA) (http://wwwswpc.noaa.gov/products/d-region-absorption-predictions-d-rap).

Identification of a PCA event is achieved by monitoring the >10 MeV solar proton flux measured by the GOES satellites. A value of ≥10 proton flux units (pfu) indicates a solar proton event is underway and PCA is possible. The frequency of occurrence of solar proton events of varying magnitude is summarized in Table 1. Although the frequency of PCA events is relatively low, the phenomenon can be relatively long lived and has the potential to incapacitate HF communication for a period of several days. This is a particular problem in Canadian airspace because the ionospheric disturbances impacting HF communication are more intense in the high-latitude regions. The greater number of planes flying on transpolar routes has further highlighted the need for space weather services in this region.

Flux level of > 10 MeV particles (ions)	Frequency (per 11-year solar cycle)
10^5	<1
10^4	3
10^3	10
10^2	25
10^1	50

Table 1: Frequency of solar proton events of varying magnitude, which is characterized by the level of >10 MeV solar proton flux (https://www.swpc.noaa.gov/sites/default/files/images/NOAAscales.pdf).

Post-Storm Maximum Usable Frequency Depression (PSD)

The maximum useable frequency (MUF) for radio communication depends on the electron density in the E and F regions of the ionosphere. Due to the dependence of electron density on the level of photoionization, this leads to both diurnal and seasonal variations of the MUF which is reduced on the nightside and during winter months compared to the dayside and summer months. Enhanced particle precipitation causing auroral absorption often occurs in association with a geomagnetic storm. This enhanced precipitation ionizes the auroral zone D-region increasing the LUF and preventing the transmission of the lower frequencies in the quiet-time transmission window, requiring a shift to higher frequencies for transmission. However, after the initial <24 hours, there is a decrease in the ionospheric densities of the F-layer causing a reduction in the MUF which can last several days. The reduced MUF prevents transmission of the higher frequencies in the quiet-time transmission window requiring a shift to lower frequencies for transmission. MUF depression is defined as the percentage decrease in the MUF determined over a vertical transmission path compared to the 30-day median MUF determined for the same local time sector.

IV. EXPECTED TIMELINES

The space weather phenomenon affecting HF radio communication has impact durations of very different timescales (see Figure 7). Radiation from solar X-ray flares reaches the Earth within 8 minutes producing SWF for periods generally <2 hours limited to the dayside of the Earth. Polar cap absorption events begin 1-3 hours after a solar proton event erupts on the sun and can last up to ~7 days with dominant impacts on the sunlit side of the high-latitude region. CMEs erupting on the sun take 1-3 days to travel to the Earth causing disturbances leading to energetic electron precipitation into the ionosphere. This causes auroral absorption which impacts local regions for ~1-3 hours with a potential to recur for 1-2 days. These three (3) types of absorption are caused by increased ionization in the D-region ionosphere and cause an increase in the LUF degrading or blocking HF radio wave propagation for the lowest frequencies of the quiet-time HF transmission band, forcing a shift to higher frequencies. The arrival of energetic electrons causing auroral absorption also causes enhanced ionization in the F-region ionosphere lasting <24 hours followed by a depression which can last on the order of 1-2 days lowering the MUF and degrading the highest frequencies in the HF transmission band.

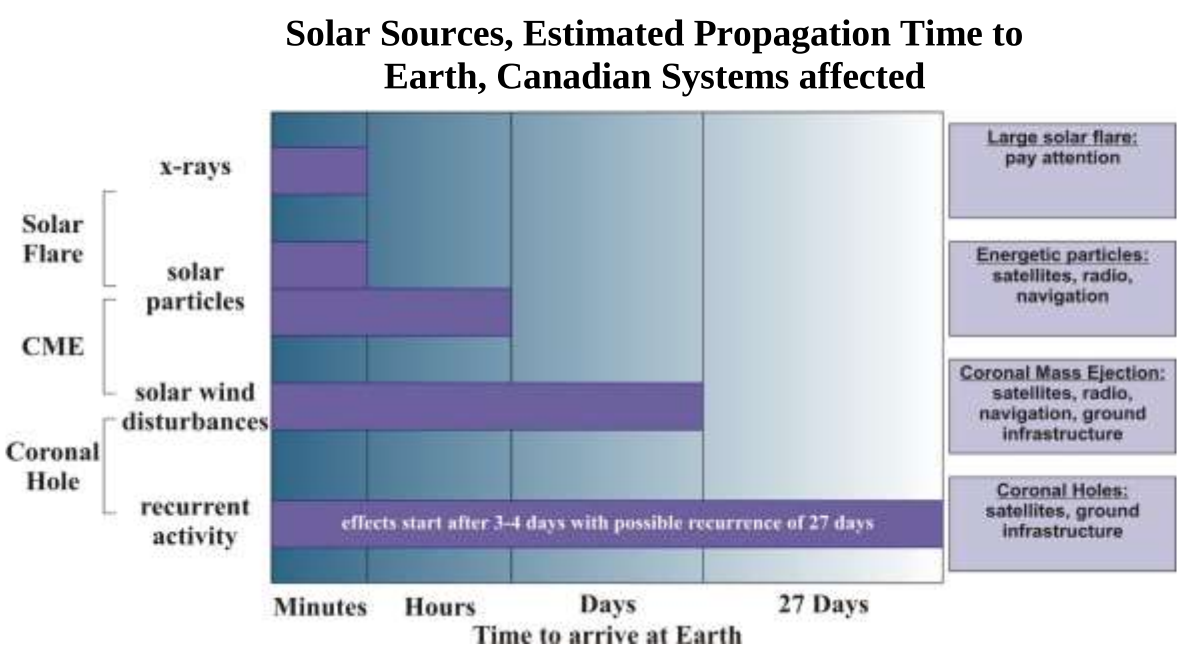

Figure 8: Timeline of space weather phenomenon with the potential to impact satellites, radio systems, and ground systems. Reproduced from *Guide to the Space Weather Bulletin* (https://doi.org/10.4095/293873).

V. SUMMARY

This article describes two space weather phenomena which have the potential to severely disrupt HF communication: post-storm maximum usable frequency depression (PSD), and absorption. These phenomena can impact HF radio communication on timescales of hours to days with the potential to recur on a regular daily basis.

Space weather is a natural hazard impacting critical infrastructure and technology across a wide array of industries. Of particular relevance to aviation are the ionospheric disturbances that can affect HF radio communications used by aircraft. This is a notable problem in Canadian airspace because the ionoshperic disturbances are more intense in the high latitude region in which Canada is located. The need for space weather services in this region has also increased because of the greater number of planes flying on transpolar routes. On November 8, 2019, an advisory service, initiated by ICAO, began operation to help the aviation industry mitigate the impact of space weather to aviation.

About the Authors

Dr. Robyn Fiori *is a research scientist for the Canadian Hazards Information Service of Natural Resources Canada specializing in space weather. Her research is applied to the development and improvement of space weather tools and forecasts to be used by operators of critical infrastructures and technologies in Canada. Her research has been published in numerous peer reviewed scientific journals including the Journal of Geophysical Research, the Journal of Atmospheric and Solar-Terrestrial Physics, and Space Weather. Dr. Fiori received her B.Sc., M.Sc., and Ph.D. from the University of Saskatchewan Department of Physics and Engineering Physics while studying in the Institute of Space and Atmospheric Studies.*

Dr. David Boteler *has extensive experience in engineering and geophysics, including work on multidisciplinary projects in the Arctic and Antarctic. He spent two years running the ionospheric programme at Halley Bay, Antarctica and initiated a study of the ionospheric conditions that caused blackout of radio communications. Since 1990 he has been a research scientist with Natural Resources Canada where he specialises in space weather and its effects on technological systems. He is currently head of the space weather group within the Canadian Hazards Information Service.*

Over-the-Horizon Radar for Early Warning of Airborne Threats to Canada

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Abstract
This paper provides a concise introduction to Over-the-Horizon Radar (OTHR) as applied to the early warning of airborne threats to Canada. Relevant physical principles of the technology are reviewed, along with a couple commonly encountered performance issues. A review of the state of development of the technology in North America is documented.

I. INTRODUCTION

Over-the-Horizon Radar (OTHR) is a High Frequency (HF) radar configuration that uses the electrically conducting bottom side of the Earth's ionosphere to reflect HF radio waves and illuminate the Earth's surface beyond the line-of-sight horizon (Headrick, 1974; Kolosov, 1987; Shearman, 1987; Headrick 1990a; Fabrizio, 2013). This configuration provides a high-altitude vantage point that permits radar surveillance to a range of approximately 3,000 kilometers. Thus, OTHR technology can provide early warning of airborne threats. A conceptual view of an OTHR is shown in Figure 1.

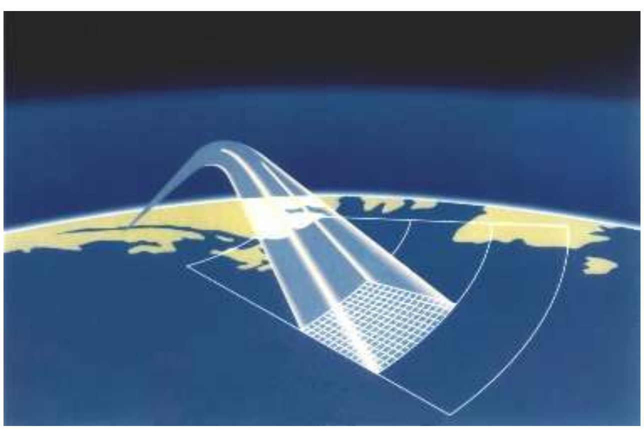

Figure 9: Conceptual view of OTHR (Source: US Government).

This figure shows an OTHR in Maine, United States, providing surveillance of the North Atlantic Ocean. The radar transmitter radiates a beam of HF radio waves toward the ionosphere at a low elevation angle. The waves reflect from the ionosphere and illuminate a sector of the ocean. Illuminated targets in the transmit beam echo the radio waves back to the radar via a similar propagation path, where they are detected by the radar receiver. The receiver resolves the echoes into fine azimuth cells. In addition, by timing the round-trip wave propagation time, one can also resolve the echo into range cells. The resulting range-azimuth cell pattern is then searched for targets, which appear as local maxima of received radio power in a cell relative to the surrounding cells. The local maxima are declared as detections. Tracking the location of these detections over time provides target trajectories (or "tracks"), which can be correlated with other sources of information to confirm the identity of the targets.

It should be noted that the target echo arrives at the radar alongside a very strong echo from the ground or ocean underneath the target. Generally, the target and ground/ocean echoes can be resolved by observing the Doppler shifts of the echoes. A fast-moving aircraft target generally produces a small, but noticeable Doppler shift (a few Hz) that is sufficient to separate the target echo from the ground/ocean echo.

II. PHYSICAL PROPERTIES

The proper operation of an OTHR depends on an appreciation of the basic properties of the Earth's ionosphere. The ionosphere is a broad layer of ionized gas, called a plasma, located in the region at 50-1,000 km in altitude above the Earth's surface. The ionosphere is classified into several sub-regions, including the D-region (< 90 km), E-region (90-160 km), and F-region (> 160 km). The F-region is generally the broadest and most strongly ionized layer, and the most relevant for long-range surveillance. In this region, the ionized species are predominantly atomic oxygen and electrons. The peak plasma density is located at approximately 250 km altitude, although there is a diurnal variation of about +/-50 km.

The steady-state profile of plasma density arises from competing physical processes. With increasing altitude, the intensity of ionizing ultraviolet radiation increases, while the density of neutral gas available for ionization decreases. Models of the physics yield the expected steady-state plasma density profile. The earliest and most fundamental model of the processes yields the Chapman profile (Budden, 1985), shown in Figure 2, in units of ionized electrons per cubic metre. A simple three-dimensional model of the ionosphere comprises a plasma density that is uniform in the horizontal plane and varies with altitude according to the Chapman profile. The peak density N_{max} in the Chapman profile varies widely with time of day, season, and number of sunspots, and can be predicted to some degree by standard empirical ionosphere models (AIAA, 1999).

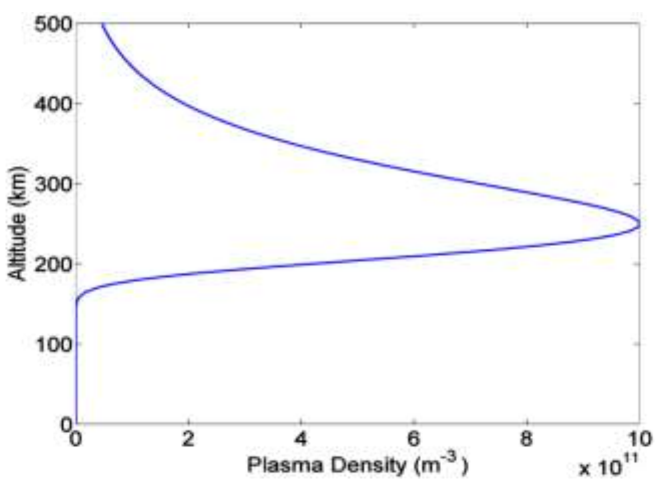

Figure 10: Chapman profile of ionosphere (Source: Author)

In a simple isotropic radio propagation model (Budden, 1985), the ionosphere will reflect radio waves at an altitude where the plasma density N in electrons per cubic metre is numerically equal to $\sin^2$□ $f^2/81$, where □ is elevation angle of the radio wave propagation (or "ray") with respect to the horizon and f is the radio frequency in MHz. If we launch a ray at elevation □ and frequency f such that $\sin^2$□ $f^2/81 > N_{max}$ then this ray will pass through the ionosphere and escape into space. For example, if $N_{max} = 10^{12}$ m^{-3}, then the ionosphere can reflect vertical (□ =90 degrees elevation) rays at frequencies up to 9 MHz and reflect low-elevation (□ =20 degrees) rays at frequencies up to 26 MHz.

Coverage Range

Generally we want to choose a radar frequency that will allow the transmitted rays to escape into space at vertical incidence, to avoid the radar interfering with itself by overhead reflections from the ionosphere. Referring to Figure 3, we see that this choice leads to a region of no target illumination in front of the radar referred to as the skip zone.

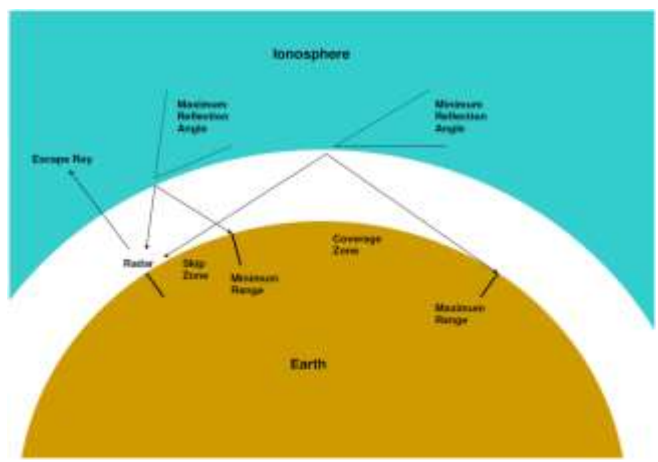

Figure 11: Geometry of coverage and minimum/maximum radar ranges (Source: Author)

Current OTHR systems are generally designed for skip zones around 1,000 km in range. Shorter skip zones are possible, although they require appropriate design of the transmitting antenna to efficiently radiate energy at high elevation angles.

In terms of maximum range, the physical limit is about 3,000 km due to blockage by the curved surface of the Earth, also shown in Figure 3. At this maximum range, the launch angle is nearly zero degrees elevation ("two-hop" propagation, discussed later, can access further ranges).

In practice, however, one often finds that a single radar frequency cannot effectively illuminate the entire coverage zone as shown in Figure 3. For example, if one picks a frequency low in the HF band to obtain the 1,000 km minimum range, one will often find that this frequency propagates well in the vicinity of the minimum range, but suffers considerable attenuation at the further ranges. The bulk of the wave attenuation occurs in the ionospheric D-region (50-90 km in altitude), where the attenuation rate varies with the inverse square of the radar frequency (Shearman, 1987; Sturrock, 1994). Long-range, low-elevation radio propagation involves long ray paths through the D-region and therefore large amounts of attenuation. Thus, to get sufficient radar target illumination over the entire coverage zone shown in Figure 3, one often has to sequence the radar through two or possibly more different frequencies.

Target-Locating Accuracy

Target-locating accuracy in range is limited by the ability to convert the observed round-trip radio wave delays into ground ranges. This conversion process is referred to as coordinate registration. Even with good ionospheric characterization, the accuracy is generally no better than a couple tens of km and thus coordinate registration continues to be an active area of research. One research result (Barnum, 1998) has been to use identifiable ground terrain echo features as reference points, which has demonstrated the potential to provide up to a factor of 5 improvement in absolute positional accuracy. If the region under surveillance is in friendly territory, then ground-based transponders can be used to provide a similar form of range calibration to achieve good coordinate registration.

Target-locating accuracy in azimuth is constrained by bearing errors introduced by the ionospheric plasma. Lateral deviation of the rays during ionospheric propagation can be predicted by accounting for anisotropic plasma effects, but there will always be additional variation due to unknown ionospheric plasma structure in the horizontal dimension. Again, terrain-based features and/or transponders can be used to provide an angular calibration to within a fraction of a degree, allowing for linear azimuthal ground accuracies similar to the range accuracies.

Detectable Target Sizes

Target sizes for radar are measured in terms of a Radar Cross Section (RCS) in decibels (dB) relative to one square metre (dBsm). The dominant influence on target RCS is the size of the object relative to a radar wavelength. Targets that are larger than a wavelength tend to have RCS values that are similar to their physical size. Objects that are smaller than a wavelength have RCS values that vary with the inverse fourth power of the radar wavelength, referred to as the Rayleigh scattering limit. Thus, the major issue with target RCS is that small targets become invisible at the lower end of the HF band (Lewis, 1992). For example, a cruise missile is comparable to a radar wavelength at 30 MHz (10-metre wavelength), and may have an RCS of 10 dBsm. However, at 3 MHz (100-metre wavelength), the RCS may drop to around -30 dBsm. In comparison, a large aircraft with an RCS of 30 dBsm, such as a passenger airliner or a long-range bomber, is about ten times the linear size of a cruise missile, and remains at least a wavelength in size throughout the HF band, and thus maintains fairly consistent RCS with frequency.

Most current OTHR designs are scaled to permit routine (>10 dB SNR) detection of 30-dBsm RCS targets throughout the entire coverage region, 24 hours a day. However, the requirement to detect small targets at night, when frequencies at the bottom of the HF band are being used, requires observation of targets perhaps 40 dB or more below the detection threshold of current OTHR designs. Small-target detection may be possible during the day, in good conditions, but 24-hour coverage is difficult. To overcome the low RCS values that result from working at low HF frequencies at night, improvements to the power and size of the radar need to be made. Transmitter power and gain are constrained to around 100 MW Effective Isotropic Radiated Power (EIRP) to avoid artificial modification of the ionosphere (Kotik, 1998). One possible area for improvement is to increase receive gain using a two-dimensional planar receive array, which will outperform the onedimensional line arrays currently used in most systems (Riddolls, 2017).

III. PERFORMANCE ISSUES

This section looks at two prominent issues regarding OTHR performance in Canada. The first is the presence of a low-altitude E-region plasma layer that prevents propagation of HF radar waves to distant ranges. The second is the presence of long-range high-Doppler auroral ionospheric echoes (or "clutter") that confounds aircraft target detection.

E-Region Problem

The occasional formation of strong plasma layers in the ionospheric E-region can prevent the propagation of radar waves up to the F-region of the ionosphere. This phenomenon of "blanketing" occurs when the peak plasma density of the E-region plasma exceeds the peak density in the F-region. The result is that the maximum radar range is reduced from about 3,000 km to about 1,800 km during periods of this blanketing effect. The occurrence patterns of this phenomenon have been studied at various latitudes (Thayaparan, 2005). For OTHR operation in the middle-latitude and auroral regions, the occurrence rate of the blanketing effect is in the 20-40% range, with a maximum occurrence in the summer time period and a minimum occurrence in the winter time period. There is no strong diurnal variation. The effect of intense E-region plasma layers could be mitigated by exploiting two-hop propagation modes; in other words, the radar wave would reflect from the ionosphere, reflect from the ground, reflect from the ionosphere again, and then illuminate the target. This two-hop propagation requires traversing the ionosphere D-region eight times as opposed to four in the normal one-hop propagation mode of the OTHR, and thus attenuation is increased. However, in daytime conditions, there is ample SNR, and the effects of blanketing should be possible to overcome using a two-hop propagation mode. Assuming no diurnal variation in the E-region plasma layer occurrence patterns, the radar coverage would therefore be reduced from 3,000 km to 1,800 km between 10% (winter) and 20% (summer) of the time.

Auroral Ionospheric Clutter Problem

The persistence of OTHR detection capability in the auroral region can be influenced also by the convection of plasma irregularities. Shown in Figure 4 are two radar rays. The first is the trajectory of a radar wave that travels to and from a target. The second is the trajectory of a radar wave that scatters from ionospheric irregularities. Both the target and the irregularities are at the same slant range, thus the target will appear buried in clutter.

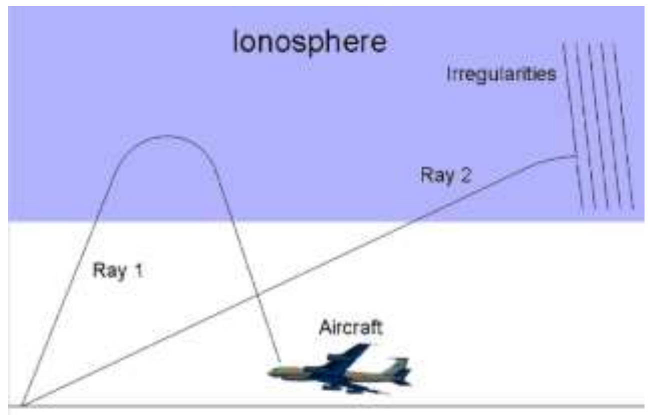

Figure 12: Origin of ionospheric clutter (Source: Author)

The irregularities consist of small-scale plasma drift waves driven by the large-scale plasma density gradients resulting from the generalized Rayleigh-Taylor instability (Kelley, 1989). The phase speed of the drift waves is on the order of the plasma diamagnetic drift velocity (<20 m/s) which means that the Doppler shift produced by these irregularities is small compared to typical aircraft speeds (>100 m/s). Thus, the aircraft appears free from clutter after Doppler processing. This is the case in the mid-latitude ionosphere. In the auroral ionosphere, however, the action of the solar wind on the Earth's magnetosphere drives convection patterns within the auroral region (Kelley, 1989). Shown in Figure 5 is the typical auroral two-cell plasma convection pattern in the ionosphere. The plasma drifts along the black oval contours at speeds up to 2,000 m/s. This convection transports the aforementioned plasma irregularities at aircraft-like speeds, so the radar clutter becomes sufficiently spread in Doppler to obscure aircraft echoes. The coloured vectors in portions of the convection cells show actual HF radar Doppler measurements of the moving irregularities.

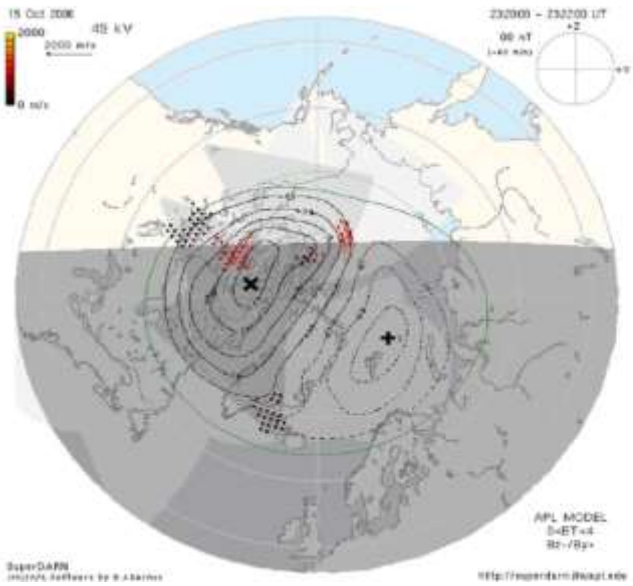

Figure 13: Auroral convection diagram (Source: SuperDARN project)

One possible defence against clutter from auroral plasma irregularities would be elevation angle control in the transmit and/or receive subsystems of the radar. As can be seen in Figure 4, for a given target range the clutter originates from an elevation angle lower than that of the target echo, and elevation control should be able to mitigate the clutter problem to some extent.

IV. State of Development

A number of experimental and operational OTHR systems have been deployed around the world. We briefly document the situation in North America (U.S. and Canada).

U.S. Mid-Latitude Experimental Systems

Although it has been known since the 1930s that ground clutter could be observed by HF sounding using a reflection from the bottom side of the ionosphere, it was not until the early 1950s that sounding experiments were done in the United States to determine if the ionosphere was sufficiently stable to allow for use in over-the-horizon radar detection of aircraft targets. To demonstrate the feasibility of using Doppler processing to separate target echoes and ground/ocean clutter in OTHR applications, in the late 1950s the U.S. Naval Research Laboratory (NRL) built the experimental Magnetic-Drum Radar Equipment (MADRE) radar in Chesapeake, Virginia (Headrick, 1974; Thomason, 2003). The radar used a horizontally polarized linear antenna array with beam steering by mechanical transmission line extenders. The waveform was a 100 microsecond pulse at an average power of 25 kW. The data was recorded on a magnetic drum device (hence the radar name) and the recorded data was fed into a cross-correlation signal analyzer. By 1961, aircrafts flying across the Atlantic Ocean were detected and tracked by this radar.

The second experimental OTHR built in the United States was the Wide Aperture Radar Facility (WARF) in central California, which pioneered the use of vertically polarized antennas, Frequency Modulated Continuous Wave (FMCW) waveforms, and a large receive antenna array aperture (2.5 km in length). The radar, originally installed by Stanford University in the early 1960s, was later transferred to SRI. One aim of WARF has been to extend the capability of OTHR to allow ship detection within intense low-Doppler sea clutter. The wide aperture provides sufficient angular resolution to reduce the amount of sea clutter within a resolution cell to the point that ships can be resolved (Maresca, 1982; Barnum, 1986). There has also been much interest in developing ocean remote sensing techniques with the radar, as the radar echo carries information regarding ocean currents and directional ocean wave spectra.

U.S. Mid-Latitude Operational Systems

The first attempt at an operational OTHR radar was a joint project between the U.S. Air Force (USAF) and the UK Royal Air Force under the name Cobra Mist (Fowle, 1979; Thomason, 2003). While the project was intended for deployment in Turkey to provide surveillance of the western Soviet Union, Turkey denied the U.S. a site for the radar, and the USAF later accepted an offer from the UK to host the radar at Orfordness, UK. A contract was awarded in 1966 to RCA, and testing began in 1971. By 1972, it became clear that the radar receiver noise floor was approximately 20-30 dB higher than expected across all range and Doppler cells over land areas, and this caused a massive degradation in detection and tracking capability. An intensive effort was undertaken by the USAF and a team of industry experts to determine the source of the spread-Doppler noise. By May 1973, no conclusive evidence for a source of the problems in either the radar hardware or the environment could be found, and the following month the project was cancelled.

The second operational U.S. OTHR was another USAF effort, this time to provide surveillance of the approaches to the United States by bomber aircraft from the Soviet Union (Headrick, 1990b). The program, termed OTH-B, was ambitious, consisting of 180-degree azimuth coverage radars on the U.S. east and west coasts, a 240-degree azimuth south-looking radar in the central U.S., and a 120-degree azimuth west-looking radar in Alaska. Photos of some of the radar transmit and receive antenna arrays are shown in Figures 6 and 7. Combined with the North Warning System (NWS) in the Canadian North, OTH-B provided coverage of all approaches to the continental United States. A contract was awarded to General Electric in 1982 to develop the radars, and limited operations began in 1988.

Figure 14: OTH-B transmit array, showing canted dipoles in front of a backscreen (Source: US Government)

Figure 15: OTH-B receive array, showing vertical monopoles in front of backscreen (Source: US Government)

Meanwhile, the United States Department of Defense became aware of the submarine-launched cruise missile threat to the U.S. in the early 1980s, and soon expressed a goal that the system be able to detect cruise missiles. However, the capability of this system against cruise missiles was eventually determined to be rather limited, particularly at night, and the goal was dropped in 1989. The subsequent collapse of the Soviet Union removed the primary bomber threat for which the radar was intended to address, and the project was suspended in 1991.

The third operational U.S. OTHR radar was a U.S. Navy effort to develop a relocatable system to provide surveillance in support of battle groups deployed at sea. The program was termed ROTHR, for Relocatable Over-The-Horizon Radar (Headrick, 1998). Following the development of a prototype system, a contract was awarded in 1989 to Raytheon for the procurement of three operational systems, with an option for a fourth. Today, three ROTHR systems are currently deployed in Virginia, Texas, and Puerto Rico, respectively. Over the years, priorities have shifted such that the radars are currently aimed toward the south in an attempt to monitor the approach of small airplanes to the U.S. in support of the United States counter-drug effort. In particular, the Puerto Rico radar points deep into South America. These radars provide a long-range complement to the current deployment of aerostat-based microwave surveillance radars along the southern U.S. border. ROTHR is the only OTHR currently in use in the United States.

U.S. High-Latitude and Canadian Systems

In 1971, the Rome Air Development Center (RADC) installed the northward-pointing Polar Fox II OTHR in Caribou, Maine, along with transponders in Narssarssuaq and Thule, Greenland, and Keflavik, Iceland (Campbell, 1972). The aim was to determine OTHR performance within the auroral zone. Data gathered by Polar Fox II, along with a review of related auroral propagation studies, were eventually reported (Elkins, 1980).

A year after the Polar Fox II installation, a collaboration between the USAF and the Canadian Defence Research Board led to the installation of the Polar Cap III OTHR in Hall Beach, Northwest Territories, Canada, along with a second receive site in Cambridge Bay (Yool, 1973). As suggested by the project name, the aim was to determine OTHR performance in the location of the Earth's polar cap, near the geomagnetic pole.

In 2006, an effort was launched in Canada to revisit OTHR technology in light of improvements in digital radio technology (Riddolls, 2006). It has been postulated that auroral clutter can be mitigated through large digitally instrumented two-dimensional antenna arrays. The approach is described in detail in a recent technical paper (Riddolls, 2017). To date there has been a small proof-of-concept system built with 256 digital receive channels in western Ottawa, and a larger-scale system built with 1,024 digital receive channels in the Arctic, referred to as Polar OTHR (POTHR). The Ottawa system contends primarily with auroral radar clutter to the north of the radar, whereas the POTHR system lies deep within the auroral zone and must contend with clutter from plasma irregularities at all azimuth angles. Current work is focused on mitigating auroral clutter with the digital antenna arrays. A photo of the two-dimensional POTHR receive antenna array is shown in Figure 8.

Figure 16: Two-dimensional POTHR receive antenna array with 1,024 antennas (Source: Author)

About the Author

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UPCOMING EVENTS

SPRING / FALL 2020

EVENT	DATE / LINK
Spring / Fall 2020 Training Courses	January to December 2020 https://carleton.ca/irrg/training/
4th International Urban Security and Resilience Symposium Jun 24th, 2020	https://carleton.ca/irrg/cu-events/4th-international-urban-security-and-resilience-symposium/
2020 IRRG Dean's Lecture The Dean's Annual Lecture Series – Infrastructure Security and Resilience: Economic Security, Resilience and De-Carbonization of Heavy Industries Quebec Suite, Fairmont Chateau Laurier Hotel 1 Rideau Street, Ottawa, Ontario Ottawa, Ontario	November 18 2020 (8:30 am – 5:00 pm) https://carleton.ca/irrg/cu-events/2019-deans-lecture-2/
Lecture Speaker Series	Watch for details