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Canadian Space Agency WildfireSat Mission Requirements Document

Natural Resources Canada
Canadian Forest Service
Great Lakes Forestry Centre
Information Report
GLC-X-41

The Great Lakes Forestry Centre, Sault Ste. Marie, Ontario

The Great Lakes Forestry Centre is one of five research centres within the Canadian Forest Service, which is the national and international voice for Canada's forest sector. One of the core mandates of the Service is to conduct scientific research on Canada's forests. This research can be used to inform forest management planning and policy decisions and to assist the forest industry, the public and other scientists. The research projects cover diverse forestry related issues including climate change, forest fires, pests, and remote sensing. The results of this research are distributed in the form of scientific and technical reports and other publications.

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Canadian Space Agency WildfireSat Mission Requirements Document.

The WildFireSat Canadian Operational Mission (WFS-COM) Mission requirements was authored jointly by the Canadian Space Agency and Natural Resources Canada. This document defines the scope, operational, technical and functional requirements for the WFS satellite mission. The WFS-COM Mission requirements serves as the baseline description of the WFS mission and was produced to guide the procurement process and provide information to the bidders of the WildFireSat mission. The WFS-COM Mission requirements also provides a baseline for the Government of Canada developers of the WildFireSat mid- and downstream segments.

Some modifications have been made since the version initially published as part of the request for proposals in 2023.

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Canada

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Canadian Space Agency

WildFireSat

Mission Requirements Document

Revision C

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1. INTRODUCTION

1.1 PURPOSE OF THIS DOCUMENT

The Mission Requirements Document (MRD) is the top-level document describing the WildFireSat (WFS)[1] mission objectives and requirements.

1.2 BACKGROUND

Wildfire monitoring is currently supported by a network of publicly owned satellites. Primarily these are geostationary weather satellites, which also provide near constant observations of actively burning wildfires. However, in higher latitude regions such as Canada, geostationary weather satellites are not able to detect most wildfires, leaving Canada to rely on far less effective scientific polar orbiting satellites for wildfire monitoring. Furthermore, there are no available public or commercial satellites that Canada can leverage to fulfill the specific needs of active fire management in Canada, in particular during the critical late afternoon period when fires are most intense.

This situation inhibits on-the-ground firefighting partners and emergency management organizations from having access to the wildfire and smoke information they need to make most effective and timely operational response and evacuation decisions. Recent catastrophic fire seasons (e.g. British Columbia in 2017, 2018 and 2021, and Australia in 2019-2020, and all of Canada 2023) again demonstrate the serious impacts associated with facing limited operational information. Looking forward, wildfires pose a significant ongoing threat to the safety and security of Canadians and the economy. The threat of wildfires under climate change is growing, which increases the urgency for a solution to Canada's wildfire monitoring needs.

Natural Resources Canada (NRCan), Environment and Climate Change Canada (ECCC), Canadian Provincial/Territorial fire management organizations and Academia, both in Canada and abroad, have therefore expressed the need for a space-based operational wildland fire monitoring system.

A future operational wildland fire monitoring system with near real-time data delivery (i.e. approximately 30 minutes), coverage of the Canadian or global landmass, and frequent revisits, will require access to dedicated space-based sensors. To render such a solution affordable, these sensors must utilize a technology allowing them to be hosted and operated with limited resources from the accommodating platform.

One such enabling technology is based on microbolometer technology, which can perform thermal measurements without cooling. This reduces drastically the necessary resources (mass, volume, power) to accommodate the instrument on a space platform and therefore enables the possibility of use in a constellation, contrary to the thermal instruments on today's large weather satellites.

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[1] In the following, we use WildFireSat (WFS) to ease up the reading of the document. GardeFeu is used in the French version to designate the same system.

The WildFireSat (WFS) mission will deliver such a fully operational wildfire monitoring system that detects and monitors wildfires from satellites. WFS will be a complete information system, observing wildfires during their peak burning period (late afternoon) as well as early morning, and delivering detailed analysis of the fires as fast as possible directly to the operational partners making decisions on the front lines. The primary outputs and outcomes of the mission are as follows:

1. Canadian wildfire managers (i.e., Provincial and Territorial agencies, Parks Canada) will be provided fire management products on all active wildfires, daily, and in near real-time;
2. Air quality, smoke, and carbon emissions from wildfires will be better forecasted and monitored and;
3. There will be a significant reduction of the economic and societal risks and losses associated with the threat of wildfires.

WFS will enable safer and more informed evacuations, which is of critical importance as they are becoming more frequent.

1.2.1. Current Capability and Gap

Wildfire detection practices in Canada vary widely across jurisdictions and response zones. The land- and air-based fire detection methods that are most frequently used are fixed-wing patrols, look-out towers (including automated tower systems), field-staff patrols and public reporting. Where wildfires are actively suppressed (e.g. generally in Zone A, as defined in D-1) these detection methods are effective in locating newly ignited fires and frequently exceed the ability to detect wildfires from existing EO detection products (Johnston et al. 2018[2]). With this in mind, significant improvements are possible in the domain of fire monitoring.

The fire monitoring infrastructure currently in place (including land, air, and space assets) does not provide the level of data that is required to improve wildfire management, and smoke and air quality forecasting. Aircraft reconnaissance flights are costly, cover limited areas, require the use of experienced personnel (better suited to direct response operations), carry inherent safety risks, and yet must be conducted regularly for large fires regardless of their response objectives. Furthermore, aircraft are often in short supply during escalated fire situations and may be unable to fly due to smoke induced visibility issues. Even under ideal conditions, it is not possible to fly over all fires in Canada daily. The cost, logistics and availability issues related to these operations are major drivers in the pursuit of alternative fire monitoring solutions.

Fire monitoring by Earth observation is a natural alternative to airborne reconnaissance. However, the EO satellites that are currently used for wildfire monitoring purposes were not primarily designed for this purpose. Most notably, geostationary satellites provide active fire detection and Fire Radiative Power (FRP) estimates. Unfortunately, the spatial resolution and

[2] Johnston JM, Johnston LM, Wooster MJ, Brookes A, McFayden C, Cantin AS, Satellite Detection Limitations of Sub-Canopy Smouldering Wildfires in the North American Boreal Forest, Fire, 2018;1: 28.

atmospheric interference rapidly degrades geostationary data quality as the latitude increases, effectively nullifying this option for Canada. Polar orbiting data has been found to be useful in forensically reconstructing past fire events, yet their data latencies and overpass times are not well suited to operational fire management (MNP, 2017[3]). For example, the majority of active fire data currently available from polar orbiting satellites comes from systems designed for general purpose applications, with overpass times designed to accommodate a broad range of users (typically at ~10:00 or ~13:00 local solar time), and spatial resolutions typically of much coarser resolution than the ideal of 400 m or better required for accurate FRP measurement.

Critically, although these satellites are valuable in documenting wildfire activity early in the daily burning period, they fail to capture activity during the late afternoon time frame when wildfires are at their peak intensity (Figure 1-1). The temporal gaps throughout the coverage are highly problematic as we find significant periods of intense fire activity with no observations, effectively leaving 10-hour periods of fire growth undocumented and a substantial lack of situational awareness for operational users.

In order to meet the needs of operational fire management, WFS will collect active fire observations directly within these temporal gaps. The data will be of suitable spatial resolution and delivered in near real-time to the End Users. In doing so WFS will close the afternoon and early morning gaps and provide a reliable source of reconnaissance data for use in strategic planning operations, reducing the reliance on airborne surveys.

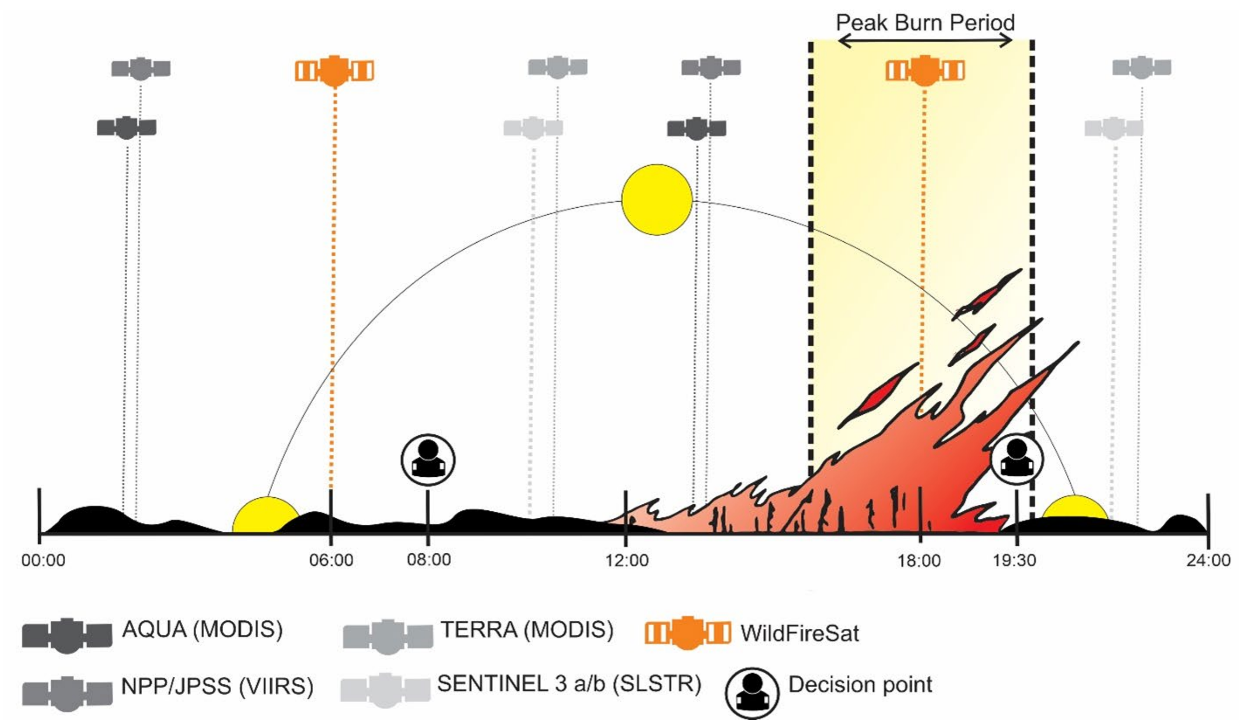

Figure 1-1. Active-fire satellites overpass times.

[3] A review of the 2016 Horse River Wildfire: Alberta Agriculture and Forestry Preparedness and Response. In. A review of the 2016 Horse River Wildfire: Alberta Agriculture and Forestry Preparedness and Response. Edmonton, Alta., MNP LLP, 2017.

1.2.2. Past Efforts

The need for improved wildfire monitoring from space has been investigated since 2006 and related instrument technology was partly demonstrated in space in 2011[4]. In 2013 the Canadian Wildland Fire Monitoring System (CWFMS) was proposed as one of five microsatellite missions to undergo a Phase 0 (feasibility) study which was carried out successfully in 2014-2016. Several Space Technology Development Program (STDP) activities have been carried out in parallel to increase the maturity of mission enabling instrument technology.

In March 2019, the WFS project was approved by the Canadian Space Agency (CSA). Phase A of the project acquired further insights through conceptual design and TRL advancement work executed by two parallel contracts with industry. Following Phase A, a RFI and calls for Letters of Interest was issued by CSA in December 2021 to solicit industry feedback for a reduced-scope, single-satellite mission referred to as the Pathfinder.

In April 2022, before the start of procurement activities for a Pathfinder mission, the Government of Canada announced a significant investment to expand the scope of the mission, enabling an operational mission with daily peak-burn overpasses over Canada paired with early morning observations. Additionally, this funding envelope includes support for the ground segment, and downstream data product development, end-user knowledge exchange and integration into smoke monitoring systems. This release of this MRD reflects the requirements for the new mission scope.

The above change of scope led to the refined set of mission requirements in this document. Note that the User Requirement Document (URD) was not maintained after transition to phase A, therefore several of the mission requirements are coming from RD-02.

1.2.3. Mission Concept

The WFS system will be comprised of a Space Segment, Ground Segment and User Segment, as shown in Figure 1-2.

[4] The New InfraRed Sensor Technology (NIRST) instrument was demonstrated with partial results on the international partnership Aquarius SAC-D mission (2011-2015).

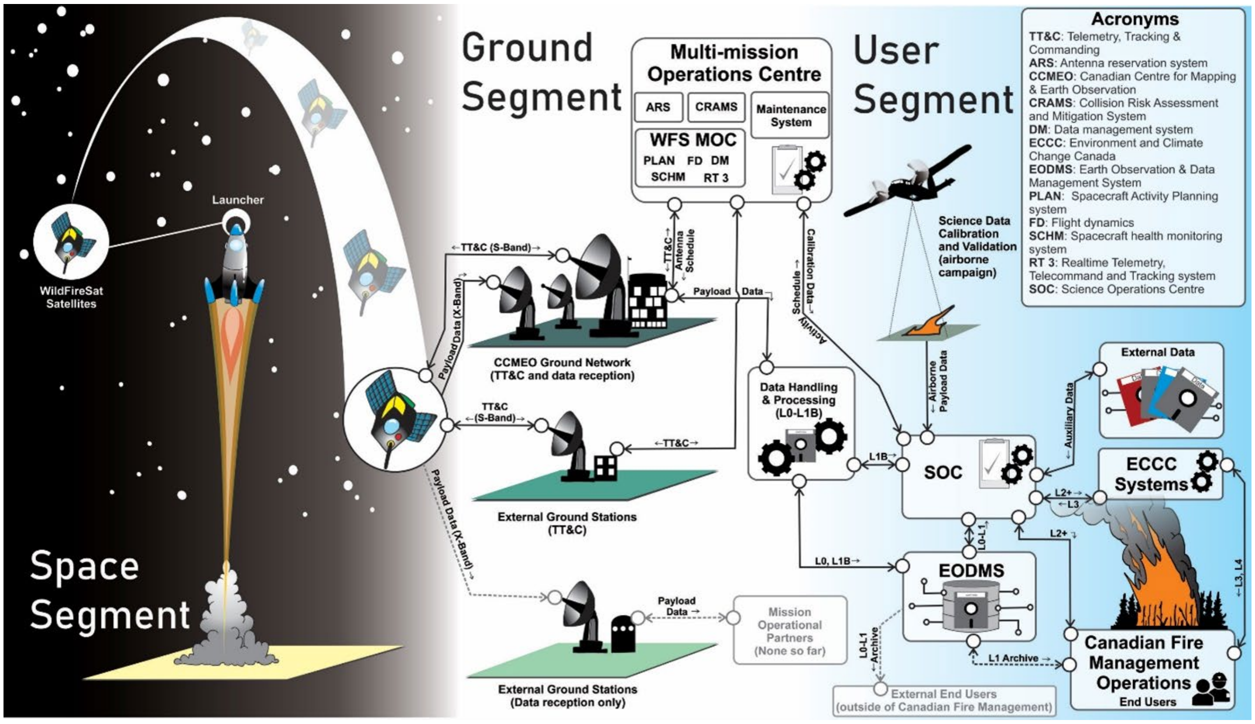

Figure 1-2. Mission concept.

The Space Segment will be made up of several spacecraft in Low Earth Orbit (LEO), each carrying a multi-band payload to provide Earth observation measurements in a range of Infrared (IR) and visible bands. These bands have been specified by the users to provide the data required to characterize FRP, hotspots, perform burned area mapping, and determine fire Rate of Spread (ROS).

The Ground Segment will comprise spacecraft Tracking, Telemetry, and Control (TT&C), spacecraft operational planning and tasking capabilities, data handling and data processing to Level 1-b.

Preliminary concepts for the mission comprised nadir-pointed satellites that collect data in a pushbroom configuration for all access opportunities over the Canadian Area of Interest (AoI) during the active fire season[5]. Data downlink in these concepts would operate in a bent-pipe configuration to meet the latency requirements, utilizing a ground segment based on the Ground Station Network (GSN) of the Canada Centre for Mapping and Earth Observation (CCMEO) (Gatineau, Inuvik, and Prince Albert stations). The spacecraft would be operated from the Multi-Mission Operations Centre (MMOC) located at the CSA in Saint-Hubert.

Downlinked data will be processed to Level-1b and transferred to the User Segment for storage, processing and dissemination. The Earth Observation Data Management System (EODMS), located at the CCMEO, will house the downlinked and Level-1b data in long-term storage. The Science Operations Centre (SOC), located at NRCan, will temporarily store Level-1b data, and

[5] For the purpose of this project, the Canadian active fire season is defined as the period between the 1st of March and the 31st of October.

manage auxiliary data to support near real time processing of Level 2+ products at this centre. Level 2+ data products will be stored in the SOC, and disseminated in multiple accessible formats to End-Users such as Environment and Climate Change Canada (ECCC), through SOC services. EODMS may also store long-term archival of Level 2+ data products.

The User Segment will consist of the appropriate resources required to process the data provided by the Ground Segment to the level required by End-Users, as well as the archival and distribution of mission data as appropriate. The User Segment will also plan payload activities as per the operational and science directives of the mission.

1.3 MISSION OBJECTIVES

The objectives of the WFS mission are to:

- Provide an operational wildland fire monitoring service to End-Users, that will produce:
    - Near real-time information in support of wildland fire management and research;
    - Smoke and air quality forecasts, and emissions estimates, in support of international requirements for carbon reporting.
- Monitor wildfire activity in Canada on a daily basis, with overpasses in late afternoon when no satellite fire monitoring data sources currently exist, and wildfire activity is typically at its peak;
- Provide End-Users with reliable fire products with the required accuracy within 30 minutes of data acquisition;
- Integrate WFS data into existing and new tools for wildfire management, carbon reporting, smoke and air quality reporting.

1.4 SCOPE AND OUTLINE

The Mission Requirements Document scope encompasses the end-to-end mission, from wildland fire data acquisition to delivery of Science Data Products to End-Users. However, the requirements focus on the ones pertaining to the Space and Ground Segment to be delivered by the main CSA Contractor, and the interfaces to the User Segment and the Ground Segment components and services offered by the Government of Canada. The Concept of Operations (RD-06) can provide the reader with a better understanding of the overall data flow and how all interfaces to Government of Canada furnished services and components come into play in the overall WFS mission.

The document is organized as follows:

Section 2: identifies applicable and reference documents.

Section 3: presents definitions relevant to the document.

Section 4: presents the mission products and discusses the trade-offs between different aspects of the mission.

Section 5: presents the mission requirements for the WFS mission.

Section 6: defines acronyms and abbreviations used in the document.

2. DOCUMENTS

For this project, the Mission Requirement Document is considered as the root source of all WildFireSat requirements. The users have co-authored the Mission Requirements considering their needs plus the outcomes of Phase 0 and Phase A. Earlier iterations of this project had included a User Requirements Document, but this document is now considered obsolete. This extends to the specifications outlined in RD-02, which is included for contextual reference only. As such, the User requirements are captured within the Mission Requirements described herein.

2.1 APPLICABLE DOCUMENTS

The following documents of the exact issue date and revision level shown are applicable and form an integral part of this document to the extent specified herein.

AD	Document Number	Revision	Title
AD-01	Radio Regulations (itu.int)	2020	ITU Radio Regulations
AD-02	Government of Canada Bill C-25		Remote Sensing Space Systems Act
AD-03	Guide_Probability_Failure_110205.pdf (faa.gov)	1.0	Guide to Probability of Failure Analysis for New Expendable Launch Vehicles
AD-04	https://www.nasa.gov/sites/default/files/189893main_ER-2_handbook_02.pdf	August 2002	NASA ER-2 Airborne Laboratory Experimenter Handbook

2.2 REFERENCE DOCUMENTS

The following documents provide additional information or guidelines that either may clarify the contents or are pertinent to the history of this document.

RD	Document Number	Revision	Title
RD-01	CEOS/WGISS/DSIG/GLOS	1.3	Long Term Preservation of Earth Observation Space Data Glossary of Acronyms and Terms
RD-02	https://www.mdpi.com/1424-8220/20/18/5081	Published 2020-09-07	Development of the User Requirements for the Canadian WildFireSat Satellite Mission
RD-03	Llis (nasa.gov)	1994-12-01	NASA Lesson: Availability Prediction and Analysis
RD-04	https://www.ic.gc.ca/eic/site/063.nsf/eng/h_97992.html	Feb 2020	Roadmap for Open Science
RD-05	https://www.tbs-sct.canada.ca/pol/doc-eng.aspx?id=28108	2014-10-09	Directive on Open Government
RD-06	CSA-WFS-CO-0001	Rev. A	WFS Concept of Operations
RD-07	DOI:10.1016/S0034-4257(01)00192-4	2001	Application of the Dozier retrieval to wildfire characterization: a sensitivity analysis. Remote Sensing of Environment 77, 34-49
RD-08	https://doi.org/10.1016/j.rse.2014.06.010	2014	A global feasibility assessment of the bi-spectral fire temperature and area retrieval using MODIS data. Remote Sensing of Environment 152, 166-173
RD-09	https://doi.org/10.1016/0034-4257(81)90021-3	1981	A Method for Satellite Identification of Surface Temperature Fields of Subpixel Resolution. Remote Sensing of Environment 11, 221-229
RD-10	http://dx.doi.org/10.1007/978-94-007-6639-6_18	2011	Remote Sensing of Open Biomass Burning and Wildfire Regimes. King's College London

3. DEFINITIONS

D-1. Canadian AoI

The Canadian Area of Interest (AoI) is defined shown in Figure 3-1.

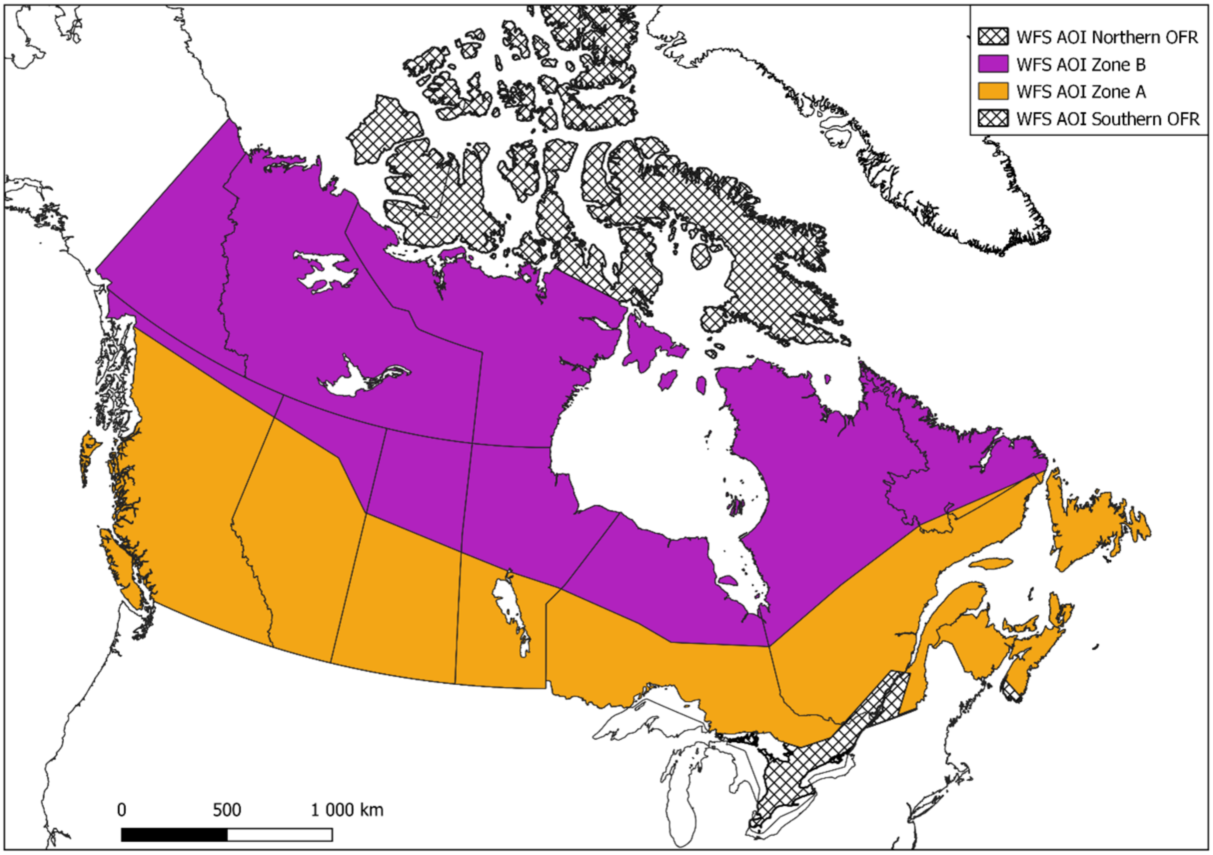

Figure 3-1. WFS area of interest.

Figure 3-1 is the map of the Canadian AoI as it relates (in broad generality) to wildfire management operations in Canada. The region in purple is referred to here as Zone B, while that in orange as Zone A. All other regions of Canada are the Out Fire Region (OFR) and are not considered as part of the Canadian AoI. Zone B represents areas where fires are typically monitored rather than suppressed. Areas in Zone A are more densely populated and so fires typically are suppressed. All other areas of the country, essentially the Windsor-Quebec corridor and maritime coasts, typically do not experience important wildland fires due to urbanization or lack of forest fuels. With this in mind, operational fire management is governed by a wide array of regional priorities, policies and agreements which are dynamic in nature. In any of the zones outlined above circumstances may dictate any number of situationally appropriate responses wildfires, the zonation provided here is purely to aid in high level mission planning.

The difference in user needs between the purple and orange area is as follows. In the orange Zone A, wildfire management organizations will try to respond to a fire as soon as possible. As such, these organizations will need information on newly detected fires, and updates on a fire's current activity as quickly as possible. A high revisit frequency (i.e. the revisit frequency that is required for an operational mission) is therefore needed in this zone, as well as a low data latency. In Zone B (purple), often only monitoring of fires is needed and no operations will need to be set in motion when a wildfire is detected in this zone.

Note: Shape files (.shp) of these coverage areas are available in conjunction with this document.

D-2. Burning Period

The burning period is that part of each 24-hour day when fires are generally the most active. Typically, this is from mid-morning until after sundown, although it varies with latitude and the time of year. For the purposes of this mission planning we accept the broad definition of: “from 09:00 to 22:00 local solar time”.

D-3. Peak Burning Period

Peak burning period is that portion of a burning period in which fire activity typically reaches a maximum due to diurnal conditions. For the purposes of this mission planning the definition of peak burn is: “from approximately 15:00 to 20:00 local solar time”.

D-4. Co-Elevation Angle

The co-elevation angle is defined as the angle between the local normal of the center of a pixel as determined from the reference geodetic sub-satellite point, as shown in Figure 3-2 (excluding local topographical features) and the line of sight to the spacecraft.

D-5. Sub-Satellite Point

The sub-satellite point unless otherwise specified, refers to the geodetic sub-satellite point (by opposition to geocentric sub-satellite point). The geodetic and geocentric sub-satellite points, which differ due to the Earth not being a perfect sphere, are illustrated in Figure 3-2. The geocentric point is the point where a vector from the satellite to the center of the Earth crosses the reference Earth geoid surface. The geodetic sub-satellite point is the point on the reference Earth geoid where a vector normal to its surface points to the satellite.

D-6. Noise Equivalent Temperature Difference (NETD)

NETD is the change in target temperature at the input to the optical system that would produce an equivalent signal change equal to the temporal Root-Mean-Square (RMS) noise. NETD is defined for a specific target temperature (typically 300K unless specified otherwise) and time period for the temporal RMS (typically 1 second unless specified otherwise).

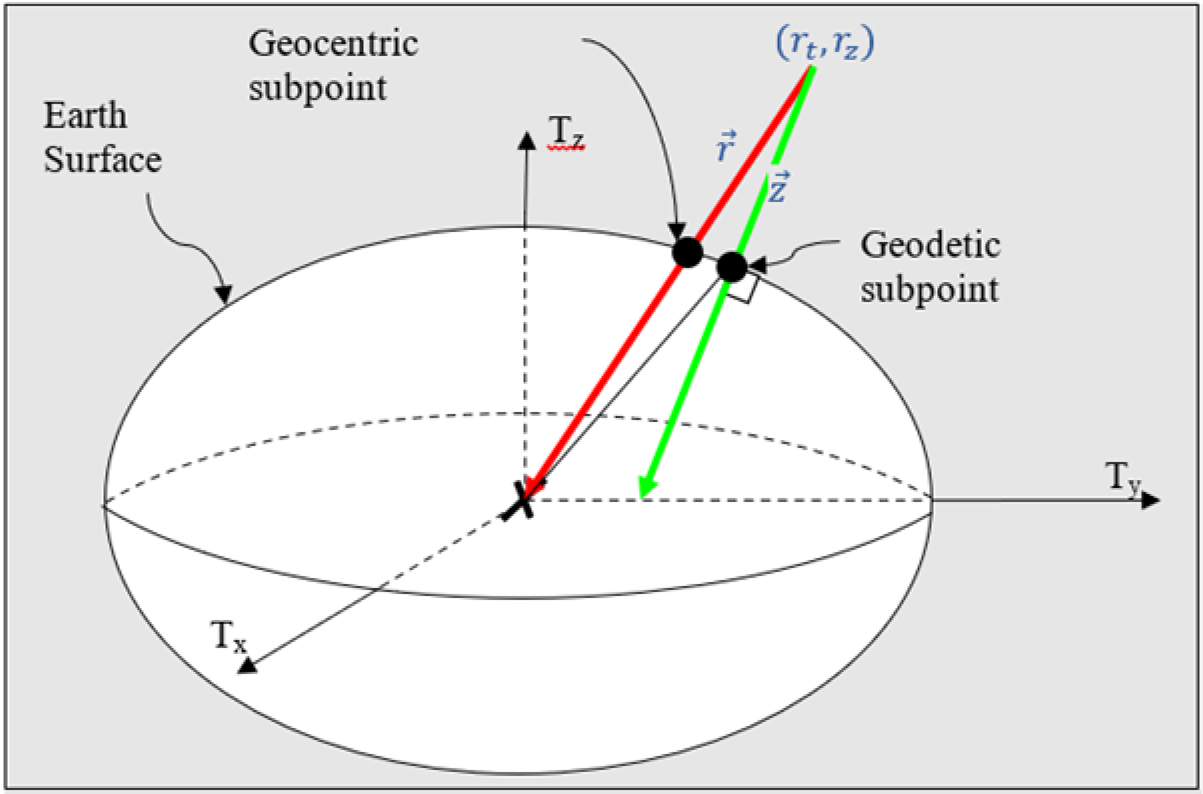

Figure 3-2. Geodetic sub-satellite point coordinates.

D-7. Noise Equivalent Power (NEP)

NEP is the change in radiative power directly incident on a detector pixel that would produce an equivalent signal to the RMS of the detector pixel's temporal noise signal over a specific period.

D-8. Noise Equivalent Spectral Radiance (NESR)

The Noise Equivalent Spectral Radiance (NESR) is the change in scene radiance input to an optical system that would produce a signal change equal to the RMS of the temporal noise signal over a specific period. NESR is expressed in units of spectral radiance (W m^{-2} sr^{-1} μm^{-1}).

D-9. Signal to Noise Ratio (SNR)

The SNR is the ratio of the signal power to the power of the noise (noise power) at the output of a single detector pixel.

D-10. Space Segment

The space segment consists of everything that is on-board of the spacecraft and launcher. This can also potentially include inter-satellite data relay although it is not baselined for WFS.

D-11. Ground Segment

The ground segment consists of the ground stations for Telemetry, Tracking and Command, and data reception, all equipment for planning spacecraft activities, monitoring, controlling and monitoring the spacecraft, and the on-ground processing necessary to provide Level-1b data and ancillary data to the User Segment.

D-12. User Segment

The user segment consists of the ground processing of the data from the format provided by the ground segment (Level-1b and ancillary data) to the level(s) required by the End-Users. It also includes the planning of the payload activities and the archival and distribution of the data.

D-13. End-Users

Canadian users of data products produced by the SOC for the purposes of operational decision making. This includes but is not limited to, Provincial and Territorial Fire Managers, and operational staff using data products for situational awareness, smoke and air quality forecasting, and carbon emissions reporting.

D-14. External End-Users

International users of data products produced by the SOC, and Canadian users of data products produced by the SOC that are not used for fire management, or operational uses.

D-15. Partner End-Users

Partners in the mission who will develop value-added data products provided by the User Segment and use data for research purposes (e.g. Natural Resources Canada-Canadian Forest Services (NRCan-CFS), Environment and Climate Change Canada (ECCC)).

D-16. Mission Partners

CSA, NRCan-CFS, NRCan-CCMEO and ECCC are Partners with direct involvement in the mission development and delivery.

D-17. Data Products

Data Products are classified as Tier-1, Tier-2 and Tier-3. A description of the WFS data products is provided in Section 4.1.

D-18. Fire Radiative Power (FRP)

FRP is the rate of radiant heat output of fires. FRP is an instantaneous measurement, typically calculated from thermal infrared measurement of the radiant output from fires, and is expressed in megawatts (MW).

D-19. Ensquared Energy

The ensquared energy is the fraction of the total energy in the Point-Spread Function (PSF) of a point source, perfectly co-aligned with a square pixel, that is captured by this pixel.

D-20. Point-Spread Function (PSF)

The Point-Squared Function of an optical system is the normalized intensity distribution of a point-source and a measure used to reconstruct the (Modulation Transfer Function) MTF of the optical system. The PSF is the optical system's impulse response and a measure of how object points are blurred in the image.

D-21. Modulation Transfer Function (MTF)

MTF is a measure of the optical system's ability to transfer contrast at a particular resolution from object to image.

D-22. Time-Delayed Integration (TDI)

A specialized detector readout mode used for observing non-stationary scenes in order to improve the signal-to-noise ratio. This is done by averaging a target's radiance signal at different times and pixel location as it moves through the imaging plane. Note that in the context of WFS, the term "TDI" is intended to have a broader meaning than its typical definition in the context of charge-coupled device (CCD) photoelectric detectors, where it refers to shifting of photoelectrons to compensate for the motion of objects. Indeed, in the context of thermal detectors such as microbolometers, TDI refers to the post-acquisition co-addition of the image pixels in several image frames which are determined to view the same object on the ground.

D-23. Field of View (FOV)

The span over which a given scene is imaged. The shape of the FOV matches the shape of the detector array and not the shape of the aperture.

D-24. Instantaneous Field of View (IFOV)

The angle subtended by a single detector pixel on the optical axis.

D-25. Ground Instantaneous Field of View (GIFOV)

The instantaneous ground distance covered by a single detector pixel, measured in units of length.

D-26. Ground Track

The ground track is the path on the planetary surface directly below the WFS satellite’s trajectory. Along-track is defined as a vector projection of the satellite FOV on the planetary surface parallel to the satellite’s trajectory, and across-track is defined as a vector projection of the FOV on the planetary surface perpendicular to the satellite’s trajectory.

D-27. Spatial Resolution

In this document, "spatial resolution" is a general term indicating the size of the smallest object that can be resolved by a sensor array.

4. OPERATIONAL SERVICES NEEDS AND TRADE OFFS

The WFS Space Segment is an integral part of the new wildfire monitoring satellite system announced in Budget 2022. Based on the EO data produced by WFS, this system will provide an end-to-end fire intelligence service for operational decision makers, and in particular Provincial and Territorial wildfire managers.

The WFS space segment will collect multispectral data with an emphasis on precision radiometric mid-wave (3-5 µm) and long-wave (8-14 µm) infrared measurements with data attributes compatible with VIIRS. These data will be collected twice daily, most importantly during the peak burn (late afternoon ~ 17:00 local solar time) period and again 12 hours later during the reciprocal overpass. The timing of these observations is critical to align with known gaps in existing coverage, and to align with fire management decision making cycles.

Data collected by WFS spacecraft will be passed to the ground segment, processed to Level-1b and transferred to the Partner End-Users at the SOC. Using these data, the SOC will then generate fire intelligence products based on the WFS observations and provide them to the End-Users (fire managers) in near real-time.

The timeliness of this overpass-production-delivery cycle is critical to achieve success in the mission objective of supporting strategic decision making in wildfire management. Although each jurisdiction manages wildfires in their own way, generally speaking all fire management agencies engage in two strategic planning exercises daily. First, at the end of the day following the peak burning period (~18:00-19:00 local solar time) an assessment of the response effectiveness and prioritization for the next day is conducted. Secondly, the evening assessment is re-evaluated based on any overnight activity prior to mobilization in the morning (~06:00 local solar time). With the timely delivery of WFS Science Data Products prior to these planning sessions, and with the intelligence they represent being no more than 30 minutes old, it is possible for this monitoring system to enable meaningful change in the quantity and quality of information used in strategic planning operations.

4.1 DATA CLASSIFICATION

This section provides a general overview of the data processing terminology, classification, and product classes which will be generated by the SOC to meet the needs of the End-Users.

Data types classified as data belonging to the Space Segment, Ground Segment, and User Segment. Data product classification and is listed in Table 4-1, and illustrated in Figure 4-1.

TABLE 4-1. DATA TYPE CLASSIFICATION

Mission Segment	Data Type	Data Label	Definition
Space Segment I	On-Board Science Data	Ancillary Data	Image, payload and bus data including temperature measurements, gain tables and offset tables.
		Scene Signal Data	The unprocessed binary data generated by the detectors.
		On-Board processed data	Corrected, averaged and/or noise-cleaned image data.
	Telemetry Data	Bus Telemetry	Telemetry data packet from the Bus.
		Payload Telemetry	Telemetry data packet from the Payload.
Ground Segment	Science Data Products	Raw Data Level 0 Level 1a Level 1b	See Table 4-2.
		Scene Signal Product	Special data product, reconstructed packets consist of unprocessed Scene signal data and metadata.
		Other Ancillary Data	Image, payload or bus data not received from the satellite (for example, correction factors, and additional information required for geocoding).
User Segment	Data Products	Tier 1 Tier 2 Tier 3	See Section 4.3
	Data Inputs	External EO Data	Data from non-WFS Earth Observation assets, for example Moderate Resolution Imaging Spectroradiometer (MODIS).
		Other Auxiliary Data	Additional non-WFS data used to generate Tier-3 Data Products, for example vegetation type, soil moisture or fire risk metrics.

Raw Data is received in packets with CCSDS overhead, and can be a combination of Ancillary Data, Scene Signal Data, and on-board processed data.

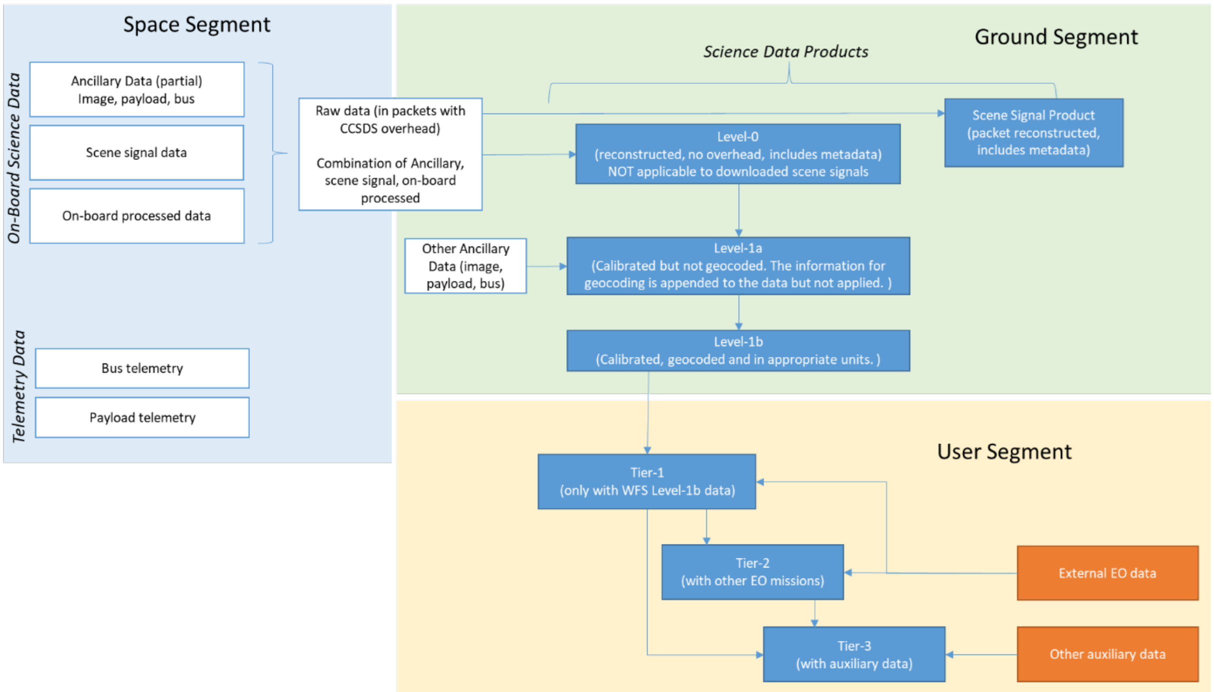

Figure 4-1. WFS data product classification.

4.2 DATA PROCESSING LEVELS

The National Aeronautics and Space Administration (NASA)-standard data processing levels are as defined in RD-01. Applicable Data Processing levels are recalled in Table 4-2 for convenience. Note that the NASA-defined Level-2, Level-3 and Level-4 Science Data Products are not currently mapped to any Tier of Science Data Product as defined by user needs in Section 4.1. Therefore, Levels 2 – 4 Science Data Products are considered non-applicable for this mission at this time.

TABLE 4-2. DATA PROCESSING LEVELS

	Data Processing Level
Raw data	Data in their original packet as received from the spacecraft.
Level-0	Raw instrument data which has been reconstructed from the Raw data packets.
Level-1a	Calibrated but not geocoded. The information for geocoding is appended to the data but not applied.
Level-1b	Calibrated, geocoded and in appropriate units.

4.3 DATA PRODUCTS

Tier-1 and 2 products are intended for delivery in near real-time. A list of the required accuracy levels for selected MRD-related data items within the data products is provided in Table 4-3.

- **Tier-1 Data Products**
  Tier-1 products represent those which will be generated exclusively using WFS Level-1b data and are the level of data which the SOC provides to ECCC for smoke and air quality applications. The central objective of Tier-1 is to locate actively burning wildfires and quantify their Fire Radiative Power (FRP). Precise FRP measurements are relevant to fire behaviour, smoke monitoring and carbon accounting activities.

  These products include fundamental components such as:
  - Cloud masks: An essential input to the contextual fire detection algorithm (requires: Visible/Near Infrared (VIS/NIR)).
  - Fire detection: Contextual analysis of thermal anomalies in the scene, including multi-spectral tests to identify probable fire pixels known as “hotspots” (requires Mid-Wave Infrared (MWIR), Long-Wave Infrared (LWIR), VIS/NIR).
  - Fire characterization: Sub-pixel analysis of hotspot pixels to determine effective fire area and temperature (requires MWIR and LWIR).
  - Fire Radiative Power: measurement of the rate of thermal emission of actively burning pixels (requires MWIR, and potentially LWIR).
  - Burned Area Mapping: For added context, a map of the previously burned area associated with the active hotspots will be provided (requires VIS/NIR, and optionally MWIR and LWIR).
- **Tier-2 Data Products**
  Tier-2 products are those which require the merger of WFS Tier-1 products with auxiliary non-WFS EO data products, in particular VIIRS active fire data products. This data synthesis process enables the SOC to automate active fire change detection between the VIIRS (~1300 and 0100) and WFS overpass time, effectively quantifying wildfire growth parameters during the elapsed period.

  These products are aimed at describing fire behaviour and include estimates of fire growth and progression rates, direction of spread, and fireline intensity. The accuracy of these products is closely tied to the spatial resolution, MWIR image clarity, overpass time, and FRP integrity.
- **Tier-3 Data Products**
  Tier-3 products provide enhanced contextual analysis and forecasting associated with the observations in Tiers 1 and 2 through the use of auxiliary geospatial datasets and modelling tools. This includes data layers containing information on : (1) the location of communities, structures, infrastructure and industrial installations, (2) census data, (3) wildland fuels and their condition, (4) fire danger, (5) topography, and (6) weather forecasts. Tier-3 products will be obtained from a number of modelling tools including fire growth models all of which extend from the broader fire science community. The

Tier-3 products will provide (amongst other things) assessments of the potential threat to communities and infrastructure at varying temporal scales, as well as potential options for mitigation.

TABLE 4-3. DATA ACCURACY OF SELECTED DATA PRODUCTS RELEVANT TO THE MRD

Tier	Data Item	Accuracy*	Format (units)
1	Cloud Mask	<25% average uncertainty in categorical assignment	Categorical raster (0-4): 0 – cloud free 1 – mostly cloud free 2 – partial cloud 3 – full cloud 4 - smoke contaminated
1	Active fire detection	<10% average of omission and commission errors for a 5 MW fire	Binary raster
1	FRP	< 15% uncertainty for fires of 5 MW or higher	Active fire attribute: (MW)
1	Sub-pixel characterization	< 25% uncertainty in retrievals	Active fire attribute: Effective fire Area (pixel fraction) Effective fire temperature (K)
1	Burned Area	<25% average of omission and commission errors when compared to higher fidelity products	Binary raster
2	Fire progression	< ~ 5 m/min over sample period	Vector data estimate fire spread rate between VIIRS and WFS overpass (m/min)
2	Spread direction	< ~ 15 degrees	Attribute to fire progression (azimuth degrees)

(*) **Note**: all accuracies are intended to reflect final product uncertainties in consideration of all sources of error including (but not limited to) those related to environmental, contextual, payload, target characteristics, external datasets, and algorithmic factors.

4.4 RATIONALE FOR REQUIREMENT DEVELOPMENT

In developing the requirements for the WFS mission numerous, certain trade-off decisions were made in an effort to optimise performance for the central aim of the mission: delivering operational near real-time support to wildfire managers. It is of paramount importance to note that all operational near real-time products for this mission will be automated, with minimal human intervention (except where debugging is required). With this in mind, data consistency and artifact minimization are key priorities. In this section some of these trade-offs are addressed, particularly where multiple requirements directly compete with one another or where the rationale for requirements is less transparent. That said, this section is not intended to be comprehensive in its treatment of mission requirements nor in the rationale it provides for their definition. The mission requirements describe a system which is interdependent with a high degree of complexity, and it is rarely the case that any one factor determines a requirement. Often the requirements are an expression of competing scientific knowledge, operational demands, practical limitations, and encroachment of other requirements. Notably, all requirements have evolved and been refined throughout iterative analyses conducted in Phase-0 and Phase-A. As such, the rationale that follows typically cannot be traced to the precise numbers listed in many requirements (as those are also informed by what was learned to be feasible from the Phase-A studies conducted by industry). Rather, these rationales demonstrate the priorities and considerations which informed requirement definition.

4.4.1. Coverage vs co-elevation

In many Earth Observation systems, coverage is the number one requirement driving cost and complexity. The WFS requirements do not demand 100% daily coverage of the Canadian AoI at each overpass time, although it would be possible to achieve this by relaxing the restrictions on co-elevation angle to widen the swath. However, it is crucial to restrict the co-elevation angle to less than 30 degrees in order to ensure adequate fire product quality.

This is in part because optical performance, atmospheric transmission and GIFOV deformation are all affected by the co-elevation angle (and by extension the camera FOV angle). Limiting the co-elevation angle to less than 30 degrees ensures that the combined effective transmission from camera relative illumination, atmospheric transmission and GIFOV deformation effects will not drop to below half its nadir-viewing value, as shown in Figure 4-2 below which is based on a simple calculation assuming a cos4 angular dependence on relative illumination typical for classic imaging systems. Such a drop in transmission results in significantly decreased FRP accuracy due to reduced detector radiometric sensitivity and increased errors when compensating for atmospheric effects.

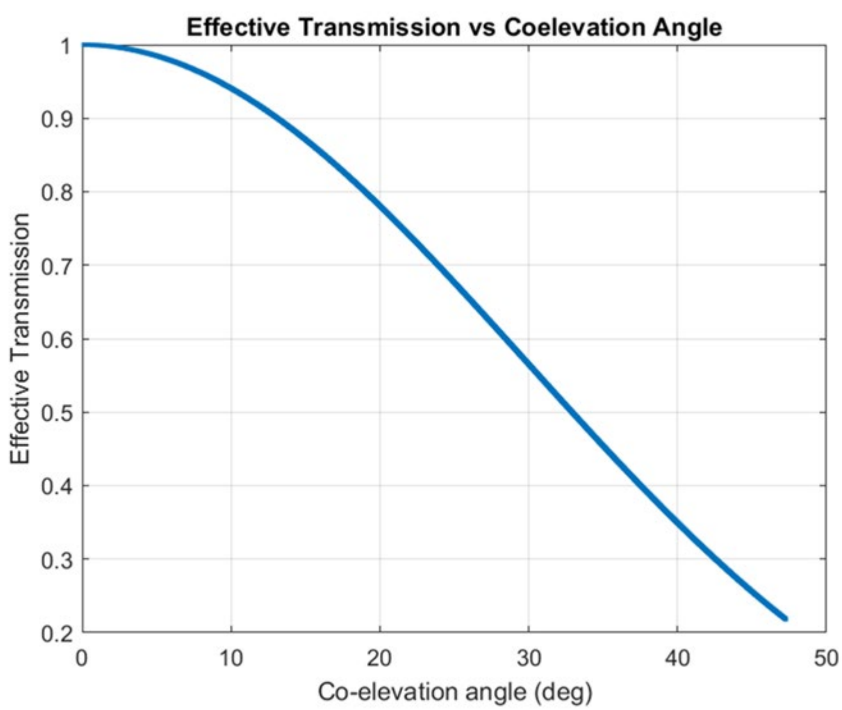

Figure 4-2. Effective transmission versus co-elevation angle of a sub-pixel ground feature seen by a nadir viewing camera in low earth orbit, including effects of camera illumination, atmospheric transmission and ground sampling.

Furthermore, limiting the co-elevation angle to 30 degrees reduces the frequency of coverage gaps caused by mountainous terrain and forest canopies, and mitigates parallax errors resulting from geo-locating clouds and smoke plumes viewed at oblique angles. In addition, beyond 30 degrees co-elevation angle the frequency of smoke plume induced artifacts in the active products becomes substantially higher (a significant barrier for operational use and near real-time interpretation of the products).

In consultation with international experts within the field, it was agreed that 30 degrees co-elevation angle is the point at which significant loss of data quality is apparent in active fire products from the VIIRS and MODIS systems[6]. This co-elevation angle is approximately where the VIIRS pixel uniformity significantly degrades and atmospheric transmission effects increase substantially, resulting in a drop in detection sensitivity and increased uncertainty in FRP retrievals.

4.4.2. MWIR and LWIR bands

The thermal bands are required for detecting active fire pixels and collecting radiometric measurements of these pixels for wildfire characterization. To accomplish this, they must meet a number of stringent requirements, not all of which will be addressed in this section. It is important to note that MWIR performance is considered the highest priority for the payload, closely followed by the LWIR.

4.4.3. MWIR Band Placement

The long-standing precedence for measuring FRP from EO data comes from MODIS Band-21, an extremely narrow band centered at 3.9 µm. Similar spectral bands have been used extensively in experimental FRP work over the last 20 years (e.g. Wooster et al., 2005, and many others). As a general rule the narrowest band possible at 4.0 um is the optimal point for estimating FRP. However, this precise MWIR spectral band is not essential as demonstrated by the Sentinel-3 SLSTR fire channels (3.74 µm, Xu et al., 2020[7]) and the VIIRS instrument (Channel I4 = 3.55 to 3.93 µm, centered at 3.74 µm, Schroeder et al 2014[8]). What is critical is that the upper bound of the spectral band does not cross into the CO_2 band at 4.2 µm which will cause instability in the retrievals. The lower bound of the MWIR band is primarily concerned with solar reflection. In order to avoid high incidence of false positives and confounding signals in the FRP estimate, it is important to limit the amount of solar reflection present in the MWIR band. Generally speaking, the majority of the solar reflection can be avoided with a spectral band above 3.5 µm.

In defining the spectral band requirements for the MWIR, considerations were also made for improving SNR at ambient levels (where the MWIR radiance is minimal). A wider band is beneficial in this effort, but the constraints noted above were considered. The band as it is currently defined insists upon a peak response centered at 3.9 µm, while cutting off sharply at

[6] M. Wooster, W. Shroeder, personal communication.
[7] 10.1016/j.rse.2020.111947
[8] 10.1016/j.rse.2013.12.008

4.2 µm and allowing a more relaxed lower bound of ~ 3.4 µm (provided that this is within the tail of the Spectral Response Function (SRF) of the instrument).

4.4.4. Sensitivity, Precision and Accuracy Requirements

4.4.4.1. Sensitivity

The thermal payload must have the sensitivity required to detect and characterize sub-pixel High Temperature Events (HTEs) of 200 m^2 or less with the baseline NESR in order to meet the needs of the Partner End-Users. In order to accomplish this, we require an NESR such that these HTE pixels will elevate the pixels signal to beyond the 3 sigma noise threshold. This sensitivity requirement is contingent on fractional pixel area. To illustrate, Figure 4-3 presents a simple simulation of a sub-pixel target of varying sizes with an average temperature of 800 K (representing the average apparent brightness temperature of a typical emerging wildfire including both flaming and smoldering combustion and accounting for emissivity) over a 300 K background, for pixels with 400 and 500 m GIFOV (assuming an ensquared energy of 0.75) with 80% atmospheric transmittance. As can be seen, when applying a 3 sigma noise threshold, a 200 m^2 HTE is detectable with a GIFOV of 400 m, but not at 500 m.

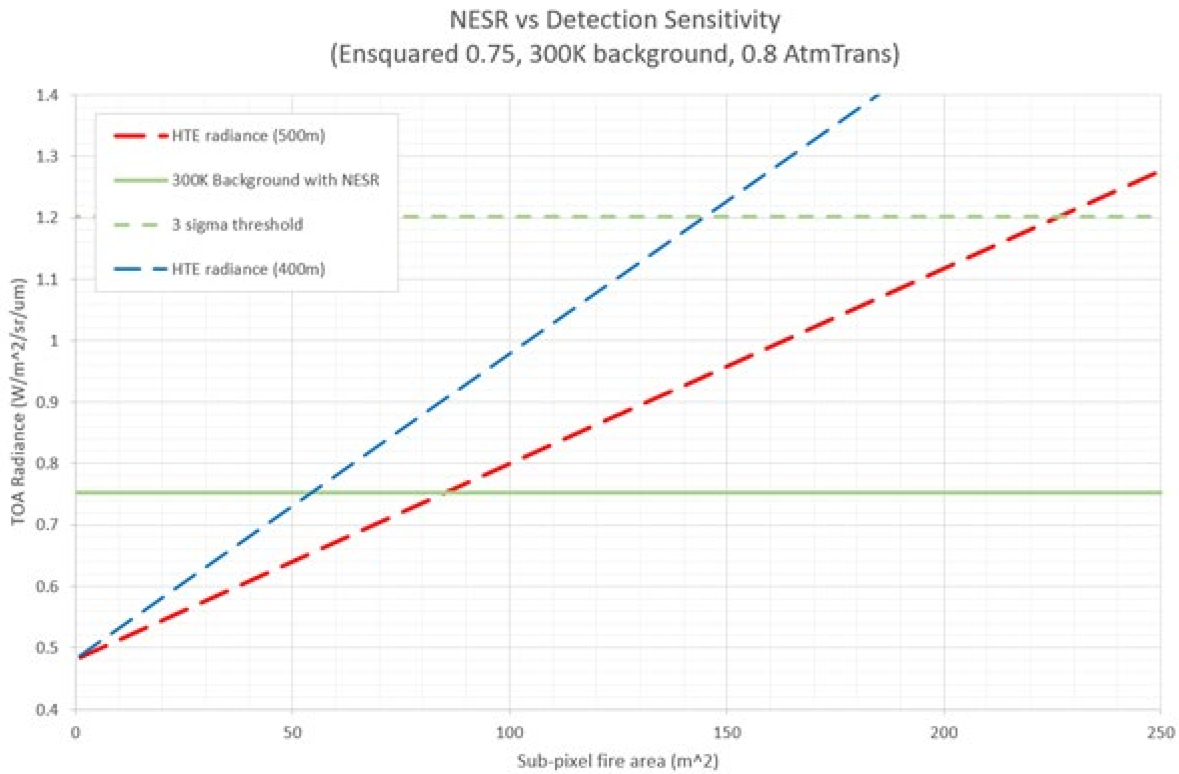

Figure 4-3. Relationship between sub-pixel detectable area of a 800 K target on a 300 K background and NESR.

4.4.4.2. <u>Precision</u>

Although detection sensitivity is contingent on both spatial resolution and NESR, the NESR requirements themselves are driven by measurement precision. As noted above, the first order pixel screening described in Figure 4-3 only identifies candidate fire pixels. In order to confirm fires and reject other thermal emitters, further analysis must be conducted. This process, known as contextual fire detection (Roberts and Wooster, 2008[9]; Wooster et al., 2012[10]; Schroeder et al., 2014[11]; Giglio et al., 2016[12]; Xu et al., 2020[13]), requires multi-spectral analysis of the HTE pixel within the context of other landscape features which can cause false positives (e.g. proximity to water bodies, urban or industrial areas, etc). In the MWIR the precision requirement only necessitates the ability to differentiate gross geographic features in the

[9]Roberts G, Wooster MJ, Fire Detection and Fire Characterization Over Africa Using Meteosat SEVIRI, IEEE Transactions on Geoscience Remote Sensing, 2008;46: 1200-18.

[10]Roberts G, Wooster MJ, Fire Detection and Fire Characterization Over Africa Using Meteosat SEVIRI, IEEE Transactions on Geoscience Remote Sensing, 2008;46: 1200-18.

[11] Schroeder W, Oliva P, Giglio L, Csiszar IA, The New VIIRS 375 m active fire detection data product: Algorithm description and initial assessment, Remote Sensing of Environment, 2014;143: 85-96.

[12]Giglio L, Schroeder W, Justice CO, The Collection 6 MODIS Active Fire Detection Algorithm and Fire Products, Remote Sens Environ, 2016;178: 31-41.

[13] Xu W, Wooster MJ, He J, Zhang T, First study of Sentinel-3 SLSTR active fire detection and FRP retrieval: Night-time algorithm enhancements and global intercomparison to MODIS and VIIRS AF products, Remote Sensing of Environment, 2020;248: 111947.

ambient background (e.g. land surfaces vs lakes etc.), to ensure that HTE is indeed a wildland target. In contrast, the LWIR is relied upon to provide finer scale contextual information in compensation for the poorer ambient temperature sensitivity of the MWIR. The LWIR must be capable of measuring the background ambient surface radiances with a sufficient precision and image uniformity to enable resolving adjacent image features with 0.1 K temperature differences, for an ambient temperature of 300 K. Often, when executing such detection algorithms, similar precisions are found in both the MWIR and LWIR bands (e.g. the Visible and Infrared Imaging Radiometer Suite (VIIRS)). That said, in the case of the present requirements a concession was made to relax the MWIR NESR requirement to the absolute maximum allowable level to allow consideration of new technologies. This consideration was motivated by the prevalence of MWIR-sensitive two dimensional (2D) uncooled microbolometer detector arrays which allow additional data for false positive screening (e.g. temporal information), thus reducing the demand on MWIR contextual precision. However, it is important to note that in the requirements the NESR is stated as the noise prior to any correction factors as it is assumed that these levels may be further lowered through sampling approaches. Minimizing the MWIR noise levels is considered to be one of the highest priorities in the payload design, this is why a requirement exists for TDI.

4.4.4.3. <u>Accuracy</u>

The thermal bands must also collect accurate radiometric measurements of the data in order to characterize the detected wildfires. Fire characterization includes FRP characterization and sub-pixel fire temperature and area characterization. The MWIR measurement accuracy is driven by the need to achieve an accuracy within ±15% when estimating the FRP of a 5MW or higher fire. The threshold of ±15% maximum accuracy error was selected based on current best performance estimates for existing satellite-based small fire FRP products, and was found to be achievable in Phase-A of the mission. The radiometric measurement accuracy is driven by (1) the detector sensitivity (NESR), and (2) the ability to accurately calibrate the detector and compensate for thermally induced signal drifts. At the lower end of the MWIR band dynamic range, the achievable accuracy will mostly be limited by the NESR. In contrast, at the high end of the dynamic range calibration errors are expected to be the driving factor in radiometric measurement accuracy. A radiometric measurement accuracy within ±5% error should allow a ±15% FRP retrieval accuracy. This performance is considered achievable based on recent studies which demonstrated that an appropriately calibrated microbolometer-based radiometric imager similar to the one baselined in Phase-A could achieve this level of agreement with conventional cooled systems when observing high-temperature radiances from experimental burns (Dufour et al., 2021[14]). Regardless, this accuracy requirement has a trickle-down effect of imposing a need for rigorous pre-launch calibrations over the full dynamic range and periodic gain calibrations in orbit.

[14] Dufour, D, Le Noc, L, Tremblay, B, Tremblay, MN, Généreux, F, Terroux, M, Vachon, C, Wheatley, MJ, Johnston, JM, Wotton, M, Topart, P (2021) A Bi-Spectral Microbolometer Sensor for Wildfire Measurement. Sensors 21, 3690.

The LWIR measurement accuracy is driven by the need to accurately estimate land surface radiances for both ambient and HTE pixels for use in the Dozier method for sub-pixel characterization. The reader will note that the measurement accuracy requirements are far more stringent for the LWIR band at near-ambient temperatures. Estimates of land surface background temperatures derived from the LWIR band will also be used to approximate the MWIR ambient signal using Planck's law which will otherwise have too much uncertainty. With precise measurements of background radiances in the LWIR, approximations in the MWIR and unsaturated HTE radiances in both bands, it is possible to estimate sub-pixel fire area and mean temperature through bi-spectral radiometric analysis. This sub-pixel characterization is essential in accurately characterizing newly detected small fires as well as describing wildfire behaviour in larger fires being monitored.

4.4.4.4. Summary

The sensitivity, precision and accuracy requirements as outlined here meet the threshold requirements of the End-Users, however the overall performance at ambient radiances is limited. It is preferable for scene characterization to be able to discern more subtle variations in ambient surface features in order to contextualize the scene. Overall the NESR values remain at the outer limit of what is useable for these purposes. Every effort must be made to minimize the NESR in both bands. This is the basis for the TDI requirement.

4.4.5. Spatial resolution

The spatial resolution of the MWIR and LWIR bands is noted as a critical variable throughout Section 4. Many of the requirements scale with this area, most importantly because the MWIR and LWIR bands are being used for radiometry (often of sub-pixel events). It is also critical that the ground area being sampled by the MWIR and LWIR remain similar to ensure that the HTE radiances observed are proportionate and vary primarily only due to their spectral properties. This minimizes uncertainties in sub-pixel bi-spectral analysis. Furthermore, the spatial area of these bands must not exceed ~400m as these bands are also the primary tool for estimated fire spread rates which elapse between the VIIRS overpass (~13:00 local solar time) and the WFS observation (~17:00 local solar time). Precision in estimating wildfire ROS is tied to the positional uncertainty of locating the flame front position sub-pixel (amplified by its non-linear structure), as well as the temporal uncertainty of when the spread event occurred and for what duration during the elapsed time. The accuracy of these estimates is also contingent on the speed of the spreading fire being observed. Wildfire ROS varies extensively around its perimeter as well as with even minor changes in wind speed, direction and topography. Generally typical spread rates are well below 20 m/min, but in extreme cases can exceed 100 m/min. Coarser spatial resolutions (or earlier overpass times) would result in only more extreme fire behaviour being detectable, and in the majority of cases preventing estimation of spread rates.

4.4.6. MWIR and LWIR temporal signatures

Even by using the LWIR to describe the background context of HTE pixels detected in the MWIR, the ability to conduct precise contextual analysis in the fire detection algorithm will be somewhat limited by MWIR NESR. As noted previously, the premise of the mission is to provide monitoring support (not specifically detection). However, it is still necessary to reject false positives which have been screened in through the SNR thresholding shown in Figure 4-3. For this reason the Partner End-Users have emphasized the need for additional HTE temporal data to aid in the classification of HTEs (e.g. fires vs volcanos vs sunglint vs industrial sites, etc.).

Field measurements have demonstrated significant turbulence in the emitted radiance of biomass fires, regardless of their size. Such signatures are distinctive and not easily mistaken for the time series of more static emitters, significantly reducing the errors of commission.

In addition to false-positives identification, providing the time series data for the HTE pixels (not all pixels) enables further image processing to improve the accuracy of the fire products, through techniques such as de-aliasing, super-resolution, etc.

4.4.7. MWIR and LWIR dynamic ranges

The MWIR and LWIR bands are intended to collect radiometric measurements of wildfires during the peak burn period. It is of utmost importance that these bands do not saturate, as any saturated pixel will lose all of its value in radiometry. Notably, there has never been an EO satellite system capable of measuring wildfire radiances at the proposed spatial resolution during the peak burning period, that is to say it is not easy to compare this dynamic range with existing systems. Furthermore, it is known that Canadian wildfires even when observed at ~ 10:00 local solar time are the most intense targets in the circumboreal forest (Wooster and Zhang, 2004[15]).

In order to define the saturation point of the system a modelling exercise was conducted. In the proposed scenario a 50 m deep flame front with apparent brightness temperature of 1100 K (accounting for emissivity and heterogeneity) traverses the pixel diagonally, trailed by a 50 m deep cooling burnscar with mean apparent brightness temperature of 400 K, all of which rests on a 300 K background. The arrangement of these zones is such that the flaming area is maximized in the sample area, Figure 4-4.

[15] Wooster MJ, Zhang YH, Boreal forest fires burn less intensely in Russia than in North America, GEOPHYSICAL RESEARCH LETTERS, 2004;31.

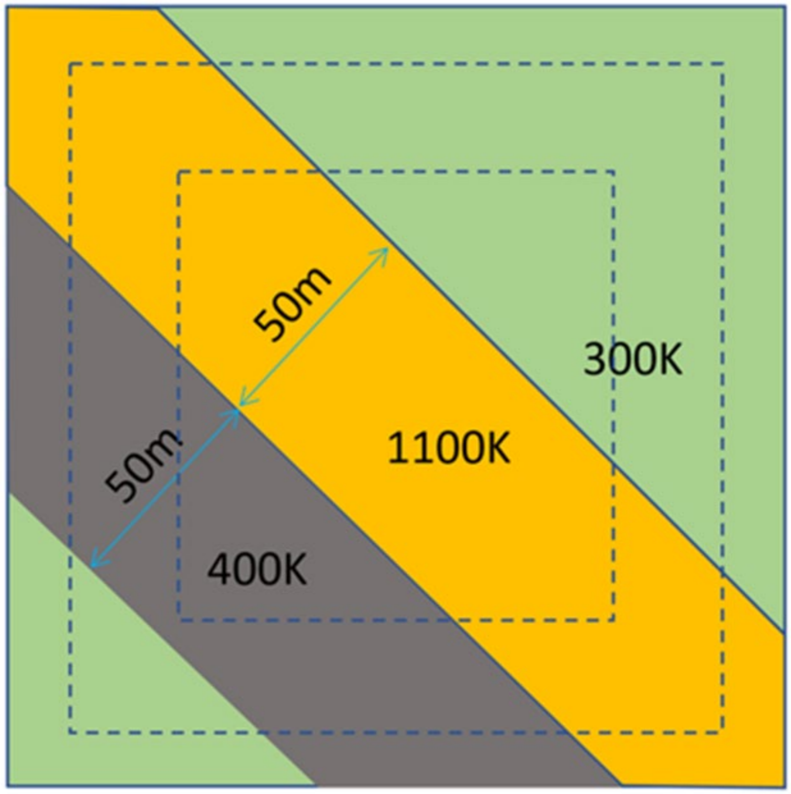

Figure 4-4. Maximum surface level brightness.

The maximum surface level brightness temperature assumes a detector pixel is sensing an intense fire front in such a way as to produce the maximum apparent temperature: the pixel is centered over a diagonal 50 m deep fire line of temperature 1100K, and behind this front there is a smoldering zone 50 m deep with a temperature of 400K.

An estimation of the maximum effective temperature that would be observed by the detector was estimated by considering 1) the complete sampling footprint at the ground level (centered on the scene as shown in Figure 4-4, 2) the radiance of the target area in the wavelength bands of interest assuming it behaves as a perfect blackbody radiator, 3) the ground-projected Point Spread Function of a detector pixel (a series of 2D Gaussian PSFs with different Full Width at Half Maximum (FWHM) values was assumed), and 4) a maximum realistic atmospheric transmittance (90%).

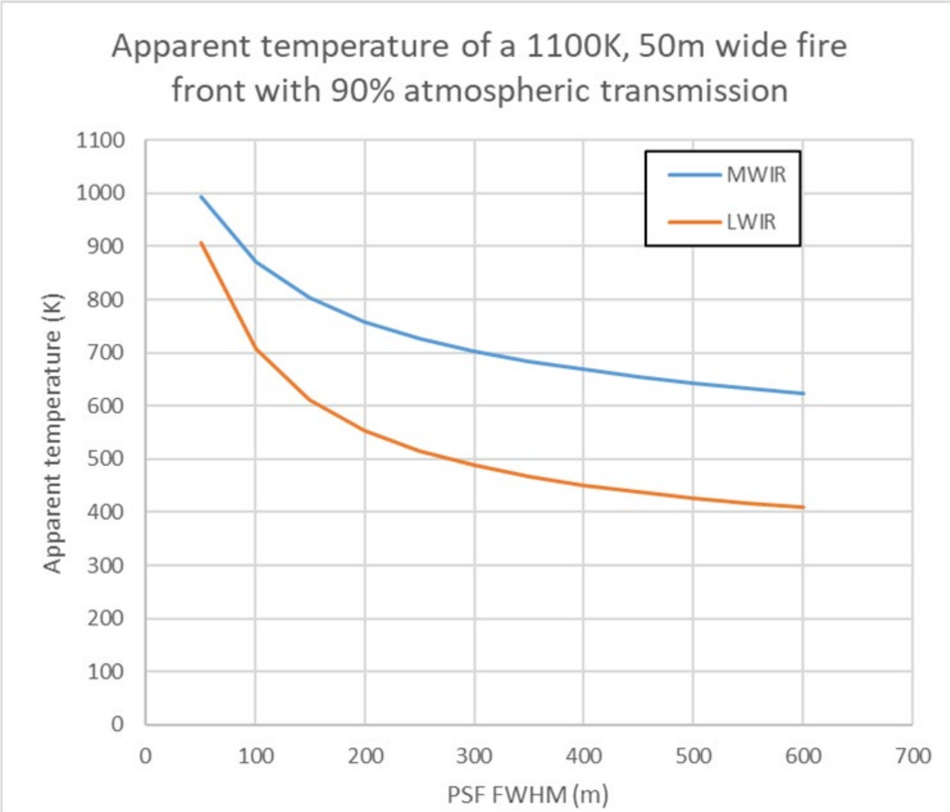

Figure 4-5. Simulated TOA brightness temperatures.
Note: the simulated Top of Atmosphere (TOA) brightness temperatures which can be expected at varying ground-projected spatial resolutions.

There is a strong relationship between spatial resolution and dynamic range as can be seen in Figure 4-5. This simulation is roughly in agreement with the saturation point defined for the VIIRS 750m MWIR band which is used in FRP measurement. The optimum resolution for the WFS mission lies somewhere between 300 and 500 m, since within this interval the sensitivity to ROS is preserved without placing excessive demands on the dynamic range (saturation temperatures ~ 700K). The exact saturation point for the band must be refined through this simulation once all of the spectral and optical properties are known and hence a more accurate PSF can be defined.

4.4.8. VIS/NIR bands

The primary purpose of the VIS/NIR bands is to provide contextual information for use in the active fire detection algorithm (e.g. cloud masking). However, they are also intended for use in identifying previously burned areas, smoke columns, and adjacent zones where significant changes have occurred in the forest fuels.

These bands must be capable of observing boreal forest reflected radiances at the time of a peak burn overpass. It is critical that these data are provided coincident with the MWIR and LWIR bands and covering the full swath as it is not possible to execute the detection algorithm without a cloud mask which spans the full MWIR dataset. There is a need for stability between observations collected in successive days of observation, and a basic level of pre-flight radiometric calibration. Throughout the mission life the Partner End-Users intend to execute periodic vicarious calibrations to maintain this calibration if and when required.

To define the radiance dynamic range requirements for the VIS/NIR bands, the following maximum and minimum scene brightness were assumed:

1. Maximum Brightness: Sunlight reflecting off a cloud (assumed to be a Lambertian diffuser with albedo=1), for the lowest late-afternoon Zenith Angle (52^{o}, corresponding to a 45^{o}N location on June 21st).

2. Minimum Brightness: Sunlight reflecting off a dark land surface (assumed to be a Lambertian diffuser with albedo = 0.1), for a high late-afternoon Zenith Angle (80^{o}, corresponding to a 60^{o}N location on September 1st).

An adequate Signal to Noise Ratio (SNR) is also required to identify burn scars from surrounding terrain. A scenario was considered where a burn scar (albedo = 5 %) was to be discriminated from a black spruce forest (albedo = 10%). A dark illumination scenario (solar zenith = 80^{o}) was assumed, and thereby the reference radiance level was calculated by considering the Earth diffuse reflectance for a surface albedo of 5% (burn scar).

The required SNR at this level was calculated knowing that the end goal is to identify pixels with at least 75% burned area to be labelled as a "Burn" pixel. Assuming we want the noise level to be low enough to resolve 5% burn area per pixel, then the corresponding albedo difference between a 100% forest pixel and a 95% forest + 5% burn pixel is:
The corresponding SNR level at the burn scar reference albedo level is 0.05/0.0025 = 20. Therefore, a minimum SNR value of 20 is required for the dark-illuminated reference scenario.

4.4.9. Co-registration requirements

An emphasis is placed on cross band co-registration in all possible definitions. In summary, all of the bands must be compared directly to one another for a specific target location on the ground. This multispectral analysis must be possible across the entire swath. This requires a close alignment of the centroids of each pixel. In the case of the MWIR and LWIR the requirement is even more stringent due to the intimate interaction of the two bands in compensation for the elevated MWIR NESR, and because we must also be certain that we are measuring the radiance from near identical ground areas. This is of particular importance in implementing the sub-pixel characterization of fire temperature and area (Dozier, 1981[16]) which is known to be highly sensitive to co-registration errors (Giglio and Kendall, 2001[17]). For this reason the pointing knowledge of coincident MWIR and LWIR pixels must be highly accurate. To illustrate, Figure 4-6 shows the effect of misalignment of the projected image of a small sub-pixel HTE with respect to a detector pixel's center on the amount of energy captured by said pixel (ensquared energy). The scenario assumes near diffraction-limited optics in the LWIR band

[16] Dozier J, A Method for Satellite Identification of Surface Temperature Fields of Subpixel Resolution, Remote Sensing of Environment, 1981;11: 221-29.
[17] Giglio L, Kendall JD, Application of the Dozier retrieval to wildfire characterization: a sensitivity analysis, Remote Sensing of Environment, 2001;77: 34-49.

and a 28 µm pixel pitch (for perfect alignment of the HTE image with the pixel the ensquared energy fraction is seen to be 80%). Under these conditions, expected to be typical and achievable, a maximum slope of 1 for the ensquared energy fraction versus pixel misalignment fraction of can be seen. Therefore, to keep the subpixel radiance error due to pointing to less than 15%, a value deemed acceptable for applying the Dozier method, the pointing knowledge should be better than 15% of the IFOV.

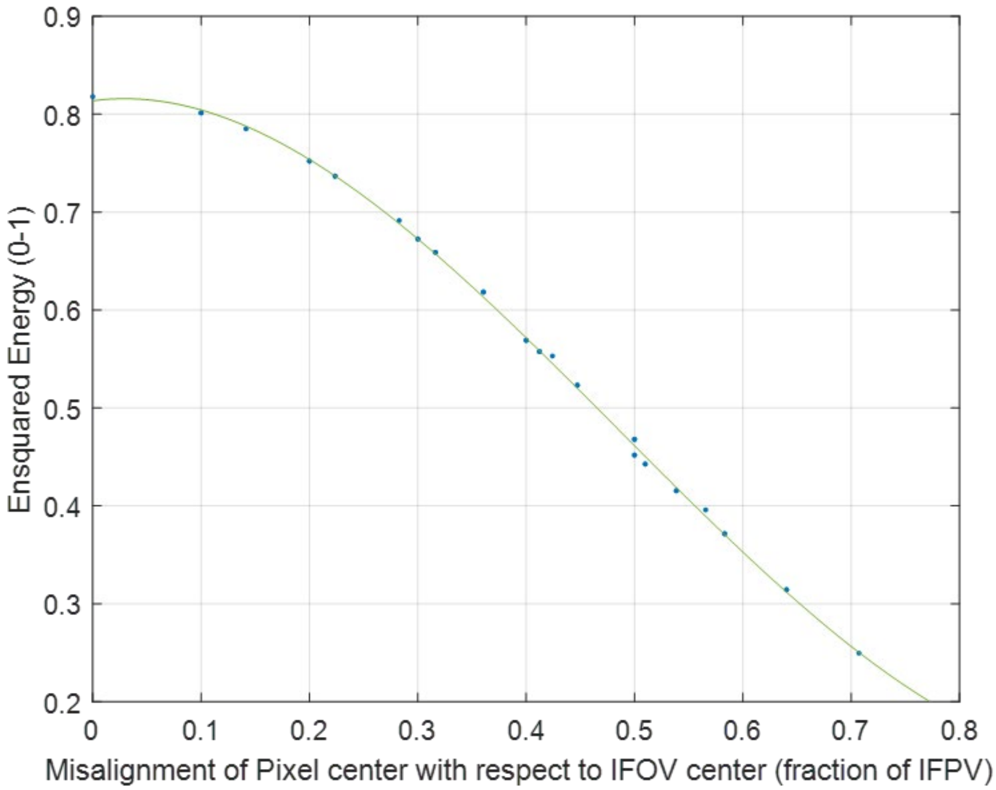

Figure 4-6. Effect of misalignment of a point source on the ensquared energy captured by a pixel.

The angle of observation is also relevant in the co-registration of the VIS/NIR image with the corresponding MWIR/LWIR images. Accurate VIS/NIR to MWIR/LWIR image co-registration ensures that the VIS/NIR-derived cloud mask correctly identifies the MWIR/LWIR pixels to be removed from analysis. Thereby the angle of observation (i.e. the co-elevation angle) must be constrained to avoid excessive cloud masking parallax errors due to the altitude of the clouds with respect to the ground. A maximum co-elevation angle requirement of 30 degrees ensures the impact of parallax errors on cloud masking are minimized. At a 30 degree co-elevation view angle, a simple geometric calculation shows that a cloud at an altitude of 700m would be offset by a distance equivalent to the targeted GIFOV distance (400 m) when projected to the ground, i.e. corresponding to a 1-pixel error.

Finally, the temporal instability of wildfire energy imposes constraints on temporal co-registration of the MWIR/LWIR bands in addition to spatial registration. Ideally a temporal overlap is required for the MWIR and LWIR signals to properly account for wildfire energy fluctuations which occur at large and small temporal and spatial scales. However, given that micro fluctuations in emitted flame front energy will be averaged over the entire pixel area, the primary driver of temporal energy variations are changes in fire behaviour. As such minor temporal gaps (e.g. ~ 5-10 seconds) between the two bands may be permissible.

4.4.10. Data latency

The highly dynamic wildfire operational response environment creates a scenario in which data becomes obsolete at a very high rate. Johnston et al., (2020[18]) surveyed Canadian fire managers to determine their needs with regards to data latency for WFS. In that study it was found that 30min data latency was the threshold for tactical applications of surveillance data, and at 2 hours the data became obsolete for strategic applications (necessitating receipt of the data within ~1hr to enable its use). But also, in order to be usable in operations it needs to be available to the End-Users prior to 18:00 and 06:00 (local solar time) daily to fit with decision making cycles. Data latency must take into account the local over pass time and the additional processing required by the Partner End-Users to transform the Level-1b Science Data Products into usable Science Data Products (Section 4.1).

At the time of Phase-0, typical data latencies for active fire products ranged from 1 hour to > 3 hours, limiting their utility in fire management operational response (MNP, 2017[19]). Since then this situation has changed dramatically, and as of June 2022 NASA is now producing MODIS and VIIRS active fire products in under 60 seconds for Canada and the United States[20]. This calls into question whether the definition of "near real-time" should be updated. Even still, at present the intent remains to deliver WFS Level-1b data to the SOC within 20 min in order to meet the need for 30 min data latency to the End-Users. However, the need to achieve the lowest latency possible for the mission cannot be over emphasized.

[18]Johnston JM, Jackson N, McFayden C, Ngo Phong L, Lawrence B, Davignon D, Wooster MJ, van Mierlo H, Thompson DK, Cantin AS, Johnston D, Johnston LM, Sloane M, Ramos R, Lynham TJ, Development of the User Requirements for the Canadian WildFireSat Satellite Mission, Sensors, 2020;20.

[19]MNP. A review of the 2016 Horse River Wildfire: Alberta Agriculture and Forestry Preparedness and Response. Edmonton, Alta., MNP LLP, 2017.

[20] https://www.earthdata.nasa.gov/news/feature-articles/firms-adds-ultra-real-time-data-from-modis-viirs

4.4.11. Minimum Field of View

In order to detect wildfires in the imagery it is important to have accurate contextual information of the portions of the scene which are not burning. Background pixels which are not cloud obscured are of central importance to automated contextual fire detection algorithms (e.g. Roberts and Wooster, 2008[21]; Wooster et al., 2012[22]; Schroeder et al., 2014[23]; Giglio et al., 2016[24]; Xu et al., 2020[25]). It is not possible to state an explicit minimum swath necessary to meet this requirement as the diameter of the fire targets vary dramatically from sub-pixel events to over 1M hectares. There is however no precedence for automating a contextual fire detection algorithm with the spectral bands on WFS when using a swath smaller than 1400km in the context of an operational mission (Sentinel-3, SLSTR). Notably, the German Aerospace Center's (DLR) Technology Experiment Carrier-1 (TET-1) (178km swath) collected experimental data at a smaller swath than the minimum threshold of 200 km for WFS, though no automated contextual fire detection products are known to have been implemented.

Precedence is not necessarily a driver for demanding a minimum swath width for WFS, however there are a number of practical considerations which must also be weighed. In the absence of a minimum swath requirement one can envision a scenario in which a swarm of hosted payloads or pico-sats would deliver data with extremely narrow co-elevation angles. Though well intended, such a scenario would prevent the Partner End-Users from sampling background pixels from the same detector package (which is essential at this level of data processing). Furthermore, the calibration and mosaicking of an excess number of datasets would be logistically and computationally impractical and result in substantial rises in data latency. It is not the place of the Partner End-Users to determine the optimum number of payloads or platforms necessary to deliver the mission. Rather, the constraints defined here only relate to the suitability of the data and the practicalities of processing it effectively. Ultimately, the requirement of a 200 km minimum swath is driven by the probability of capturing a large fire within a single swath. Typically, remote Canadian wildfires requiring routine monitoring grow to very large sizes over time. The minimum swath width here is such that a 150k Ha fire has a 75% chance of being captured within the swath if it is perfectly circular and ~ 50% probability of being contained within the swath if it is elongated with a length to breadth ratio of 2.5. This

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[21] Roberts G, Wooster MJ, Fire Detection and Fire Characterization Over Africa Using Meteosat SEVIRI, IEEE Transactions on Geoscience Remote Sensing, 2008;46: 1200-18.

[22] Wooster MJ, Xu W, Nightingale T, Sentinel-3 SLSTR active fire detection and FRP product: Pre-launch algorithm development and performance evaluation using MODIS and ASTER datasets, Remote Sensing of Environment, 2012;120: 236-54.

[23] Schroeder W, Oliva P, Giglio L, Csiszar IA, The New VIIRS 375 m active fire detection data product: Algorithm description and initial assessment, Remote Sensing of Environment, 2014;143: 85-96.

[24] Giglio L, Schroeder W, Justice CO, The Collection 6 MODIS Active Fire Detection Algorithm and Fire Products, Remote Sens Environ, 2016;178: 31-41.

[25] Weidong Xu, Martin J. Wooster, Jiangping He, Tianran Zhang, First study of Sentinel-3 SLSTR active fire detection and FRP retrieval: Night-time algorithm enhancements and global intercomparison to MODIS and VIIRS AF products, Remote Sensing of Environment, Volume 248, 2020: 111947.

definition also ensures that in the majority of scenarios sufficient background pixels will exist to conduct contextual analysis (allowing for losses to cloud, and adjacent fires).

5. MISSION REQUIREMENTS

The nomenclature for the WFS mission requirements is of the following structure:
WFS-MRD-[CATEGORY]-[ID]

Where

- [CATEGORY] can take the following values:
  - FUN for functional requirements
  - OPE for operational requirements
  - CON for constraints
  - [ID] is a sequential number corresponding to the requirement for the given category.

Each requirement is presented using the following structure:
WFS-MRD-[CATEGORY]-[ID] Title

Requirement statement.

Rationale: Description of the rationale of the requirement.

The convention for the wording of the requirements statements is as follows:

- "SHALL" and "SHALL NOT" indicate a (mandatory) requirement.
- "SHOULD" and "SHOULD NOT" indicate a goal or preferred alternative. Such goals or alternatives must be treated as requirements on a best efforts basis, and verified as for other requirements. The actual performance achieved must be included in the appropriate verification report, whether or not the goal performance is achieved.
- "MAY" and "NEED NOT" indicate a permission or option.
- "WILL" indicates a statement of fact or intention.

5.1 FUNCTIONAL AND PERFORMANCE REQUIREMENTS

5.1.1. Coverage

WFS-MRD-FUN-010 Coverage during Peak Burning Period
The mission SHALL provide the capability to observe, for every day, between 16:30 and 18:00 local solar time:

- at least 80% of the Canadian AoI Zone A region (as defined in D-1), and
- at least 90% of the Canadian AoI Zone B region (as defined in D-1).

Rationale: This requirement is derived from the users' needs and based on the actual maximum co-elevation angle requirement (WFS-MRD-FUN-030). Covering all points in the Canadian AoI during the peak burning period within 24 hours is overly constrictive, given the co-elevation angle limitation of WFS-MRD-FUN-030. The requirement is thus expressed in terms of percent daily coverage that is readily achievable considering WFS-MRD-FUN-030.

This requirement explicitly identifies an overpass time period to ensure a sufficient temporal offset from the VIIRS data, while enabling WFS data delivery prior to the operational decision-making time. For the purpose of fire behaviour monitoring the optimal observation time is the center of the period (~17:00 local solar time). An earlier overpass would reduce the temporal offset from VIIRS and would consequently reduce the number of detectable spread events and have negative impacts to core fire behaviour monitoring products of WFS. A later overpass time could negatively impact timely data delivery for the operational decision-making time requirement of 1800 LST (1900 LDT).

WFS-MRD-FUN-011 Coverage outside Peak Burning Period

The mission SHALL provide the capability to observe the same regions as of WFS-MRD-FUN-010, during the reciprocal orbital overpass, i.e. during the morning period.

Rationale: The observation during the morning is also of interest in operational wildfire management applications. As such the Partner End-Users intend to use the data collected during both the Local Time of Ascending Node (LTAN) and Local Time of descending Node (LTDN) in product applications.

WFS-MRD-FUN-012 Total Coverage

The mission SHALL provide the capability to observe 100% of the Canadian AoI during any 3 consecutive peak burning periods.

Rationale: Based on the actual maximum co-elevation angle requirement (WFS-MRD-FUN-030). While gaps in 24-hour coverage are expected, the orbit should be selected such that coverage gaps do not persist for more than 3 days. The fire season in Canada is currently between March 1st and October 31st. However, due to climate changes, this period will change over time. The coverage need outside the fire season is thus less than what is stated in this requirement.

WFS-MRD-FUN-013 Coverage Scalability

The mission SHALL provide the capability to image all year round, over the entire vegetated area of the Earth. The shapefile describing this area is available upon request.

Rationale: Due to the international interest of wildfire data, there is a high probability that the mission will be used to fulfill international partner's needs as well as commercial interest. However, the intent of this requirement is not to drive the design by imposing a specific coverage every X days, but to enable the mission to be used to image over international vegetated areas to the maximum extent possible given the system capabilities. The achievable global coverage is expected to be provided as a compliance evidence to this requirement.

WFS-MRD-FUN-015 Deleted

WFS-MRD-FUN-020 Deleted

WFS-MRD-FUN-022 Consistent Observation Time during Peak Burning Period

The mission SHALL provide the observations defined in WFS-MRD-FUN-010 at the same time of the day, with a maximum variation of 30 minutes drift over the as-designed operational mission lifetime.

Rationale: The fire behaviour product quality is largely dependent on the VIIRS overpass time, and therefore the difference in overpass time between VIIRS and WFS has to be stable. Furthermore, multiple Tier-1 algorithms are sensitive to solar angle variations.

WFS-MRD-FUN-030 Maximum Co-Elevation Angle

The maximum co-elevation angle (defined in D-4) for each pixel of each instrument SHALL not exceed 30 degrees for observations to be considered valid.

Rationale: See Section 4 for a discussion on the effect of co-elevation angle on data quality.

WFS-MRD-FUN-035 Deleted

WFS-MRD-FUN-040 Minimum across track FOV

The effective across track FOV for each of the spectral bands defined in WFS-MRD-FUN-060 SHALL be greater than or equal to 200 km.

Rationale: A minimum swath width of 200 km is the minimum required to get a 75% chance of fully capturing an elliptical 150,000 hectare fire. This fire size is characteristic of a large fire requiring routine monitoring. This swath size allows for the fire to be captured while including enough background pixels to enable contextual analysis in the active fire detection and characterization algorithms. Section 4 provides more details. Note that a smaller FOV would require additional image stitching on the ground in order to capture the required size of fires; any non-compliance with the across-track FOV requirement would need to be analyzed end-to-end before deciding whether it can be accepted.

WFS-MRD-FUN-050 Swath O**verlap Across Bands**

The ground-projected across-track FOV swaths for all bands defined in WFS-MRD-FUN-060 SHALL overlap.

Rationale: The Partner End-Users require co-located data from all bands described in WFS-MRD-FUN-060 for automated fire extraction processing.

5.1.2. Instrument

WFS-MRD-FUN-060 Spectral Bands

The payload SHALL provide for acquisition of radiance image data in each of the following spectral ranges:

- MWIR: Includes 3.9 µm wavelength and is as narrow as possible within the bounds:
  - Lower bound ≥ 3.4 µm
  - Upper bound ≤ 4.15 µm
- LWIR: one or more bands within the 8.2-9.2 µm and/or 10.1 – 12.4 µm atmospheric windows.
- Visible (VIS): 0.57 - 0.73 µm (red), 0.37 - 0.53 µm (blue), 0.47 - 0.63 µm (green)
- Near Infrared (NIR): 0.77 – 0.93 µm

Note: Refer to WFS-MRD-FUN-070, WFS-MRD-FUN-071, WFS-MRD-FUN-072, WFS-MRD-FUN-073, WFS-MRD-FUN-074, WFS-MRD-FUN-075, WFS-MRD-FUN-076, WFS-MRD-FUN-077, WFS-MRD-FUN-078 and WFS-MRD-FUN-079 for detailed spectral response requirements.

Rationale: Derived from user's needs to reflect refinement of spectral bands requirements done in phase A. The LWIR band(s) is required for bi-spectral radiometric analysis, and has to be above 8 µm to ensure sufficient separation from the MWIR. However, the precise placement of the LWIR band(s) is not prescribed here providing that it is restricted to an atmospheric window within the defined range. Some overlap of the VNIR bands is acceptable for the intended application. Furthermore, this allows more flexibility in using COTS filters rather than having to develop custom ones.

WFS-MRD-FUN-065 Deleted

WFS-MRD-FUN-070 MWIR Band Relative Spectral Response

The MWIR band SHALL have a normalized relative spectral response between the upper bound and the lower bound defined in Table 5-1 and shown in Figure 5-1.

Rationale: Derived from user's needs to reflect refinement of spectral bands requirements done in phase A.

TABLE 5-1. MWIR RELATIVE SPECTRAL RESPONSE REQUIREMENTS

Wavelength (µm)	Lower Bound	Upper Bound
3.30		0.0
3.35		0.0
3.40		0.2
3.45		0.6
3.50		0.8
3.55		1.0
3.7		1.0
3.75	0.0	1.0
3.80	0.0	1.0
3.85	0.6	1.0
3.90	0.8	1.0
3.95	0.6	1.0
4.00	0.0	1.0
4.05		1.0
4.10		0.8
4.15		0.2
4.20		0.0

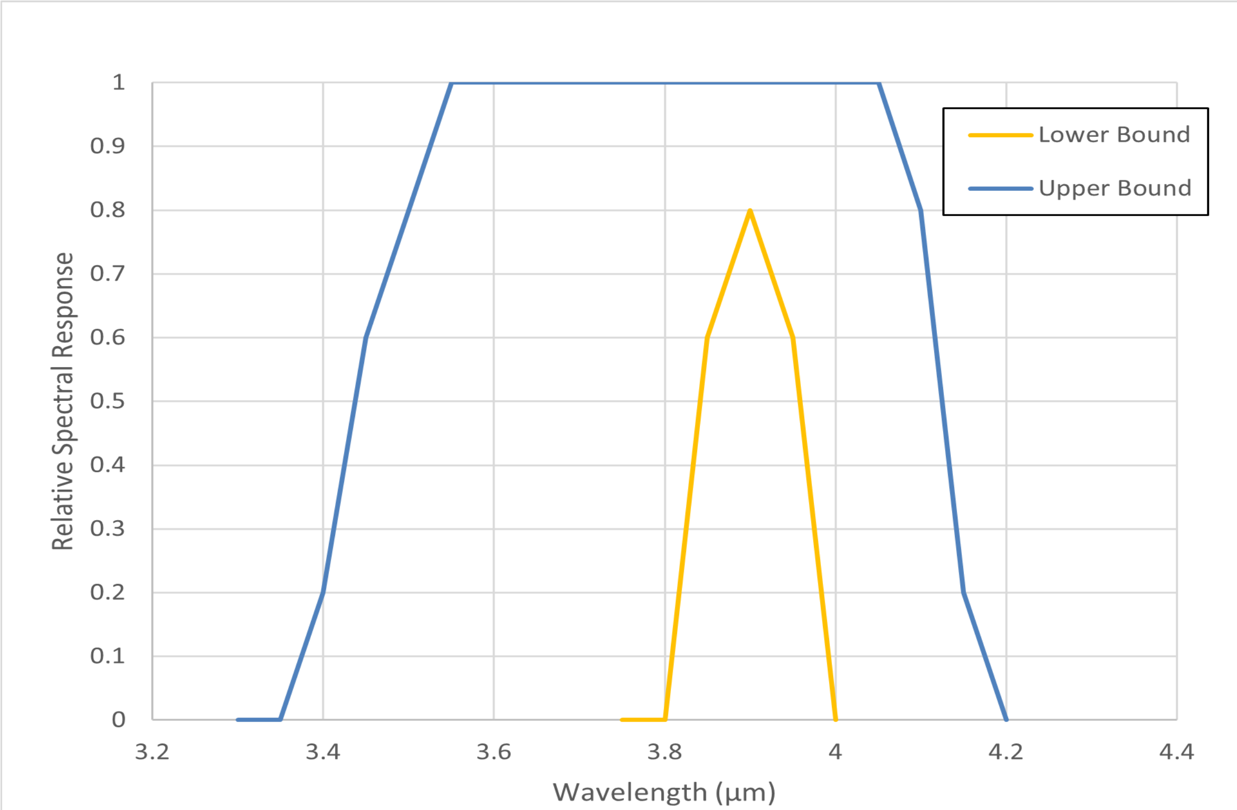

Figure 5-1. MWIR relative spectral response bounds.

WFS-MRD-FUN-071 Deleted

WFS-MRD-FUN-072 MWIR Out-of-Band Response

The contribution of out-of-band radiance from all sources SHALL be less than 50% of the 1-sigma in-band noise equivalent radiance.

The out-of-band radiance is defined as the radiance contained in the spectral range from 1 to 50 µm excluding the MWIR spectral response portion specified in the requirement WFS-MRD-FUN 070.

Rationale: Detailed specification of band characteristics.

WFS-MRD-FUN-073 **LWIR Band Relative Spectral Response**

The LWIR band(s) SHALL have a normalized relative spectral response within one or more of the upper bounds defined in Table 5-2 and shown in Figure 5-2.

Rationale: In order to reliably collect radiometric measurements of land surface temperatures for use in support of the MWIR band for fire detection and characterization and for bi-spectral radiometric analysis of sub-pixel high temperature events, one or more LWIR spectral bands are required. The precise positioning of this band(s) within the specified wavelength range can be optimized during the design to accommodate a range of optical designs.

TABLE 5-2. LWIR RELATIVE SPECTRAL RESPONSE REQUIREMENTS

Wavelength (µm)	Upper Bound
8.15	0
8.2	0.2
8.25	0.4
8.3	0.6
8.35	0.8
8.4	1
8.45	1
8.5	1
8.55	1
8.6	1
8.65	1
8.7	1
8.75	1
8.8	1
8.85	1
8.9	1
8.95	1
9	1
9.05	0.8
9.1	0.6
9.15	0.4
9.2	0.2
9.25	0,0
10.05	0,0
10.1	0.2
10.15	0.4
10.2	0.6

Wavelength (µm)	**Upper Bound**
10.25	0.8
10.3	1
10.35	1
10.4	1
10.45	1
10.5	1
10.55	1
10.6	1
10.65	1
10.7	1
10.75	1
10.8	1
10.85	1
10.9	1
10.95	1
11	1
11.05	1
11.1	1
11.15	1
11.2	1
11.25	1
11.3	1
11.35	1
11.4	1
11.45	1
11.5	1
11.55	1
11.6	1
11.65	1
11.7	1
11.75	1
11.8	1
11.85	1
11.9	1
11.95	1
12	1
12.05	1
12.1	1
12.15	1

Wavelength (µm)	Upper Bound
12.2	1
12.25	0.8
12.3	0.6
12.35	0.4
12.4	0.2
12.45	0.0

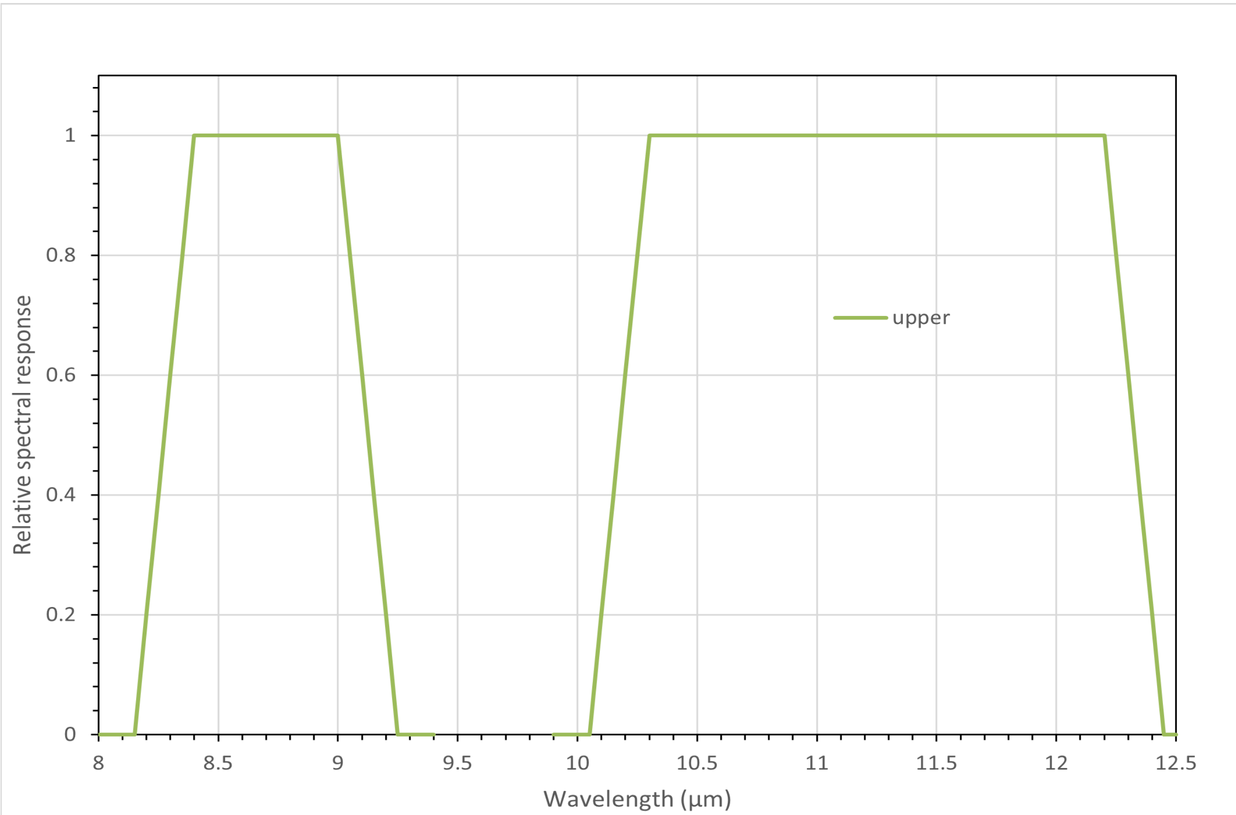

Figure 5-2. LWIR relative spectral response bounds.

WFS-MRD-FUN-074 LWIR Out-of-Band Response
The contribution of out-of-band radiance from all sources SHALL be less than 50% of the 1-sigma in-band noise equivalent radiance.

The out-of-band radiance is defined as the radiance contained in the spectral range from 1 to 50 µm excluding the LWIR spectral response portion specified in the requirement WFS-MRD-FUN 073.

Rationale: Detailed specification of band characteristics.

WFS-MRD-FUN-075 VIS (Red) Band Relative Spectral Response

The VIS (Red) band SHALL have a normalized relative spectral response within the threshold upper bound defined in Table 5-3 and shown in Figure 5-3.

Rationale: Detailed specification of band characteristics.

TABLE 5-3. VIS (RED) RELATIVE SPECTRAL RESPONSE REQUIREMENTS

Wavelength (µm)	Upper Bound
0.55	0.0
0.57	1.0
0.59	1.0
0.61	1.0
0.63	1.0
0.67	1.0
0.69	1.0
0.71	1.0
0.73	1.0
0.75	0.0

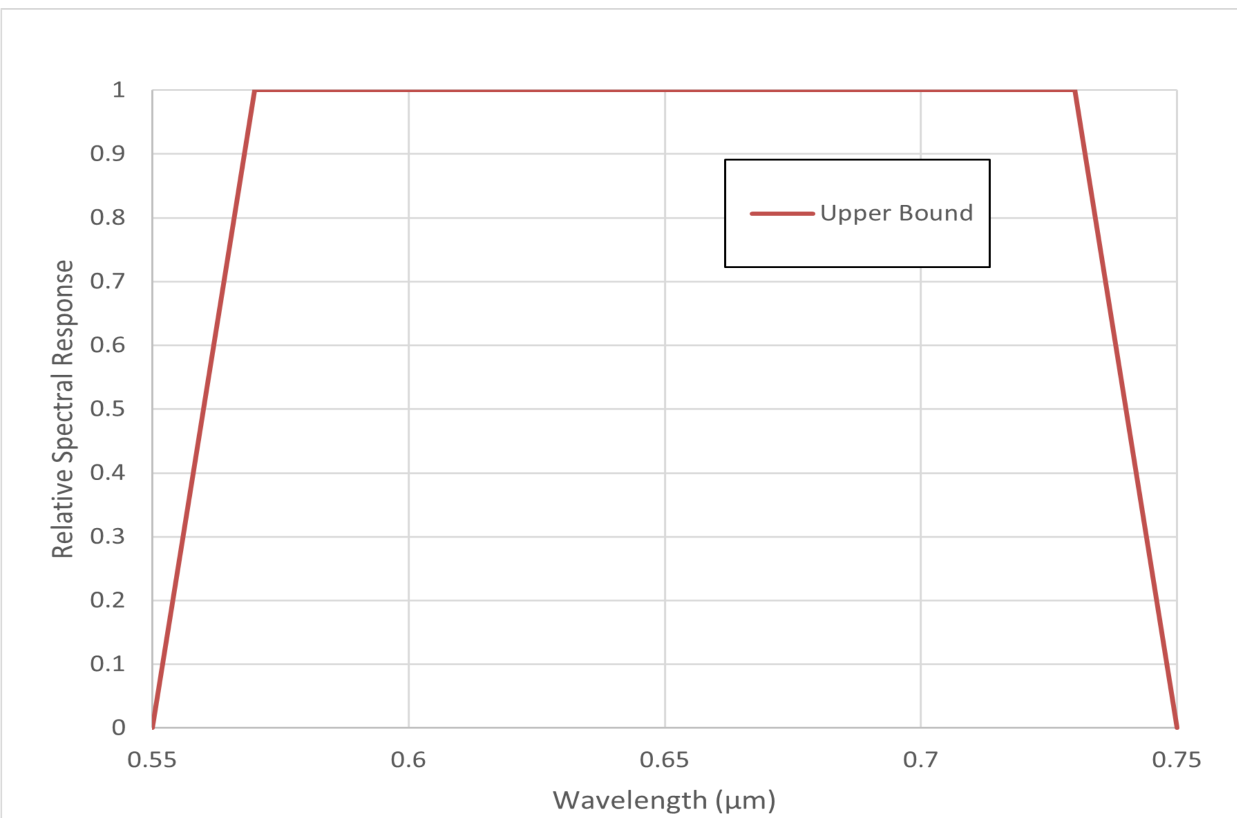

Figure 5-3. VIS (red) relative spectral response bounds.

WFS-MRD-FUN-076 NIR Band Relative Spectral Response
The NIR band SHALL have a normalized relative spectral response within the threshold upper bound defined in Table 5-4 and shown in Figure 5-4.

Rationale: Detailed specification of band characteristics.

TABLE 5-4. NIR RELATIVE SPECTRAL RESPONSE REQUIREMENTS

Wavelength (µm)	Upper Bound
0.75	0.0
0.77	1.0
0.79	1.0
0.81	1.0
0.83	1.0
0.87	1.0
0.89	1.0
0.91	1.0
0.93	1.0
0.95	0.0

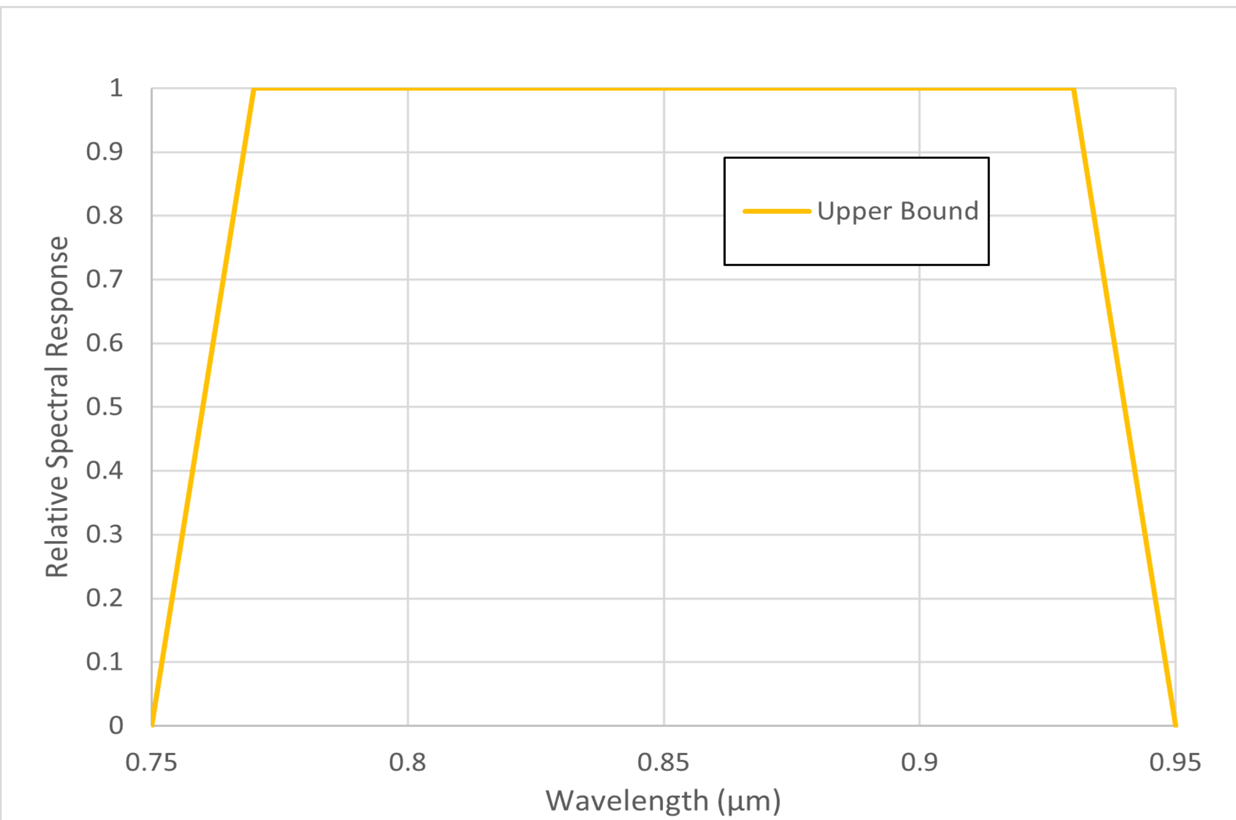

Figure 5-4. NIR relative spectral response bounds.

WFS-MRD-FUN-077 VIS (Blue) Band Relative Spectral Response

The VIS (Blue) band SHALL have a normalized relative spectral response within the threshold upper bound defined in Table 5-5 and shown in Figure 5-5.

Rationale: Detailed specification of band characteristics.

TABLE 5-5. VIS (BLUE) RELATIVE SPECTRAL RESPONSE REQUIREMENTS

Wavelength (µm)	Upper Bound	
0.35	0.0	
0.37	1.0	
0.39	1.0	
0.41	1.0	
0.43	1.0	
0.47	1.0	
0.49	1.0	
0.51	1.0	
0.53	1.0	
0.55	0.0	

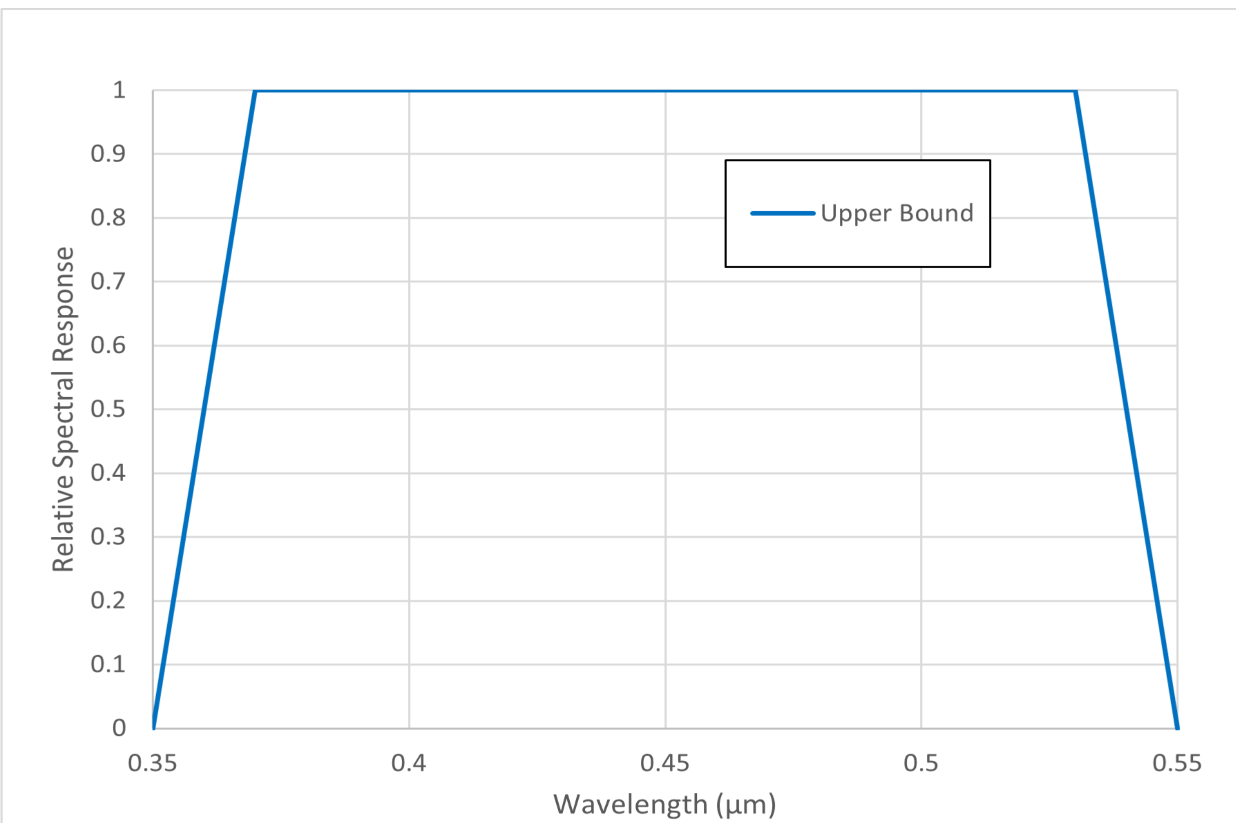

Figure 5-5. VIS (blue) relative spectral response bounds.

WFS-MRD-FUN-078 VIS (Green) Band Relative Spectral Response

The VIS (Green) band SHALL have a normalized relative spectral response within the threshold upper bound defined in Table 5-6 and shown in Figure 5-6.

Rationale: Detailed specification of band characteristics.

TABLE 5-6. VIS (GREEN) RELATIVE SPECTRAL RESPONSE REQUIREMENTS

Wavelength (µm)	Upper Bound
0.45	0.0
0.47	1.0
0.49	1.0
0.51	1.0
0.53	1.0
0.57	1.0
0.59	1.0
0.61	1.0
0.63	1.0
0.65	0.0

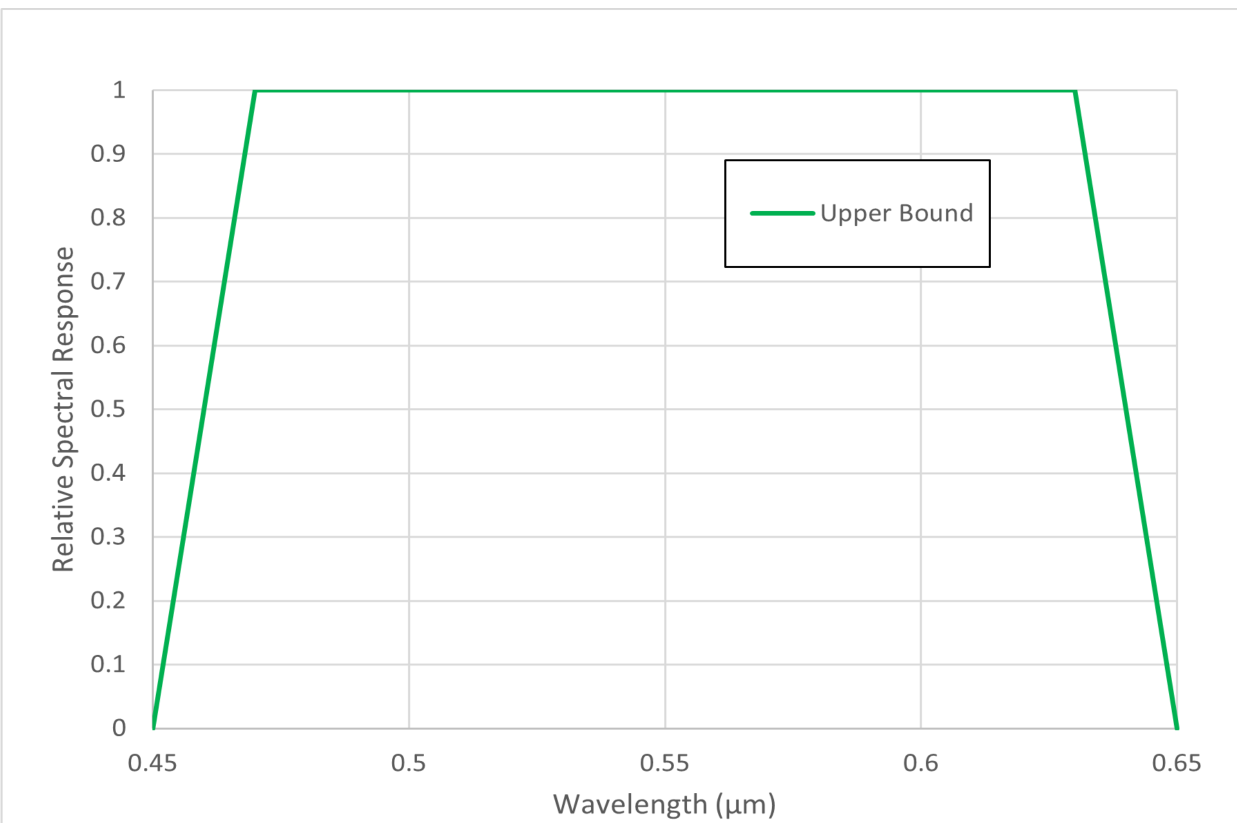

Figure 5-6. VIS (green) relative spectral response bounds.

WFS-MRD-FUN-079 VIS/NIR Out-of-Band Response

The contribution of out-of-band radiance from all sources SHALL be less than 50% of the 1-sigma in-band noise equivalent radiance.

Note: The VIS/NIR out-of-band spectral region is the entire range between 0.1 µm and 3 µm, excluding the regions within the bounds specified in the requirements WFS-MRD-FUN 076, WFS-MRD-FUN-077 and WFS-MRD-FUN-078.

Rationale: Detailed specification of band characteristics

WFS-MRD-FUN-080 Deleted

WFS-MRD-FUN-090 MWIR and LWIR Dynamic Range

The MWIR and LWIR bands of the radiometric imager SHALL be capable of measuring, within their radiometrically calibrated ranges, targets with apparent brightness temperatures in the range of at least 275 K to the apparent temperature for the scenario described in the Rationale.

Note: In the event that the design relies on co-adding of finer spatial resolution data to deliver the final GIFOV, this requirement is applied to the smallest GIFOV sampling element contributing to the functional GIFOV in order to prevent saturation of the system.

Rationale: The maximum surface level brightness temperature assumes a detector pixel is sensing an intense fire front in such a way as to produce the maximum apparent temperature: the pixel is centered over a diagonal 50 m deep fire line of temperature 1100K, and behind this front there is a smoldering zone 50 m deep with a temperature of 400K, as shown in Figure 5 6. A dry atmosphere, corresponding to a transmission factor from ground to the satellite of 90% in both MWIR and LWIR bands, is assumed in this scenario.

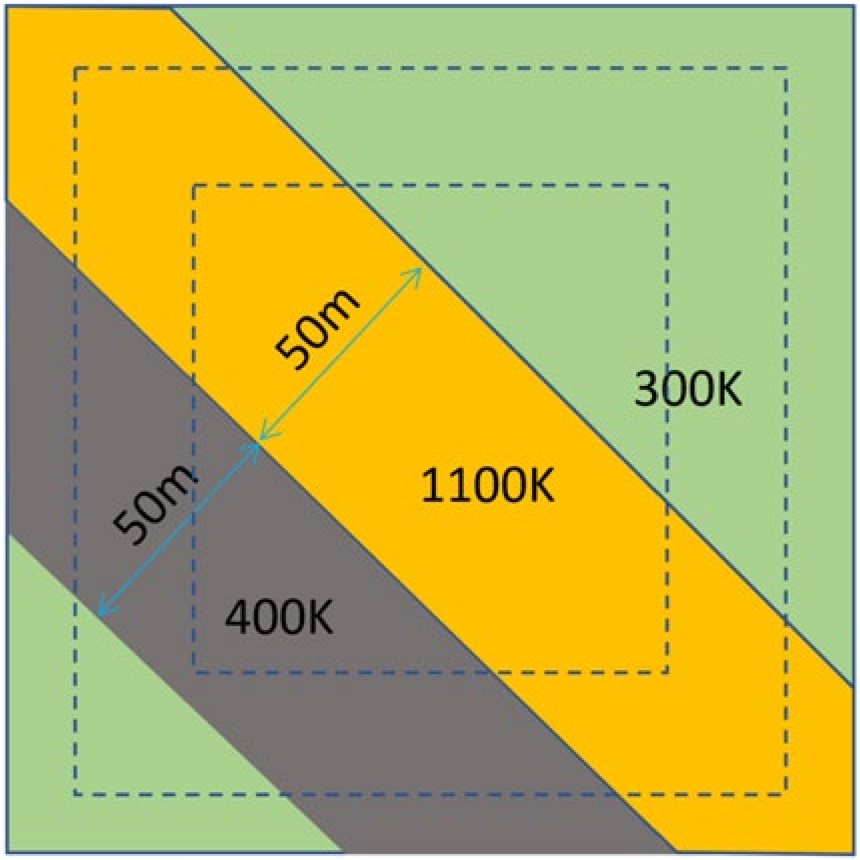

Figure 5- 7. Intense fire front scenario.

WFS-MRD-FUN-095 Deleted

WFS-MRD-FUN-100 Deleted

WFS-MRD-FUN-105 Deleted

WFS-MRD-FUN-110 VIS/NIR Dynamic Range

The dynamic range of the VIS and NIR radiometric imaging system SHALL minimally span the following TOA values:

- VIS 0.55 – 0.75 µm (red): 0.66 - 235 W m^{-2} sr^{-1} μm^{-1}
- NIR 0.75 – 0.95 µm: 0.44-157 W m^{-2} sr^{-1} μm^{-1}
- VIS 0.35 – 0.55 µm (blue): 0.72-255 W m^{-2} sr^{-1} μm^{-1}
- VIS 0.45 – 0.65 µm (green): 0.72-255 W m^{-2} sr^{-1} μm^{-1}

Rationale: See section 4 for details. The maximum radiance levels correspond to sunlight reflecting off clouds at a low solar zenith angle (52o), and the minimum levels corresponds to sunlight reflecting off a dark ground surface (burn scar) at a high solar zenith angle (80^o).

WFS-MRD-FUN-111 Deleted

WFS-MRD-FUN-112 Multispectral Capability
The payload SHALL allow multispectral analysis including all the bands (MWIR, LWIR, VIS/NIR) for 100% of the ground points within the swath.

Rationale: This requirement is to ensure that there are enough operable pixels to observe all targets falling within the field of view.

WFS-MRD-FUN-113 VIS/NIR Adjustable Dynamic Range
The dynamic range of the VIS and NIR radiometric imaging system SHALL be adjustable during operational use.

Note: The desirable minimum adjustment range will be defined by the Contractor during Phase B in collaboration with CFS and captured in the payload requirements.

Rationale: There is currently some uncertainty about the optimal dynamic range for cloud masking application, therefore a way to adjust the dynamic range, for example by changing the detector gain and/or integration time, is required. In addition, the optimal VIS/NIR dynamic range setting may vary depending on the exact local time and time of year of the overpass.

WFS-MRD-FUN-115 Deleted

WFS-MRD-FUN-116 Deleted

WFS-MRD-FUN-117 Deleted

WFS-MRD-FUN-120 MWIR Noise Equivalent Spectral Radiance
Prior to noise corrections, the mean NESR of all the operable pixels SHALL be smaller than 0.15 W m^{-2} sr^{-1} μm^{-1} in the MWIR band. The NESR for a pixel is here defined as the 1-sigma standard deviation of the radiance measured over a 1 second period.

Rationale: The NESR threshold corresponds to an NETD of 7 K at 300K in the MWIR band, before noise corrections are applied. This is the maximum NETD that will allow, once TDI noise corrections are applied to reduce the effective NETD, to discriminate between different large-scale features on the ground (e.g. forest, lakes).

WFS-MRD-FUN-125 Deleted

WFS-MRD-FUN-121 LWIR Noise Equivalent Spectral Radiance

Prior to noise corrections, the mean NESR of all the operable pixels SHALL be smaller than 0.04 W m^{-2} sr^{-1} μm^{-1} in the LWIR band. The NESR for a pixel is here defined as the 1-sigma standard deviation of the radiance measured over a 1 second period.

Rationale: The 0.04 W m^{-2} sr^{-1} μm^{-1} spectral radiance requirement corresponds to a TOA NETD of 0.3 K at 300 K in the LWIR band, as calculated using Planck's blackbody law. This is the maximum allowable NETD that will allow, once TDI noise reduction is applied, to provide scene contextual information at the desired precision of 0.1 K. See section 4 for more details.

WFS-MRD-FUN-127 Deleted

WFS-MRD-FUN-129 Deleted

WFS-MRD-FUN-130 VIS/NIR Noise

Prior to noise corrections, the SNR SHALL exceed 20 at the following low-illumination reference TOA radiance levels:

- Blue band: 3.6 W m^{-2} sr^{-1} μm^{-1}
- Green band: 3.6 W m^{-2} sr^{-1} μm^{-1}
- Red band: 3.3 W m^{-2} sr^{-1} μm^{-1}
- NIR band: 2.2 W m^{-2} sr^{-1} μm^{-1}

Rationale: See section 4 for details on the rationale. These SNR levels are to ensure adequate detection of burn scars under low illumination conditions.

WFS-MRD-FUN-135 Deleted

WFS-MRD-FUN-140 MWIR band Radiance Measurement Accuracy

The absolute TOA radiance measurement, for observations in the MWIR band within the temperature range of 400 K to the saturation temperature implicit in WFS-MRD-FUN-090, SHALL be accurate to within ±5% error. This is the mean value for all operable pixels.

Rationale: Discussed in Section 4. This is the largest permitted radiance measurement uncertainty to meet the targeted 15% FRP maximum measurement accuracy error, considering all the contributors of FRP measurement uncertainty (e.g. atmospheric corrections).

WFS-MRD-FUN-150 LWIR band Radiance Measurement Accuracy

The absolute TOA radiance measurement, for observations in the LWIR band within the temperature range of 280 K to the saturation temperature implicit in WFS-MRD-FUN-090, SHALL be accurate to within ±5 % error. This is the mean value for all operable pixels.

Rationale: Discussed in Section 4. This is the largest permitted radiance measurement uncertainty to meet the targeted 15% FRP maximum measurement accuracy error, considering all the contributors of FRP measurement uncertainty (e.g. atmospheric corrections).

WFS-MRD-FUN-160 VIS/NIR Radiance Measurement Accuracy

The radiance measurement SHALL be accurate to within ± 10% error for the VIS/NIR bands.

Rationale: In order to fulfil its mission objectives, the VIS/NIR instrument will provide calibrated radiances in order to characterize the main land cover types, in particular the vegetation types and state, density. The sensor also has the task to discriminate false alarms (such as sun glints), and to provide an image that is helpful for hot spots geo-referencing in the infrared images. The radiometric absolute calibration accuracy defined above is compliant with these requirements. Such accuracy is typical for this type of sensor.

5.1.3. Pointing

WFS-MRD-FUN-170 Pointing Maneuverability

The mission SHALL provide the capability to observe, as a minimum, one off-nadir user-provided target area, no more than 40 degrees off-nadir, per pass over the Canadian AoI.

Rationale: The capability to target event areas is desirable in the context of calibration and validation operations, and in certain extreme disaster management scenarios. Pointing maneuvers will result in loss of coverage and extended revisit periods in other areas, as such this capability will not be used routinely, nor can it be considered as an approach to meet coverage requirements. The maneuverability is limited to less than 40 degrees off-nadir, since beyond this point the fire measurement will be of limited value due to low atmospheric transmittance and degraded image quality.

WFS-MRD-FUN-171 Pointing to Deep-Space

The mission SHALL provide the capability to observe a user-defined deep space area over the entire field of view of the imagers.

Rationale: The capability to point to deep space is required for calibration and validation operations. Pointing maneuvers will result in loss of coverage, as such this capability will not be used routinely, nor can it be considered as an approach to meet coverage requirements.

WFS-MRD-FUN-180 Pointing Accuracy

The absolute camera pointing accuracy (all axes combined) of the instrument SHALL be better than 0.5 degrees (2σ / 95 % confidence) for each spectral band defined in WFS-MRD-FUN-060.

Absolute pointing accuracy is interpreted as the angular difference between the commanded direction of the camera and the actual direction of the camera.

Rationale: The requirement is to assure that detected fires (targeted fires) are actually observed by the sensor, and that thermal and intensity characteristics can be retrieved in and around the detected burning area. The required pointing accuracy around each axis is driven by different factors. For instance, pitch is driven by ground speed and pixel size, roll is driven by the pixel size and ensuring imaging of target fire, yaw is driven by the geolocation requirement, instrument swath width and ground speed. The breakdown per axis will be done as part of the system requirements definition.

WFS-MRD-FUN-181 Deleted

WFS-MRD-FUN-185 Deleted

WFS-MRD-FUN-190 Deleted

WFS-MRD-FUN-200 Deleted

5.1.4. Image Quality

WFS-MRD-FUN-210 Nadir-Pointing GIFOV

When the camera is nadir-pointing, the camera design SHALL provide imagery with GIFOV no larger than 400 m (LWIR, MWIR), and 200 m (NIR, VIS) for all pixels at less than 30 deg co-elevation angle.

Rationale: Derived from user's needs with further clarifications on resolution interpretation. More details provided in Section 4.

WFS-MRD-FUN-211 Deleted

WFS-MRD-FUN-215 MWIR and LWIR Nadir-Pointing Spatial Resolution

When the MWIR and LWIR cameras are nadir-pointing, the mission SHALL provide imagery with sufficient spatial resolution. Specifically, for all pixels, at least 75% of the Ensquared Energy of a point source perfectly centered within the GIFOV of a given pixel will be collected on that pixel.

This spatial resolution requirement is intended to encompass all its potential contributions, including, but not limited to: optical aberrations, motion blur due to the finite response time of the detectors, pixel crosstalk (thermal and electronic) and camera jitter.

Rationale: The MODIS active fire products are arguably the most well studied algorithms in the field of active fire monitoring. Although reliable in many ways, there are several known issues within the MODIS fire products related to the use of bi-spectral sub-pixel fire analysis (e.g. RD-07, RD-08). The bi-spectral technique in use (RD-09) is known to be sensitive to cross band co-registration and to the extent to which the MWIR and LWIR sample energy emitted from identical ground locations is captured. In defining the Ensquared Energy requirement, MODIS's performance (EE = ~ 0.75; RD-10) is taken as a baseline which must be exceeded in order to achieve similar or better bi-spectral analysis with WFS.

WFS-MRD-FUN-220 Deleted

WFS-MRD-FUN-225 Deleted

WFS-MRD-FUN-227 MWIR and LWIR GIFOV Equivalence

The GIFOV of the LWIR band SHALL be equal to that of the MWIR band within a tolerance of 2 % across the camera field of view for each band.

The intent of this requirement is to ensure that the MWIR and LWIR cameras have the same focal length, low optical distortion, and well co-aligned optical axes.

Rationale: It is necessary that energy collected for a given pixel in each the MWIR and LWIR bands corresponds to the same ground region within reasonable tolerances. Using dissimilar GIFOV values in MWIR and LWIR observations would reduce the accuracy of bi-spectral fire measurement, for example using the Dozier method to infer fire size.

WFS-MRD-FUN-228 GIFOV Uniformity

The GIFOV of all pixels in the MWIR and LWIR bands SHALL be equal with a maximum difference of 20 %.

Rationale: In order to produce products for operational consumption in near real-time, consistent performance is required across the full swath in terms of detection sensitivity, FRP accuracy, and flame front delineation. The constraint imposed here ensures that there is no excessive difference in product performance across the full swath. Sub-pixel detection sensitivity will suffer the most pronounced impact from GIFOV variations. In addition, GIFOV uniformity in the along-track direction is important for ensuring the accuracy of TDI averaging and the fidelity of HTE time series extractions.

WFS-MRD-FUN-230 MWIR and LWIR FOV Mapping Accuracy

The FOV mapping of the MWIR and LWIR band pixels SHALL be known and provided to an accuracy within ±15% of the GIFOV for all pixels in each of the bands.

The intent of this requirement is to ensure that the field of view along-track and across-track angular coordinates of all pixels, with respect to the common payload optical axis, are (1) accurately mapped out prior to launch, for example to account for optical distortion, and (2) that the cameras and payload are designed such that this mapping is preserved once on orbit, for example by minimizing potential thermally induced optical distortions and camera misalignment induced by launch vibration.

Rationale: This FOV mapping accuracy is the minimum that will allow sufficient co-registration knowledge between corresponding MWIR and LWIR pixels in order to apply the Dozier bi-spectral method with acceptable accuracy, given the spatial resolution requirement.

WFS-MRD-FUN-235 Deleted

WFS-MRD-FUN-236 Deleted

WFS-MRD-FUN-237 Deleted

WFS-MRD-FUN-240 VIS/NIR FOV mapping Accuracy
The FOV mapping of the VIS/NIR band pixels SHALL be known and provided within the VIS/NIR GIFOV accuracy for all pixels in each of the bands.

Note: The intent of this requirement is to ensure that the field of view along-track and across-track angular coordinates of all VIS/NIR pixels, with respect to the common payload optical axis, are (1) accurately mapped out prior to launch, for example to account for optical distortion, and (2) that the cameras and payload are designed such that this mapping is preserved once on orbit, for example by minimising potential thermally induced optical distortions and camera misalignment induced by launch vibration.

Rationale: Coming from user's needs. This requirement is necessary for ensuring accurate VIS/NIR contextual information to the MWIR and LWIR images.

WFS-MRD-FUN-241 Deleted

WFS-MRD-FUN-242 Deleted

WFS-MRD-FUN-245 Deleted

WFS-MRD-FUN-246 Deleted

WFS-MRD-FUN-247 Deleted

WFS-MRD-FUN-250 Deleted

WFS-MRD-FUN-251 Deleted

WFS-MRD-FUN-252 MWIR and LWIR Temporal Co-Registration Accuracy
The LWIR and MWIR HTE time series SHALL have a temporal gap (blind area) of less than 6 seconds between them.

Rationale: MWIR and LWIR data is combined to produce output data products for the WFS mission. Fire properties are dynamic and significant delay in sampling between bands will provide a mismatch in conditions. Ideally both bands will sample the same area at the same time (even if pixels require spatial correction) to minimize errors.

WFS-MRD-FUN-253 Deleted

WFS-MRD-FUN-255 Along Track Viewing Angle
The total spread in along track viewing angle for the co-registered portions of the bands SHALL not exceed 10 degrees. This is considered to be the maximum angle between the most aft-looking to the most forward-looking band.

Rationale: End data products are produced by processing raw data from multiple bands. Significant variation in viewing angle introduces errors due to differing pixel shapes, distortions caused by vertically separated features such as smoke plumes and clouds, etc.

WFS-MRD-FUN-260 Deleted

WFS-MRD-FUN-270 Modulation Transfer Function (MTF)
The camera MTF for all bands SHALL be greater than 0.3 for all frequencies below the Nyquist frequency.

Rationale: Coming from user's needs.

WFS-MRD-FUN-280 Time-Delayed Integration (TDI)
The WFS processing chain SHALL be able to perform time-delayed integration for an observation period corresponding up to at least 40 continuous frames on the MWIR and LWIR signals.

Rationale: TDI allows for increased sensitivity and to reduce aliasing effects of sub-pixel HTEs that would otherwise compromise the ability to detect small HTEs by reducing false positives, and to accurately measure radiances.

Note that in the context of WFS, the term "TDI" is intended to have a broader meaning than its typical definition in the context of charge-coupled device (CCD) photoelectric detectors, where it refers to shifting of photoelectrons to compensate for the motion of objects. Indeed, in the context of thermal detectors such as microbolometers, TDI refers to the post-acquisition co-addition of the image pixels in several image frames which are determined to view the same object on the ground.

Based on measurements performed with the microbolometer detector baselined in Phase A, there is limited noise reduction benefit in performing TDI over more than 40 frames.

WFS-MRD-FUN-290 HTE Thresholding
The WFS MWIR measurement and signal processing chain SHALL have the capability to detect, by thresholding image signals above a user-specified value, the presence of HTEs.

Rationale: HTEs are known to have distinctive time signatures. The HTE time series acquired during an overpass will allow to reject false positives and to better characterize the type of HTE (e.g. active fires, smoldering area, volcanoes).

WFS-MRD-FUN-295 HTE Time Signatures
The scene signals of the corresponding geo-located LWIR and MWIR HTE signals, for a time period of at least 3 seconds, SHALL be stored separately (e.g. as meta data) along with related HTE pixel coordinates to allow for further analysis of HTE events by the SOC.

Rationale: HTEs are known to have distinctive time signatures. The HTE time series acquired during an overpass will allow to reject false positives and to better characterize the type of HTE (e.g. active fires, smoldering area, volcanoes). Furthermore, temporal signatures provide valuable information related to the passage of sub-pixel HTEs through the PSF of the detector.

WFS-MRD-FUN-300 Deleted

WFS-MRD-FUN-310 LWIR and MWIR Image Uniformity Correction
The thermal payload SHALL provide a means to perform regular image uniformity correction so that potential thermal drift related image artifacts will be less than 1 K for a uniform 280 K scene, or the pixel NESR radiance, whichever is lower.

Rationale: Refer to the discussion on measurement precision in Section 4.

5.2 OPERATIONAL REQUIREMENTS

5.2.1. Data Product Handling

WFS-MRD-OPE-010 Deleted

WFS-MRD-OPE-020 Level-1b Data Production
The mission SHALL generate, as part of its Ground Segment, Level-1b Science Data Products from data received from the Space Segment and, when requested by the SOC, from archived data.

Rationale: The User Segment is only equipped to manipulate Level-1b data and above.

WFS-MRD-OPE-025 On-Board Storage of Scene Signal Data
The mission SHALL have the capability to acquire upon ground command, at least 30 seconds of Scene Signal data (i.e. unprocessed) and associated ancillary data, without interrupting the on-board processing stream, and store on-board the spacecraft until downlink is available upon command or downlink concurrently to the ground.

Rationale: Scene Signal data is required for research and operational purposes, such as anomaly resolution and algorithm development. It is required to have processed and unprocessed data available simultaneously to verify the integrity of the data processed on-board.

WFS-MRD-OPE-026 Downlink of On-Board Stored Data Upon Command
The mission SHALL have the capability, upon ground command, to downlink user-selected portions of the Science Data stored on-board the spacecraft, including Scene Signal and data at any and all stages of the onboard data processing pipeline up to Raw Data.

Note: This requirement is not subject to the latency requirements of WFS-MRD-OPE-090.

Rationale: Mainly for calibration and validation purposes and support investigation of payload anomaly.

WFS-MRD-OPE-030 Deleted

WFS-MRD-OPE-040 Archiving

The Ground Segment SHALL archive all received and generated Level-0 and Level-1b Science Data Products for subsequent retrieval.

Rationale: Archival of Level-0 and Level-1b allows End-Users, Partner End-Users and External End-Users to get access to historical data for various applications and to fulfill RSSSA requirement on archival.

WFS-MRD-OPE-041 Deleted

WFS-MRD-OPE-050 Deleted

WFS-MRD-OPE-060 Geo-Referencing

Science Data Products generated by the mission SHALL be tagged with geo-referencing information accurate to within 0.5 MWIR GIFOV (2σ / 95 % confidence).

Rationale: Coming from user's needs The geo-referencing accuracy is interpreted as the linear distance between the true ground position and the geo-referenced position of a pixel's center.

WFS-MRD-OPE-061 Deleted

WFS-MRD-OPE-070 Deleted

WFS-MRD-OPE-080 Deleted

WFS-MRD-OPE-090 Data Latency

The mission SHALL deliver Level-1b data to the SOC within 20 minutes from the image acquisition for observation made within the Canadian AoI and within the Canadian ground stations masks.

Rationale: The need is for the End-Users to get their data within 30 minutes from acquisition. This timeframe was clearly identified through consultation as critical for the products to have value in both tactical and strategic fire management decision making. 10 minutes are allocated to the SOC to process the data from Level-1b to data that can be used by End-Users. It is understood that the 20minutes can only be met if the satellite is in sight of a Canadian ground station. The requirement also excludes off-nominal operations.

WFS-MRD-OPE-092 Deleted

WFS-MRD-OPE-095 Deleted

WFS-MRD-OPE-097 Image Data Storage Capacity

The mission SHALL provide sufficient memory capacity on-board the spacecraft to store Science Data acquired over at least two orbits, under normal operations imaging conditions, including imaging outside the Canadian AoI and special imaging task requests.

Rationale: The spacecraft needs storage space in case no antenna is available to downlink the acquired data and to ensure continuous imaging of the Canadian AoI. The unavailability of downlink opportunities may happen if imagery activities are happening outside the Canadian landmass, or in case of a temporary unavailability of the Ground Segment.

WFS-MRD-OPE-100 Deleted

WFS-MRD-OPE-110 Deleted

WFS-MRD-OPE-115 Deleted

5.2.2. Mission Duration, Availability and Reliability

WFS-MRD-OPE-120 Mission Lifetime

The mission SHALL be designed for an operational lifetime of 5 years, after commissioning is complete, but with sufficient consumables for at least 7 years. The operational lifetime is defined as the time during which all mission requirements are met, unless specified otherwise, including keeping the payload thermally balanced throughout the mission to meet its performance requirements.

Rationale: Mission has been approved for an operational life of 5 years. It is common practice to plan for more consumable than the mission life, in order to account for the case of a longer mission duration. Consumable in this requirement refers to propellant. The amount of consumable required includes the amount to reach the orbit, perform the mission as per mission requirements, and safely deorbit.

WFS-MRD-OPE-130 Deleted

WFS-MRD-OPE-135 Deleted

WFS-MRD-OPE-136 Space Segment Availability

The Space Segment (excluding launcher) SHALL be available at least 90% of the time on average per month, after commissioning is complete, over the required space segment lifetime.

Note: The availability is defined as the operational availability: Uptime/(Uptime+Downtime). As per RD-03, Uptime is the total time a complete system is in an operable state (including calibration), i.e. it meets its expected performance, and Downtime is the total time the system is in an inoperable state, for any reason such as faults, corrective and preventive maintenance time, administrative delay time, and logistic support time.

Rationale: Based on operational availability budgets of other earth science missions. Also, the end data will be of limited use for fire responder if availability is lower than 90%. Allows for safehold, orbit maintenance and single event effects, etc. within the system, while preventing the design of a system requiring long maintenance periods. The requirement is explicit about the availability per month and not per year, as the spacecraft imaging and calibration time will vary depending on the months of the year (refer to WFS-MRD-FUN-010 and WFS-MRD-FUN-013). Furthermore, this requirement is applicable to the spacecraft only, and does not provide the mission end-to-end availability requirement, which would normally include the Ground and User Segments. This is a decision made by the WFS team, Availability requirements imposed on government furnished equipment will be handled outside this MRD.

WFS-MRD-OPE-137 Space Segment Reliability

The Space Segment (excluding launcher) SHALL have a reliability exceeding 0.56. Space Segment (excluding launcher) reliability is defined over a time period from insertion into the desired orbit until end of mission life as defined in requirement WFS-MRD-OPE-120.

Rationale: This requirement ensures that the system has a 0.5 probability of being fully functional at the end of mission life.

WFS-MRD-OPE-138 Deleted

WFS-MRD-OPE-139 Launcher Reliability

The reliability of the launcher SHALL exceed 0.89, from spacecraft integration to the launcher, to spacecraft deployment into its final desired orbit.

Note: Calculation of launcher reliability is based on the method described in Table A of AD-03.

Rationale: To increase the chances of mission success.

5.2.3. Ground Operations and Interfaces

Several of the following requirements include the use of systems provided as part of the Multi-Mission Operations Centre (MMOC). The MMOC is located at the CSA St-Hubert facility and its operations are managed by the Government of Canada. The components specific to the WFS mission are part of what will be referred herein to the Mission operations Centre (MOC).

WFS-MRD-OPE-140 Spacecraft Activity Planning

The mission SHALL use the spacecraft activity planning (PLAN) system provided as part of the MMOC, and configured for the WFS mission, to manage payload operations including resource constraint verifications, spacecraft housekeeping activities, and special tasking requests.

Note: The PLAN system is provided as a Government Furnished Equipment to the mission and it is understood that if there are required mission specific add-ons (tools, algorithms, etc.) these can be integrated in the PLAN in coordination with CSA.

Rationale: Using the PLAN system allows for interoperability with other missions operated at the CSA, and to reduce integration time.

WFS-MRD-OPE-141 Flight Dynamic

The mission SHALL use the flight dynamic (FD) system provided as part of the MMOC, and configured for the WFS mission, to provide past and future position of the satellite(s) based on satellite Global Positioning System (GPS) telemetry (if available) and tracking data. FD also generates and distributes all products required within or external to the MMOC that are based on orbital position and environment. The FD also provides manoeuvre planning for Orbit maintenance and Collision avoidance of the WFS Satellites.

Note: The FD system is provided as a Government Furnished Equipment to the mission and it is understood that if there are required mission specific add-ons (tools, algorithms, etc.) these can be integrated in the FD in coordination with CSA.

Rationale: Using the FD system allows for interoperability with other missions operated at the CSA, and to reduce integration time.

WFS-MRD-OPE-142 Command and Control

The mission SHALL use the Realtime Telemetry, Telecommand and Tracking (RT3) system, provided as part of the MMOC, and configured for the WFS mission. The RT3 system's main purpose is to ingest and display telemetry from the Spacecraft and to send commands to the Spacecraft based on the scheduled spacecraft and payload activities.

Note: The RT3 system is provided as a Government Furnished Equipment to the mission and it is understood that if there are required mission specific add-ons (tools, algorithms, etc.) these can be integrated in the RT3 in coordination with CSA. However, the following constraints apply:

1. RT3 has to be the system interfacing directly with the spacecraft, and not the mission specific add-ons.
2. The mission specific add-ons cannot be mission critical, i.e. cannot prevent RT3 from sending telecommands and receiving telemetry without the add-ons. As a Government of Canada owned and operated mission, CSA has to keep full control of the operations.

For commands and control specifically, CSA intends to use the Galaxy system (https://hammers.com/galaxy) for multi-mission operations.

Rationale: Using the RT3 system allows for interoperability with other missions operated at the CSA, and to reduce integration time.

WFS-MRD-OPE-143 Spacecraft Health Monitoring

The mission SHALL use the Spacecraft Health Monitoring (SCHM) system provided as part of the MMOC, and configured for the WFS mission, to provide the ability to generate telemetry analysis reports and manage Spacecraft on-board memory tables.

Note: The SCHM system is provided as a Government Furnished Equipment to the mission and it is understood that if there are required mission specific add-ons (tools, algorithms, etc.) these can be integrated in SCHM in coordination with CSA.

Rationale: Using the SCHM system allows for interoperability with other missions operated at the CSA, and to reduce integration time.

WFS-MRD-OPE-144 Data Management

The mission SHALL use the Data Management (DM) system provided as part of the MMOC, and configured for the WFS mission, to provide a central data transfer facility and short and long-term archiving capabilities.

Note: The DM system is provided as a Government Furnished Equipment to the mission and it is understood that if there are required mission specific add-ons (tools, algorithms, etc.) these can be integrated in DM in coordination with CSA.

Rationale: Using the DM system allows for interoperability with other missions operated at the CSA, and to reduce integration time.

WFS-MRD-OPE-145 Maintenance and Support

The mission SHALL include spacecraft maintenance and support capabilities to support, during operations:

- Flight software development, update and validation;
- Flight procedures and products (i.e. tables and parameters) development, update and validation;
- Training;
- Exercise and rehearsal activities;
- Spacecraft operations validation tests;
- Spacecraft anomaly investigation;

Rationale: The spacecraft operations team will need these maintenance capabilities in order to ensure maintenance of the spacecraft throughout its operational lifetime.

WFS-MRD-OPE-150 Deleted

WFS-MRD-OPE-160 Deleted

WFS-MRD-OPE-170 Deleted

WFS-MRD-OPE-180 Deleted

WFS-MRD-OPE-190 Deleted

WFS-MRD-OPE-200 Fast Tasking Capability

The mission SHALL include the capability for the SOC and operators to interrupt normal operations to perform special tasking operations within 12 hours of a request being received at the operations center. This requirement does not apply to operations staffing levels or ground station availability, only to ground system and spacecraft capabilities assuming the required staff and ground station passes are available.

Rationale: Provides the mission capabilities to implement time sensitive special pointing activities required by calibration and validation activities or emergency situations. WFS-MRD-FUN-170.

WFS-MRD-OPE-210 Deleted

WFS-MRD-OPE-211 Conjunction Services

The mission SHALL use CSA provided conjunction analysis services. The Conjunction Risk Assessment and Mitigation System (CRAMS) is intended to be used to provide conjunction analysis services to the WFS mission.

Rationale: Using the CSA provided conjunction analysis services allows for interoperability with other missions operated at the CSA.

WFS-MRD-OPE-212 Antenna Reservation Services

The mission SHALL use CSA provided antenna deconflicting and reservation services. The Antenna Reservation System (ARS) is intended to be used to provide antenna deconflicting and reservation services to the WFS mission.

Rationale: Using the CSA provided antenna deconflicting and reservation services allows for interoperability with other missions operated at the CSA, and a better coordination of the antennas used by all CSA operated missions.

WFS-MRD-OPE-215 TT&C Services

The mission SHALL use, as a minimum, the Canadian ground stations in CCMEO's Ground Station Network (GSN) (Gatineau, Prince-Albert, Inuvik) for S-band TT&C.

Rationale: NRCan has been providing ground station/satellite reception services for over 50 years. In Budget 2021, the Government of Canada made a significant commitment to building additional capacity and resiliency of these services. Under Budget 2022, NRCan received sufficient incremental funding to provide ground station network support for the WFS mission, including all uplink/downlink of TT&C signals/data through S-band stations owned and operated by CCMEO.

WFS-MRD-OPE-220 Minimizing the Number of TT&C Contacts

The mission SHALL be designed to require a maximum of two (2) daily routine and maintenance TT&C contacts per spacecraft, excluding new acquisition requests and fast tasking requests from the SOC, in order to maintain good health of all systems while meeting the mission requirements. This limit excludes special acquisition requests and fast tasking requests from the SOC.

Rationale: Optimize TT&C resource sharing across missions and minimize operational cost of the mission.

WFS-MRD-OPE-230 Deleted

WFS-MRD-OPE-240 Data Reception Services

The mission SHALL use, as a minimum, the Canadian ground stations in CCMEO's Ground Station Network (GSN) (Gatineau, Prince-Albert, Inuvik) for X-Band data reception.

Note: Inuvik and Gatineau ground stations also have Ka-Band capabilities which could also be considered.

Rationale: NRCan has been providing ground station/satellite reception services for over 50 years. In Budget 2021, the Government of Canada made a significant commitment to building additional capacity and resiliency of these services. Under Budget 2022, NRCan received sufficient incremental funding to provide ground station network support for the WFS mission, including all downlink of WFS data through X-band receiving stations owned and operated by CCMEO.

WFS-MRD-OPE-250 Data Archival and Distribution Services

The mission SHALL use the CCMEO data archival and distribution services provided through the EODMS, for the long archival of all the Level-0 and Level-1b data products generated by the Ground Segment.

Note: The WFS mission may have a commercial segment, which may or may not use the CCMEO data archival and distribution services provided through the EODMS, for the long archival of all the Level-0 and Level-1b data products generated by the commercial segment.

Rationale: NRCan has been providing Earth Observation Imagery Data Distribution and Long-Term Archiving services for the Government of Canada for many years, in accordance with the requirements of the Remote Sensing Space Systems Act (RSSSA). Under Budget 2022, NRCan received incremental funding required to extend all data archival and distribution services for WFS Level-0 and Level-1b Science Data Products in EODMS.

WFS-MRD-OPE-260 Data Acquisition Activity Planning Services

The Ground Segment SHALL rely on the SOC, developed and operated by the CFS, for the planning and generation of the payload activity schedules, such as data acquisition, or any other special payload tasking activities to support, for example, calibration, emergency situations, maintenance.

Rationale: NRCan has been providing Canadian fire management and operations personnel national-level products to support fire management for many years. The primary interface between all End-Users and WFS is the SOC, and all Level-2+ Science Data Products will be produced at this Centre. Under Budget 2022, the SOC has been funded to plan and generate the activity schedules.

WFS-MRD-OPE-270 Level-2+ -Tier 1, 2, 3 Data Processing and Distribution Services
The mission SHALL rely on the SOC, developed and operated by the CFS, for the processing and archival of Science Data Products beyond Level-1b (i.e. Level-2+ -Tiers 1, 2 and 3) and their distribution to the End-Users.

Rationale: NRCan has been providing Canadian fire management and operations personnel national-level products to support fire management for many years. Under Budget 2022, the SOC has been funded to process, archive, and distribute the Level-2+ Science Data Products through already established frameworks and systems that are well known to the End-Users.

5.2.4. Pre-Launch Validation Campaign

WFS-MRD-OPE-300 Validation Payload Instrument
The mission SHALL have access to a payload instrument adapted for an airborne campaign or a space mission, that will allow to fulfill the following pre-launch validation campaign objectives:

1. Validate the WFS measurement approach and determine the optimal settings for maximizing infrared payload sensitivity (e.g. frame rate, TDI and HDR settings)
2. Validate the WFS analysis approach and determine the optimal settings for obtaining sub-pixel fire information such as size and temperature of subpixel fires and false-positives identification (i.e. HTE processing method and parameters)
3. Provide data to help validate key elements of the WFS Tier-1/2/3 processing chain.
4. Provide an opportunity for the contractor, if part of their verification plan, to verify the radiometric accuracy of the WFS infrared sensors, determine the optimal in-flight calibration procedure and parameters, and verify the Level-0 to Level-1b processing chain, including radiometric calibration and geo-referencing.

Note: The validation of key elements of the WFS Tier-1/2/3 processing chain in objective 3 is the responsibility of NRCan-CFS.

Rationale: To support the pre-launch campaign objectives, i.e. to validate the performance of key WFS infrared payload technologies and their related acquisition methods and parameters.

WFS-MRD-OPE-310 Airborne Instrument Interface
In the case an airborne instrument is selected to meet WFS-MRD-OPE-300, the airborne campaign instrument SHALL meet the interface requirements of the NASA's high altitude research platform ER-2 aircraft (AD-04).

Rationale: The NASA ER-2 aircraft is the most likely aircraft the NRCan-CFS will be using. If any other aircraft is used, the interface requirements are assumed to be less stringent, but still compatible with the ER-2 interface requirements.

5.3 CONSTRAINTS

WFS-MRD-CON-010 Deleted

WFS-MRD-CON-020 Deleted

WFS-MRD-CON-030 Deleted

WFS-MRD-CON-040 Deleted

WFS-MRD-CON-050 Deleted

WFS-MRD-CON-060 Deleted

WFS-MRD-CON-070 Deleted

WFS-MRD-CON-080 Deleted

WFS-MRD-CON-090 Deleted

WFS-MRD-CON-100 International Telecommunications Union (ITU) Regulations
All radio-frequency emissions from WFS spacecraft and ground stations SHALL comply with ITU regulations [AD-01].

Rationale: Regulatory requirement.

WFS-MRD-CON-110 Remote Sensing Space Systems Act
The WFS mission will be subject to and SHALL comply with the Remote Sensing Space Systems Act [AD-02].

Rationale: Regulatory requirement.

WFS-MRD-CON-120 Open Data Policy
The Science Data Products produced by the mission WILL be made publicly available through EODMS, subject to applicable restrictions for security, privacy and confidentiality.

Rationale: To respect the Findable, Accessible, Interoperable and Reusable (FAIR) principles stated in the Roadmap for Open Science [RD-04] and to the spirit of the Directive on Open Government [RD-05].

WFS-MRD-CON-130 S-Band Uplink Encryption
The system SHALL provide encryption of S-Band uplink data using FIPS 140-3 (preferred) or FIPS 140-2 certified cryptographic device.

Rationale: Command authentication provides positive spacecraft control and ensures unauthorized parties do not assume control of the spacecraft. The system does not need to incorporate cryptography for telemetry, nor science data as those data will be unclassified.

WFS-MRD-CON-140 Deleted

WFS-MRD-CON-150 Spacecraft Safe Mode

The spacecraft SHALL be capable of maintaining autonomously its own safety for at least 1 month including in the case of the unavailability of the Ground Segment (including the MMOC). Maintaining safety means self-protecting all on-board equipment so that the capabilities and performances can be fully recovered once the Ground Segment re-establishes the contact with the spacecraft after the down period.

Rationale: The mission is not planning on having a hot backup control facility. However, in case of force majeure preventing the MMOC in St-Hubert to communicate with the spacecraft for a longer period than 1 month, the MMOC could potentially be deployed externally. The satellite operations team thus recommended that the spacecraft be capable of maintaining its own safety for at least 1 month without the need for ground intervention, to give them time to deploy the control system.

WFS-MRD-CON-160 Collision Avoidance

The mission SHALL be designed and operated to actively manage collision risk until the end of life.

Rationale: Clarification brought to the applicable Product Assurance Requirement on collision mitigation. The WFS mission, as an operational mission, is expected to support collision avoidance to the extent possible by its propulsion system.

WFS-MRD-CON-170 De-orbiting

The mission SHALL be designed and have sufficient consumable to be able to manoeuvre each spacecraft to de-orbit within the 5 years starting from the end of mission, with a probability of successful disposal of at least 0.9.

Rationale: This requirement is more constraining than the ISO 24113:2019 standards 6.3.3.1 and 6.3.1.1 listed in the Product Assurance Requirements. In 2002, the IADC first recommended to limit residual orbital lifetime to 25 years. Recognizing the evolution of the orbital environment, a significantly reduced orbital lifetime is now generally considered necessary. Some studies have shown that compared to 25 years, reducing the limit to 5 years leads to a significant reduction in the collision risk.

6. ACRONYMS AND ABBREVIATIONS

Item	Definition
2D	Two dimensional
AOI	Area of Interest
ARS	Antenna reservation system
CCD	Charge-coupled device
CCMEO	Canada Centre for Mapping and Earth Observation
CCSDS	Consultative Committee for Space Data Systems
CFS	Canadian Forest Service
CRAMS	Conjunction Risk Assessment and Mitigation System
CSA	Canadian Space Agency
CWFMS	Canadian Wildland Fire Monitoring System
DEM	Document sur les exigences de la mission
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DM	Data Management
DM	Data management
ECCC	Environment and Climate Change Canada
EE	Ensquared Energy
EO	Earth Observation
EODMS	Earth Observation Data Management System
FAIR	Findable, Accessible, Interoperable and Reusable
FD	Flight Dynamics Analyst
FD	Flight Dynamics
FGP	Federal Geospatial Platform
FIPS	Federal Information Processing Standards
FOV	Field of View
FRP	Fire Radiative Power
FWHM	Full Width at Half Maximum
GIFOV	Ground Instantaneous Field of View
GPS	Global Positioning System
GSN	Ground Station Network
HTE	High Temperature Event
IFOV	Instantaneous Field of View
IR	Infrared
ITU	International Telecommunications Union
LEO	Low Earth Orbit
LTAN	Local Time of Ascending Node
LTDN	Local Time of Descending Node
LWIR	Long-Wave InfraRed
MMOC	Multi-Mission Operations Center
MOC	Mission Operations Centre

Item	Definition
MODIS	Moderate Resolution Imaging Spectroradiometer
MTF	Modulation Transfer Function
MWIR	Mid-Wave InfraRed
NASA	National Aeronautics and Space Administration
NEP	Noise Equivalent Power
NESR	Noise Equivalent Spectral Radiance
NETD	Noise-equivalent temperature difference
NIR	Near-Infrared
NIRST	New Infrared Sensor Technology
NRCan	Natural Resources Canada
PLAN	Spacecraft activity planning system
PSF	Point Spread Function
RMS	Root-Mean-Square
RT3	Real-Time T3
SCHM	Spacecraft Health Monitoring system
SLSTR	Sea and Land Surface Temperature Radiometer
SNR	Signal-to-noise ratio
SOC	Science Operations Centre
SRF	Spectral Response Function
STDP	Space Technology Development Program
TDI	Time-delayed integration
TET	Technology Experiment Carrier
TOA	Top Of Atmosphere
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking and Control
URD	User Requirements Document
VIIRS	Visible Infrared Imaging Radiometer Suite
VIS	Visible
VIS/NIR	Visible/Near-Infrared
WFS	WildFireSat

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