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Subject	**ECCC/CSA update on status and plans for the Arctic Observing Mission (AOM) and Terrestrial Snow Mass Mission (TSMM) (David Harper)**
Executive Summary	The **Arctic Observing Mission (AOM)** and the **Terrestrial Snow Mass Mission (TSMM)** are two satellite mission concepts currently under study by Canada. The AOM is a Canadian-led international mission that will provide authoritative data on weather, greenhouse gas, air quality and space weather over the Arctic, while TSMM is a Ku-band radar mission to inform climate services and improve environmental prediction for snow covered regions. Both missions are aligned with *Resourceful, Resilient, Ready: Canada's Strategy for Satellite Earth Observation*, released in early 2022, and will enable Canada to take full advantage of the unique vantage point of space to address climate change and other key challenges of our time. The AOM is completing pre-formulation study activities that will refine the options for mission architecture and inform what is required for the design, implementation and operational phases of the mission and scheduled for completion in late 2024, with the outputs from the study being incorporated into AOM's business case. Canada is continuing engagement activities with existing partners and is exploring new partnerships from the international community. It is anticipated that potential partner contributions will be confirmed in 2024-25, with a finalized AOM business case available to inform any budgetary decisions in 2025-26for end-to-end mission implementation. TSMM is also in its mission formulation phase. Currently Canadian industry is continuing the advancement of the Ku-band radar hardware with the CSA for potential future implementation while science studies led by ECCC continue to focus on retrieval development, including snow and radar modelling and land surface data assimilation. Outcomes of TSMM's pre-formulation study activities will support the mission's business case and inform budgetary decisions for end-to-end mission funding implementation.

1 INTRODUCTION

The purpose of this paper is to introduce the CGMS membership to the proposed Terrestrial Snow Mass Mission (TSMM) and provide an update on the progress of the Arctic Observing Mission (AOM), first presented at CGMS in 2021. The paper will provide an overview and status of each mission, including:

- A brief description of Canada's recently released federal Satellite Earth Observation (SEO) Strategy and the accompanying SEO Roadmap
- A description of the key observation gaps that TSMM addresses
- An overview of the TSMM concept, including a description of the mission's instrument and proposed spacecraft architecture, and the key international linkages
- An overview of AOM's pre-formulation (Phase 0) study activities

2 CANADA'S SATELLITE EARTH OBSERVATION STRATEGY

In January 2022, the Government of Canada (GC) released *Resourceful, Resilient, Ready: Canada's Strategy for Satellite Earth Observation* which outlines a strategic approach to guide Canada's actions and investments related to satellite Earth observation data, technology and partnerships over the next 15 years. This includes advancing new satellite missions and analytical environments to generate solutions for climate change mitigation and adaptation, particularly in Canada's North. The Strategy is based on foundational principles: a whole-of-society and a long-term planning approach to investments; a commitment to open data and ensuring complementarity of space-based monitoring and in-situ monitoring; adopting an end-to-end perspective, considering each component of the SEO value chain; and the importance of partnerships - both domestically and internationally – to achieving success .
The Strategy has four main objectives:

1. **Open Data and Supporting the EO Sector:** Ensure that SEO data is free, open, and accessible to maximize science, innovation, and economic development
2. **Climate Change & the Environment:** Harness satellite EO to address climate change and issues that matter to Canadians
3. **Strengthening Critical Services:** Strengthen the delivery of critical services with SEO to keep Canadians healthy, safe, and informed
4. **Skills & Capacity Development:** Inspire skills and capacity development in SEO for the next generation

Coupled with the Strategy, is an evergreen SEO investment roadmap that is reviewed and updated on an annual basis to accurately reflect government priorities, engagement with private sector, academia and international partners, and on-going technology scans. The roadmap details keystone information for all existing and planned initiatives within the SEO domain, their alignment with Government priorities, the stage of their development, and an indication on when investment or directional decisions will have to be made. AOM and TSMM and have been identified as priority SEO initiatives for Environment and Climate Change Canada (ECCC). Both missions would provide invaluable satellite data critical to taking action on and adapting to climate change by enabling applications and services in many areas that support the health and well-being of Canadians. ECCC also recognize the necessity to fill observation gaps over the North and contribute to the international pool of satellite data which will enable world-class science and operations, situational awareness, and climate change adaptation..

3 THE TERRESTRIAL SNOW MASS MISSION (TSMM)

3.1 Mission Overview

For northern countries like Canada, seasonal snow cover is an essential source of freshwater. Spatially continuous, temporally consistent, and low latency information on snow mass (the amount of water stored in solid form by snow, or SWE – snow water equivalent) is needed to safeguard water and food security, support economic activities, ensure ecosystem sustainability, and protect from flood and drought risks. Despite this importance, snow mass is not adequately monitored across the northern hemisphere: surface monitoring networks are insufficient on their own, and current satellite-derived snow mass products have critical weaknesses. To address this essential data gap, the Terrestrial Snow Mass mission (TSMM) will provide previously unachieved snow mass information to determine how much water is stored as seasonal snow, and how it varies in space and time.

TSMM is a synthetic aperture radar (SAR) mission which would acquire moderate resolution (500m) dual frequency (13.5/17.25 GHz) Ku-band radar measurements over all northern hemisphere snow covered areas every 5 to 7 days. The two Ku-band frequencies have different sensitivities to snow microstructure, which will mitigate an important source of uncertainty in relating backscatter to SWE (Zhu et al., 2021; King et al., 2018). TSMM would be the first spaceborne Ku-band SAR mission of its type, and currently there is no similar mission under development at another agency. Data from TSMM would be used at ECCC to (1) provide a new level of information on the temporal/spatial variability in SWE in support of climate services, and (2) feed into environmental prediction and analysis systems to improve weather and hydrological forecasts. Minimal requirements for satellite tasking during the northern hemisphere summer means there is capacity to address additional objectives related to agriculture, wetlands, and ocean surface winds, which are currently being considered by the TSMM science team.

The development of TSMM is timely. In Canada, flood-related costs represent the largest disaster-related financial burden: losses due to snow-related floods in Canada were >$2.4 billion between 2016-2020. Freshwater supply from glaciers is finite in southern Canada (and other midlatitude regions including Europe) and will largely disappear by the end of this century, increasing pressure on the effective management of freshwater released by seasonal snowmelt. Advances in operational land surface modelling and data assimilation mean better snow mass initial conditions will improve streamflow forecasts at longer lead times. Over the past decade, the international snow remote sensing community has driven improved understanding of Ku-band radar response to snow, while industry has pushed the development of low cost, low mass spaceborne radar systems.

3.2 Ku-band Radar Measurements

Recent progress in the development and evaluation Ku-band radar-based SWE retrieval capabilities (Tsang et al., 2022) was motivated in part by activities related to the Cold Regions High Resolution Hydrological Observatory (CoReH20) mission concept, which completed Phase A under European Space Agency (ESA) support in 2012 (Rott et al., 2010). While not selected as the ESA Earth Explorer 7 mission, CoReH20 provided the impetus for technical studies on instrument concepts and design, and field and modelling studies on SWE algorithm development and data assimilation upon which the TSMM mission requirements were built (Garnaud et al., 2019).

TSMM wouldconsist of a single spacecraft inserted into a sun-synchronous orbit at an altitude of approximately 505 km. The instrument architecture would consist of a dual-polarized and dual-frequency SAR (13.5 and 17.25 GHz) implemented as a body-mounted non-deploying phased array antenna (2.5 m x 0.8 m). The instrument achieves wide swath coverage of 250 km by sequential scanning across-track sub-swaths. Two primary imaging modes would be available: a standard 500 m resolution product and a 50 m reduced swath (~30 km) product available for on-demand imaging of complex terrain (e.g. mountains) or in response to specific high impact events (e.g. floods). Three potential reference orbits are under consideration, based on the science requirement for complete coverage of a pre-defined Northern Hemisphere winter snow mask with 5 to 7-day repeat coverage.

The product development framework for TSMM is designed to optimally integrate the spaceborne radar measurements with land surface modelling systems. For applications which require a SWE retrieval, the radar backscatter measurements would be combined with snow property initial conditions (including snow microstructure) produced by an advanced version of the Soil-Vegetation-Snow (SVS) land surface model forced with short-range meteorological forecasts and state of the art precipitation analyses. Importantly, in areas without SAR coverage (e.g. due to swath gaps) or where the radar-derived SWE retrieval is highly uncertain (due to wet snow or dense forest cover), the SWE analyses would be determined by outputs from the land surface model. In this way, the remote sensing information is combined with modelling to create seamless coverage both in space and time, with quantified uncertainty. The Ku-band radar measurements would also be included in ECCC prediction systems without the use of a SWE retrieval. For land surface data assimilation needs, the Ku-band backscatter would be directly assimilated, again with the land surface model providing the required initial conditions. This approach is analogous to how L-band radiometer measurements from the SMOS and SMAP missions have improved soil moisture analysis through radiance-based assimilation (Carrera et al., 2019). The resulting enhanced snow analyses would be used to initialise ECCC weather and hydrological prediction systems.

3.3 International Linkages

TSMM is the only Ku-band SAR mission under development by any agency worldwide at this time and is supported by an international network of collaborators coordinated through the science team. The Finnish Meteorological Institute (FMI) has provided multiple seasons of experimental airborne and tower-based radar datasets (including deployment of a recently fabricated TSMM Ku-band sub-array), developed expertise in radar modelling, and advanced retrieval algorithm development. In-kind scientific support was provided by the NASA Terrestrial Hydrology Program (THP) by funding Ku-band radar flights (and subsequent radar data processing) in Canada during a 2018/19 field campaign near Inuvik NT led by ECCC. NASA SnowEx is a multi-year THP-funded project, which presents new data acquisition and analysis opportunities, including airborne Ku-band data over field sites using NASA instrumentation.
TSMM would contribute to the World Meteorological Organization Global Cryosphere Watch program through enhanced snow products, including capabilities for tracking regional and seasonal snow anomalies (https://globalcryospherewatch.org/satellites/trackers.html). TSMM provides an opportunity for enhancement to the land monitoring service of Copernicus and the Support to Operational Hydrology and Water Management (H SAF) of EUMETSAT, which currently distribute SWE information based on passive microwave data at coarse resolution. As such, these products fail to address user needs both regionally (e.g. in mountain areas) and thematically (e.g. watershed-scale water resource management). TSMM measurements would substantially augment surface snow observations available for assimilation at international operational prediction centres, such as the European Centre for Mid-range Weather Forecasts (ECMWF).

3.4 Mission Status and Timeline

TSMM completed a pre-phase 0 industrial study in March 2018, and a Phase 0 industrial study in September 2020. Since then, the mission has been in a ‘planning’ phase supported by CSA investments to increase the technical readiness and ECCC investments to advance the science readiness.

Technology advancement has focused on fabrication and testing of a Ku-band radar antenna sub-array, which is presently installed on a tower alongside multi-frequency radar instruments in Sodankyla, Finland. A new round of investment to advance the technical readiness level of the radar transmit/receive modules is underway at CSA.

Science advancement is focused on retrieval development (including snow and radar modelling, and land surface data assimilation), which will be boosted by the upcoming availability of the TSMM simulator coupled to the ECCC environmental prediction system to generate synthetic dual-frequency Ku-band radar data. The simulator is currently in development with delivery anticipated near the end of 2023. An airborne radar campaign was completed over an agricultural study site in central Ontario, Canada during the 2022/23 winter. Data from previous airborne Ku-band radar campaigns in Europe and Canada are now freely available (Lemmetyinen et al., 2022).

Programmatic positioning for the mission continues to be strengthened, including the development of partnerships with Canadian universities and collaborations with international organizations. A socio-economic benefits study was recently completed to help advance and articulate the TSMM business case.

4 THE ARCTIC OBSERVING MISSION

4.1 Mission Concept

The Arctic Observing Mission (AOM) is a satellite mission concept currently under study by the Canadian Space Agency (CSA) in partnership with Environment and Climate Change Canada (ECCC). AOM would use a highly elliptical orbit (HEO) to enable frequent observations of meteorological variables, greenhouse gases (GHGs), air quality and space weather over northern regions. This would address a current information gap caused by the sparsity in spatial and temporal coverage beyond the usable viewing range of geostationary (GEO) satellites, that measure these types of variables. More frequent observations over northern regions would lead to improvements in weather and environmental monitoring and forecasting services over the Arctic and adjacent northern mid-latitude regions, improved emission reporting and climate mitigation planning, and improvements to air quality and space weather forecasting.

AOM is envisioned to be implemented as a Canadian-led international partnership with prospective partners from the United States and Europe. To advance the mission concept, AOM is currently undergoing a 2.5-year pre-formulation study (PFS) that will refine the options for mission architecture, including the number of satellites, orbits, and other technical and design options. Throughout the pre-formulation study, Canada will continue to work with prospective international partners to define their roles and solidify their contributions to AOM in the ongoing effort towards achieving high quality quasi-geostationary northern Earth observation and space weather data for the free and open use by the international community.

4.2 AOM Pre-formulation Study

The pre-formulation study for AOM has an overall objective of defining mission requirements through the definition of all sub-systems, identify existing platforms, equipment, and facilities that could be used for the mission with minimum developments, and providing detailed cost, schedule and risk analyses for space, ground and user segments for project definition, implementation and operations phases. Detailed objectives of the PFS include:

- Update the requirements lists using prior work from AIM-North (Nassar et al., 2019) and the Polar Communications Weather (PCW) mission (Garand et al., 2014) concepts
- Refine the mission architecture established in Phase 0 and develop updated cost estimates for the elements of the mission

- Elaborate options with reduced capabilities while offering margins for potential international contributions
- Revisit some trade-offs offered by the availability of a single meteorological imaging payload
- Ensure more than one technical solution for the main elements of the mission is available
- Advance critical technologies and initiate work on a reduced-cost air-quality instrument

Additional PFS activities include a socio-economic benefits study, a space technology development study, a meteorological imager adaptation study, science/application studies, a GHG capability demonstration and ongoing national and international engagement.

The socio-economic benefits study will quantify and qualify the potential socio-economic benefits of the AOM's four proposed payloads and is scheduled for completion in mid-2023. The study will be completed by using different frameworks to measure socioeconomic impact, as well as other relevant methodologies such as cost-avoidance analysis, while employing a gender-based analysis (GBA+) lens, all based on international best practices. An extensive interview campaign was also used to gather stakeholder input across governments and agencies, industry, and academia. The socio-economic benefits study report will be an internal Government of Canada (GC) document, with the GC reserving the right to share the report with project partners.

A planned space technology development study will identify and assess commercially available detectors or focal plane array technologies for the GHG imaging Fourier Transform Spectrometer (IFTS) instrument. AOM's GHG instrument requires focal plan arrays with a relatively high frame rate compared to most commercially available products. The focal plan array must have a format of approximately 128x128 pixels or greater, and low noise over the near-infrared (NIR) at ~750 nm to shortwave infrared (SWIR) at ~2400 nm. While a single focal plane array spanning the whole spectral range is preferred, separate NIR and SWIR focal plane arrays is also acceptable. The first step of the study will assess commercially available options with information on performance, cost and export restrictions (e.g. ITAR). Following the analysis of options, a second phase of the study will involve the acquisition of the leading detectors and testing their performance in a lab.

An AOM science study will demonstrate the value of combining CO_2 and NO_2 observations for quantifying CO_2 emissions. This study will investigate the use 1) CO_2 and NO_2 observations from existing satellites; 2) Simulated AOM CO_2 and NO_2 observations and 3) Simulated AOM CO_2 and simulated NO_2 from other future missions, for applications such as urban or industrial CO_2 emission quantification (e.g. Reuter et al., 2019). ECCC is also studying how intelligent pointing of the GHG instrument can increase the fraction of cloud-free CO_2 and CH_4 observations from space. For most CO_2 and CH_4 satellites, only a small percentage of observations yield successful retrievals, with the remaining ~90% rejected, primarily due to the effects of clouds. However, AOM would use real-time cloud data in its "intelligent pointing" strategy for cloud avoidance. Multiple intelligent pointing simulations were conducted, demonstrating the significant advantages of this approach for satellites in a highly elliptical orbit (HEO), from which nearly the whole Earth disk can be observed. Multiple factors are shown to contribute to intelligent pointing efficiency such as the size and shape (or aspect ratio) of the field-of-view (FOV). For the current AOM baseline orbit and Imaging Fourier Transform Spectrometer (IFTS) observing characteristics, the monthly fraction of cloud-free observations is roughly a factor of 2 more than obtained with standard pointing (Nassar et al., submitted). A similar efficiency can be obtained in GEO with an IFTS, however, for a dispersive instrument in HEO or GEO, the gain is more modest. These results have implications for the design of future CO_2 or CH_4 monitoring satellites and constellation architectures and even other fields of satellite earth observation in which clouds significantly impact observations.

In August 2022, a stratospheric balloon campaign was carried out from the CSA-Centre National d'Etudes Spatiales (CNES) facility in Timmins, Ontario, Canada, to demonstrate the IFTS technology for AOM. These high-altitude balloon experiments have allowed AOM scientists to test how the IFTS operates in the cold, low pressure sub-orbital environment of the stratosphere, a precursor to the instrument one day operating in space. Nadir viewing IFTS measurements of CO_2 and CH_4 were acquired over boreal forest from an altitude of 37 km during a 13 hour flight (daylight and night) with 4 hours of adequate solar zenith angle. The Level 0 and Level 1 data from the experiment have been processed and Level 2 processing, analysis and validation with coincident ground-based spectrometer measurements is underway.

4.3 International Partnerships

Facilitating international collaboration and partnerships is critical to the success of AOM's pre-launch activities and to the success of the mission following launch. AOM's Canadian-led international expert team that includes US (NOAA, NASA) and European (EUMETSAT, ESA[1]) partners continues to meet to advance discussions on areas of mutual collaboration and potential partner contributions to the mission. During 2022 and early 2023, these discussions have helped to clarify potential NOAA/NASA and EUMETSAT contributions to AOM, related funding processes and schedules, helping to lay the foundation for Canada and these potential partners to enter into formal agreements in the future. Given the importance of the Arctic region and the current observation gap for weather, climate, air quality and space weather data at spatial and temporal coverages comparable to that provided by GEO satellites, AOM could provide significant socio-economic benefits in these application areas for many nations. As pre-formulation study activities progress, Canada welcomes further collaborations with international space and meteorological agencies and are happy to engage in such discussions.

5 CONCLUSIONS AND NEXT STEPS

Both TSMM and AOM mission teams will continue their respective activities to refine their business cases and prepare for potential future funding. TSMM has a current timeline that is focused on securing funds for full mission implementation in 2025-26 timeframe, with a launch target of 2032, with a minimum 3-year lifetime. AOM's pre-formulation study will end in late 2024, after which preparations will begin for a potential future funding proposal to secure funds for the next phases of the mission. AOM has a target launch date of ~2034, with a 10-year operational lifetime. A free and open data policy, currently under development, is envisioned for both TSMM and AOM. The proposed missions would each address observation gaps over the higher latitudes and make observations of key variables for climate, weather, air quality, hydrology and space weather measurements that would yield benefits globally.

[1] ESA maintains observer status in AOM's International Expert Team

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