Project Plan: Aircraft Study on Oil Sands Air Pollution Emissions, Transformation and Fate

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Project Background

The Alberta oil sands region has the third largest fossil fuel deposit in the world, after Venezuela and Saudi Arabia. The commercial production of crude oil from the Alberta oil sands started about 50 years ago, and is now among the largest oil production activities in the world. Further development of this resource is expected to continue for the next decades, as industry expands their operations and deploys new extraction technologies on a large scale. With this existing and future development, environmental impacts have become a significant public concern. Sustainable and responsible development, that includes demonstrated effectiveness in the management of environmental impacts associated with oil sands development, is the key for the long term viability of this industry. Correspondingly, it is critical to understand what environmental risks are posed by the oil sands development, and then institute policy and technology tools for minimizing these risks.

Environment and Climate Change Canada (ECCC), working with the Government of Alberta, has undertaken monitoring of oil sands pollutants in air, water, and ecosystems through the Oil Sands Monitoring (OSM) program since 2012. The ultimate goals of the Oil Sands Monitoring (OSM) plan are to understand the cumulative impact of oil sands emissions on ecosystems. The OSM Air Component has several objectives, including to find out what pollutants are emitted, how much is emitted, how far the emitted pollutants are transported and how they are transformed in the atmosphere, and where the deposition to the surface takes place. The OSM Air Component has emphasized ground based monitoring of oil sands pollutants, and has initially focused on the surface mining facilities in the Athabasca Oil Sands Region. In support of ground based air monitoring, ECCC has conducted several focused studies on air pollutants from the oil sands facilities, including a comprehensive aircraft project in the summer of 2013. This airborne measurement program focused on estimation of surface mining facility integrated emission rates for many of the Criteria Air Contaminants (CACs) and greenhouse gases (GHGs), and characterization of their transport and transformation in the atmosphere. The results from this aircraft program have also supported the ongoing effort in evaluating and improving regional air-quality modelling and validating satellite retrieval products.

Emissions. Even with these large monitoring efforts, there currently remain many knowledge gaps in air emissions from various oil sands operations. In situ facilities include non-thermal and thermal operations and a notable gap is related to quantifying the air emissions from the in-situ operations. It is known that over half of the total bitumen productions in the oil sands regions in Alberta now come from thermal in-situ operations using extraction methods such as Steam Assisted Gravity Drainage (SAGD), where there is limited information on air emissions. Presently, National Pollutant Release Inventory (NPRI) indicate low emissions of CACs from the thermal in-situ facilities. However, this could be partially due to the fact that most in-situ facilities do not have upgraders and hence emissions of some CACs (e.g., SO_2) can be low, and also partially due to the fact that sources are likely fugitive in nature at these in situ facilities and thus difficult to measure. In addition, given the energy intensity of thermal in-situ operations, by approximately 5 times higher than conventional oil production as estimated by Canadian Association of Petroleum Producers (CAPP), questions arise on the magnitude and intensity of CO_2 emissions from such operations. There is a need to obtain measurements to evaluate the currently reported emissions from the in situ facilities.

Non-thermal in situ methods are more widely used in heavy oil productions, but also in some in situ bitumen productions. For example, Cold Heavy Oil Production with Sand (CHOPS) methods are widely used in heavy oil production in Alberta and Saskatchewan from unconsolidated sand stone reservoirs as well as in some oil sands areas, from which air emissions are poorly known. CHOPS involves deliberate initiation of sand influx (sand fluidization) during well completion, maintenance of sand influx during the productive life of the well, and separation of the sand from the extracted oil for disposal. Sand is produced along with oil, water, and gas, and separated from the oil before upgrading. Optimal workover strategies, sand-disposal practices, and improved recovery methods including water flooding/polymer flooding and pressure pulsing have improved the recovery of heavy oil. A significant fraction of the gases is vented thus creating large emissions; however, the fraction of gas vented versus collected/combusted is not well known. Reports have indicated that the CHOPS region has high CH_4 emissions; however, no information is available for emissions of other pollutants including CO_2 and Volatile Organic Compounds (VOCs). Hence, measurement based validation of emission reports is necessary.

Both bitumen produced from oil sands and heavy oil produced through CHOPS undergo upgrading to synthetic crude oil. There is strong evidence that a major part of CO_2 emitted from the oil sands is from the upgrading process. In addition to the three upgraders in the Athabasca oil sands region north of Fort McMurray, the Shell Scotford upgrader processes bitumen produced in the Shell (now Canadian Natural Resources Limited (CNRL)) Muskeg River and Jackpine facilities in Athabasca oil sands region, and the Husky Lloydminster upgrader facility for conversion to synthetic crude oil. While the upgraders in the Athabasca oil sands region were part of the surface mining facilities and hence were included in the facility total emission, offsite upgraders such as the Scotford upgrader have not been measured for their total emissions using top down approaches. Emissions from the upgraders, including VOCs, CH_4, CO, and CO_2 are not well characterized and there is a need for measurements to determine the emission rates.

***Transformation*.** The 2013 aircraft study yielded some significant findings on primary air pollutant transformation during transport downwind from the oil sands surface mining facilities. The finding that secondary organic aerosol formation is on par with major urban centres in North America (Liggio et al., 2016) has revealed the importance of intermediate and semi volatile organic compounds (IVOCs and SVOCs) in affecting particular matter levels downwind. Similar analyses have shown that both emissions from the oil sands facilities and secondary processes downwind of the oil sands surface mining facilities lead to significant amounts of organic acids and isocyanic acid downwind of the oil sands region (Liggio et al., 2017a,b). These are the first such understandings of the chemical transformation processes involving oil sands primary air pollutants. However, there are many important questions on transformation of primary pollutants from the oil sands development that have yet to be addressed. For example, it is not clear how fast SO_2 and NOx are oxidized. The transformation rates of these compounds have significant impacts on their footprint on ecosystems. Another issue is how the Secondary Organic Aerosol (SOA) was formed; how much IVOCs and SVOCs are emitted, and under what conditions they are transformed into SOA, and what are the exact conversion pathways from IVOCs and SVOCs to SOAs. In general, it is necessary to understand the life times of the primary pollutants from the oil sands development and their transformation products in the atmosphere before an assessment of their ecosystem impacts can be realistically made.

***Deposition*.** Ultimately, the ecosystem impacts of oil sands air pollution emissions are driven by deposition or exposure from air. Deposition from the atmosphere onto the ecosystem is achieved through wet and dry deposition. While wet deposition can be directly measured when precipitation is collected and chemical composition in the precipitation is analyzed, there are no direct measurement methods for dry deposition of pollutants. Dry deposition flux is estimated using measured air concentrations of a pollutant (at an appropriate height) multiplied by a dry deposition velocity determined from inferential methods using meteorological observations or model meteorological predictions as inputs. The dry deposition fluxes determined this way may be validated using micrometeorological measurements over a limited spatial scale under tens of km^2.

Over larger spatial scales, dry deposition velocities have been shown to vary significantly. Despite this significant spatial variability, dry deposition fluxes are predicted using air quality models using the predicted dry deposition velocities. These dry deposition flux predictions need to be validated using measurements. During the 2013 aircraft study, it was demonstrated using mass balance, that dry deposition fluxes of sulfur compounds can be determined from aircraft measurements on a spatial scale of 10^4 km^2. Furthermore, the loss of these pollutants at distances away from the sources can be determined. However, the 2013 study on deposition was carried out during a limited number of flights, the spatial extent of the study was only to approximately 100-120 km downwind, and only a limited number of pollutants were studied. For example, a detailed study on aerosol particle depositional fluxes will provide a better understanding of primary $PM_{2.5}$ and PM_{10} spatial transport scales downwind. A more comprehensive study is needed where more downwind spatial coverage is increased. Results from such studies can be used to validate the model dry deposition flux predictions.

Satellite Data Evaluation. With the advent of newer technology and improved algorithms, the use of satellites for monitoring air quality parameters is migrating from R&D into the mainstream. The past 14 months have seen multiple sensors launched, each with increased, and in some cases unprecedented, air quality monitoring potential. Two are particularly noteworthy: the ABI (Advanced Baseline Interferometer) on the GOES-R (Geostationary Operational Environment Satellite), which is the first geostationary instrument with research-quality aerosol monitoring potential, and the TropOMI (Tropospheric Monitoring Instrument), which provides a complete coverage of air quality gases at unprecedented spatial resolution and includes methane for the first time. However, these new data products have not generally undergone a robust validation, and certainly not in the region of interest for this study. Validation is an essential step to understand the quality and limitations of the satellite observations, and can lead to a high level of scientific credibility for the data products and conclusions derived from them. It was through oil sands validation activities that a large systematic error flaw was identified in trace gas observations in other key satellite sets (McLinden et al., 2014), one that had been present for a decade despite examination by the research community.

While ground-based observations are normally used to provide ongoing validation (e.g., to detect any drift in satellite measurements), the most thorough form of validation is through the use of aircraft measurements which simultaneously samples the same three-dimensional volume of air that the satellite is sensing. The aircraft profiles provide an “apples-to-apples” comparison with the satellite observations, which facilitates validation of the satellite retrieval methodologies themselves. While other agencies perform similar validation activities, the oil sands region has unique characteristics (high latitude, sources surrounded by forests, frequent snow cover, etc.) for which specific validation programs are required. Moreover, recently launched satellite instruments have had minimal-to-no validation, and early detection of potential issues is necessary to ensure the longest, high quality satellite data record possible for use in detecting and assessing pollutant emissions and changes across large regions such the oil sands regions.

Model Prediction Evaluation. Regional and long-term ecosystem impacts by emissions from oil sands development can only be assessed and predicted using numerical air quality models. The air quality model of choice for ECCC is the Global Environmental Multi-scale-Modelling Air Quality and Chemistry (GEM-MACH) model which includes explicit physical and chemical processes for the prediction of several criteria air contaminants including gas phase pollutants (e.g., O_3, SO_2, and NO_x) and aerosols. Significant development work on the model has led to the incorporation of several new chemical and physical processes parameterizations for the GEM-MACH. These included the inclusion of secondary organic aerosol formation processes, as well as increased number of size bins to treat the aerosol evolution processes. Furthermore, emission input files have been substantively updated to reflect the results from the 2013 aircraft measurement and other updated emissions inventories. These new developments in the model need in-situ observations to evaluate the model performance.

Project Objectives

In 2018, the second aircraft measurement project led by ECCC in collaboration with the National Research Council (NCR) will be conducted in the oil sands region. The project will be jointly supported by OSM and ECCC. The project will focus on understanding and characterizing the emission, transformation, transport and fate of oil sands air pollutants and will address the knowledge gaps identified above. The primary objectives of the 2018 aircraft project are:

1. *Characterizing and quantifying emission rates of criteria air contaminants and greenhouse gases from oil sands surface mining facilities in different seasons from the 2013 study, and emissions from in-situ oil sands facilities including Cold Heavy Oil Production with Sands (CHOPS) facilities*
2. *Quantifying the rates of change of the primary pollutants and formations of secondary pollutants in the atmosphere under different oxidation conditions*
3. *Determining the dry deposition fluxes of primary and secondary S and N pollutants onto downwind ecosystems on a spatial scale of 10^4 km^2*
4. *Valid satellite remote sensing retrievals, particularly the new generation of satellites.*
5. *Evaluating and improving air quality model performance*

These objectives will be addressed as follows

(1) Facility integrated emissions characterization using the topdown approach. Measurements will be made with box/screen flight plans to apply the Top-down Emission Rate Retrieval Algorithm (TERRA) developed at ECCC to determine emission rates. Flights will be conducted over surface mining facilities, in situ operations, and upgrading/refining facilities in Fort Saskatchewan.

(2) Source characterization. Gridded tracks over selected facilities will be flown to characterize the major sources within the main surface mining facilities and for selected in situ operations.

(3) Transformation and transport. Aircraft flights will follow air pollutant plumes downwind of surface mining and in situ operations to determine the chemical transformation rates of primary pollutants and formation of products as a function of downwind distance and atmospheric conditions.

(4) Dry deposition determination. The aircraft will be flown in specifically designed flight patterns to allow mass balance analysis for dry deposition fluxes of the oil sands air pollutant plume as it is transported downwind.

(5) Remote sensing and data product validation. Conduct validation flights for retrieval products from the *TropOMI*, *CrIS*, *VIIRS*, *MODIS*, and *GOSAT* satellites, and obtain measurements

of actinic flux radiance/irradiance and infra-red aerosol optical depth. Ground level mapping of 3-D particulate matter at a suitable location in the oil sands region will help aid the satellite data comparison.

Project Implementation Plan

Environment and Climate Change Canada (ECCC) has teamed up with the National Research Council (NRC) Flight Research Laboratory (FRL) to conduct the aircraft measurement program using the NRC Convair-580 research aircraft. The collaboration is articulated in a signed Memorandum of Understanding. The NRC Convair-580 research aircraft is suitable for addressing the scientific objectives of the project. The aircraft was successfully deployed in the 2013 airborne measurement project in the oil sands region, and has been used in multiple successful air quality research projects that ECCC had conducted. Operational planning details are listed below.

1. Regions of Airborne Measurements

The aircraft measurements will be conducted in and around oil sands surface mining facilities in the Athabasca region, in situ facilities in both the Athabasca and Cold Lake regions, as well as in the CHOPS regions between Cold Lake and Lloydminster.

1.1. The Athabasca Oil Sands Region

In the Athabasca Oil Sands Region, the facilities to be studied include both surface mining facilities and in situ bitumen production facilities. Table 1 shows the list of the facilities and their geographic coordinates in the Athabasca region over which measurements are planned along with flight virtual box coordinates surrounding each facility. Seven surface mining facilities include Syncrude Mildred Lake, Syncrude Aurora, Suncor Millenium and Steepbank, Suncor Forest Hill, Canadian Natural Resources Limited (CNRL) Horizon, CNRL Muskeg River and Jackpine, and Imperial Kearl Lake (Figure 1). Except the new Suncor Forest Hill facility, the emissions from other surface mining facilities were studied during the 2013 airborne measurement programs. The measurements will be conducted over the new Suncor Forest Hill facility for the first time.

In situ facilities in operation in the Athabasca Oil Sands Region which are of interest for emission measurements are also listed in Table 1, and include the Suncor Firebag, Suncor McKay River, Husky Sunrise, and Brion McKay River facilities in the north, the Nexen Long Lake, ConocoPhillips Surmont, CNRL Kirby, and JACOS Hangingstone facilities near Anzac, and further south in the near Conklin, the Cenovus Narrow Lake and Christina Lake facilities, the MEG Christina Lake facility, the Devon Jackfish facility, the CNRL Kirby Expansion facilities, and the Statoil Leismer facility (Figure 2). Depending on the available flight hours and logistic issues, a priority list for aircraft measurement flights over the in situ facilities will be made based on two criteria (1) production volume and (2) airspace restrictions due to close proximity to the Cold Lake Canadian Forces Base. In other words, some in situ facilities in the list may not be measured.

Table 1. Athabasca Oil Sands Region facilities to be in the focus of the measurements during the 2018 aircraft study. The waypoints for the aircraft flights are for the corners of the virtual boxes for each facility.

Facility Name	Sub-facility	Facility Type	Way point 1		Way point 2		Way point 3		Way point 4		Way point 5	
			NW Corner		NE Corner		SE Corner		SW Corner			
Fort McMurray Region												
Syncrude Mildred Lake		surface mining	57°08'56"	111°48'52"	57°08'56"	111°33'57"	56°55'54"	111°33'57"	56°55'54"	111°48'52"		
Syncrude Aurora		surface mining	57°21'00"	111°34'50"	57°21'00"	111°34'50"	57°17'42"	111°25'51"	57°17'42"	111°35'23"		
CNRL Horizon		surface mining	57°24'00"	111°58'11"	57°24'00"	111°39'25"	57°18'13"	111°39'25"	57°18'13"	111°58'11"		
CNRL Muskeg River and Jackpine		surface mining	57°17'36"	111°38'50"	57°17'36"	111°16'34"	57°11'28"	111°16'34"	57°11'28"	111°37'15"		
Suncor Millenium and Steepbank		surface mining	57°03'19"	111°32'59"	57°03'19"	111°12'29"	56°49'55"	111°12'29"	56°49'55"	111°24'22"	56°58'53"	111°32'59"
Suncor Forest Hill		surface mining	57°24'05"	111°39'22"	57°24'05"	111°29'46"	57°21'25"	111°29'46"	57°21'25"	111°39'22"		
Imperial Kearl Lake		surface mining	57°26'25"	111°11'22"	57°26'25"	110°59'20"	57°21'50"	111°00'20"	57°21'50"	111°11'22"		
Brion Energy Mackay River	south	in situ	56°49'09"	112°08'23"	56°49'09"	112°03'51"	56°46'02"	112°03'51"	56°46'02"	112°08'23"		
Brion Energy Mackay River	north	in situ	56°53'30"	112°15'35"	56°53'30"	112°13'31"	56°52'31"	112°13'31"	56°52'31"	112°15'35"		
Suncor Mack River		in situ	57°05'06"	111°56'58"	57°05'05"	111°51'06"	57°01'15"	111°51'06"	57°01'15"	111°56'58"		
Suncor Firebag		in situ	57°15'02"	110°56'29"	57°15'02"	110°48'55"	57°11'35"	110°48'55"	57°11'35"	110°56'29"		
Husky Sunrise		in situ	57°16'00"	111°07'28"	57°16'00"	111°00'16"	57°12'36"	111°00'16"	57°12'36"	111°07'28"		
Anzac Region												
Nexen Long Lake	whole facility	in situ	56°30'28"	111°01'39"	56°30'41"	110°51'59"	56°16'45"	110°52'20"	56°16'45"	111°03'20"		
Nexen Long Lake	plant	in situ	56°25'50"	110°58'55"	56°25'50"	110°54'54"	56°23'42"	110°54'54"	56°23'42"	110°54'54"		
ConocoPhillips Surmont		in situ	56°14'47"	111°01'28"	56°14'47"	110°47"41"	56°08'24"	110°47'41"	56°08'24"	111°01'20"		
JACOS Hangingstone Expansion		in situ	56°20'00"	111°40'33"	56°20'00"	111°36'03"	56°16'20"	111°36'03"	56°16'20"	111°40'33"		
Conklin/Christina Lake Region												
Cenovus Christina Lake		in situ	55°35'58"	110°55'41"	55°35'58"	110°47'24"	55°33'45"	110°47'24"	55°33'45"	110°55'41"		
Cenovus Narrows Lake		in situ	55°40'40"	110°55'07"	55°40'40"	110°49'15"	55°38'08"	110°49'15"	55°38'08"	110°55'07"		
Meg Christina Lake		in situ	55°41'39"	110°43'24"	55°37'23"	110°32'28"	55°34'56"	110°35'25"	55°38'56"	110°46'57"		
Devon Jackfish		in situ	55°33'15"	111°04'16"	55°33'15"	110°51'38"	55°29'43"	110°51'38"	55°29'43"	111°04'16"		
CNRL Kirby Expansion	south	in situ	55°21'07"	111°03'23"	55°21'07"	111°00'00"	55°19'51"	111°00'00"	55°19'51"	111°03'23"		
CNRL Kirby Expansion	north	in situ	55°29'04"	111°15'45"	55°29'04"	111°10'55"	55°26'16"	111°10'55"	55°26'19"	111°15'45"		
Statoil Leismer		in situ	55°50'12"	111°27'19"	55°48'37"	111°25'32"	55°46'27"	111°28'04"	55°46'54"	111°30'03"		

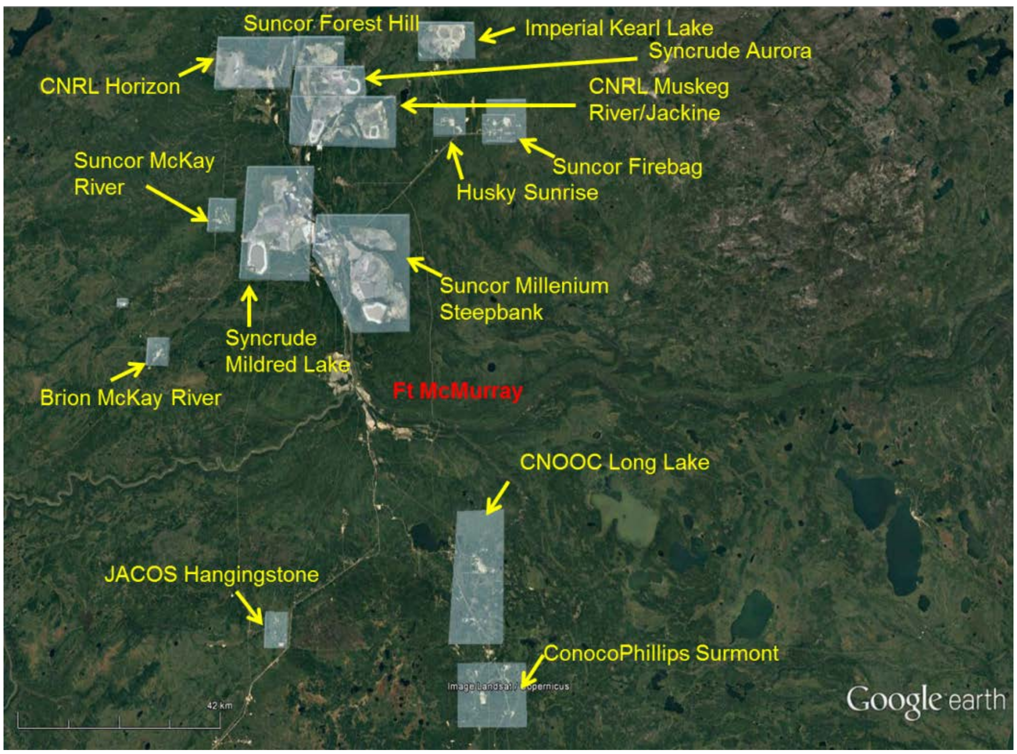

Figure 1. Surface mining and in situ facilities near Ft McMurray that will be studied during the aircraft measurement project.

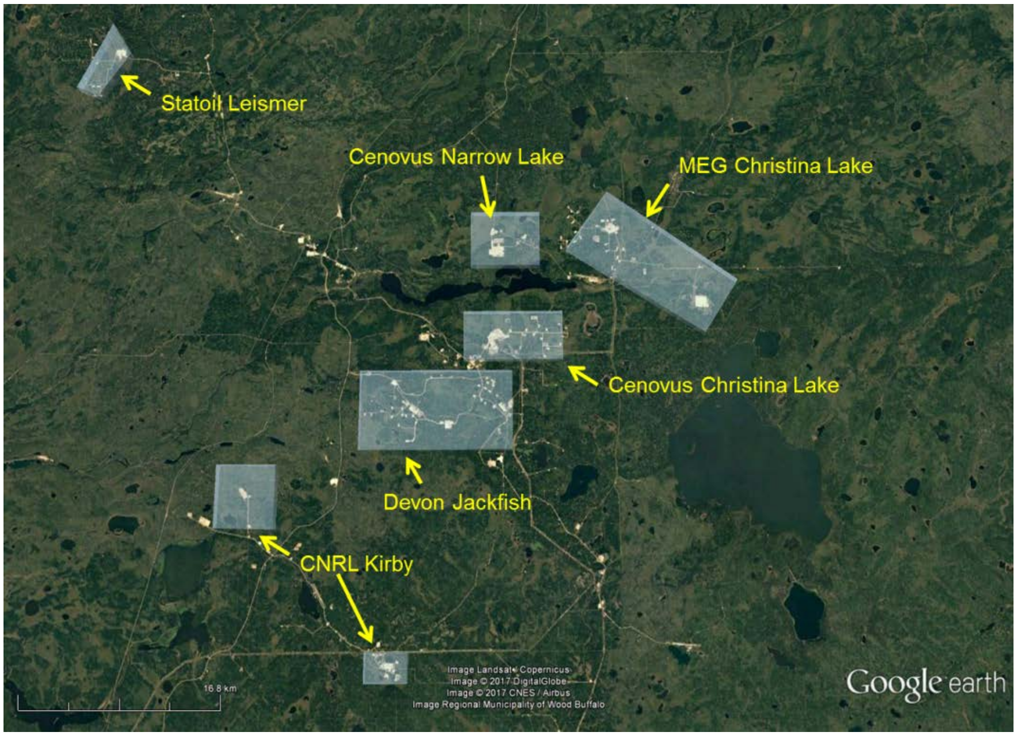

Figure 2. Major in situ facilities near Conklin, south of Ft McMurray area. The aircraft will be flown over these facilities to determine their air emissions.

1.2. Cold Lake Region

In the Cold Lake Region, the measurements will be carried out over in situ oil sands production facilities (Figure 3). Table 2 shows the facilities that the project plans to investigate. These include the Imperial facilities, the CNRL facilities, and the Cenovus Foster Creek facility.

Table 2. In situ facilities in the Cold Lake Region to be measured during the 2018 aircraft measurement project.

Facility Name	Sub-facility	Facility Type	Way point 1		Way point 2		Way point 3		Way point 4	
			NW Corner		NE Corner		SE Corner		SW Corner	
Cold Lake Region										
Imperial Cold Lake		in situ	54°44'54"	110°38'15"	54°44'45"	110°17'37"	54°33'17"	110°18'50"	54°32'58"	110°36'05"
CNRL Primrose	facility 1	in situ	54°43'21"	110°45'40"	54°43'21"	110°39'00"	51°39'53"	110°39'00"	54°39'53"	110°45'40"
CNRL Primrose	facility 2	in situ	54°56'18"	110°37'09"	54°56'18"	110°29'08"	54°45'24"	110°29'08"	54°45'24"	110°37'09"
CNRL Primrose	facility 3	in situ	54°50'03"	110°23'51"	54°50'04"	110°17'17"	54°45'24"	110°17'17"	54°45'24"	110°23'51"
Cenovus Foster Creek		in situ	55°05'56"	110°39'06"	55°05'56"	110°21'29"	55°02'06"	110°21'29"	55°02'06"	110°39'06"

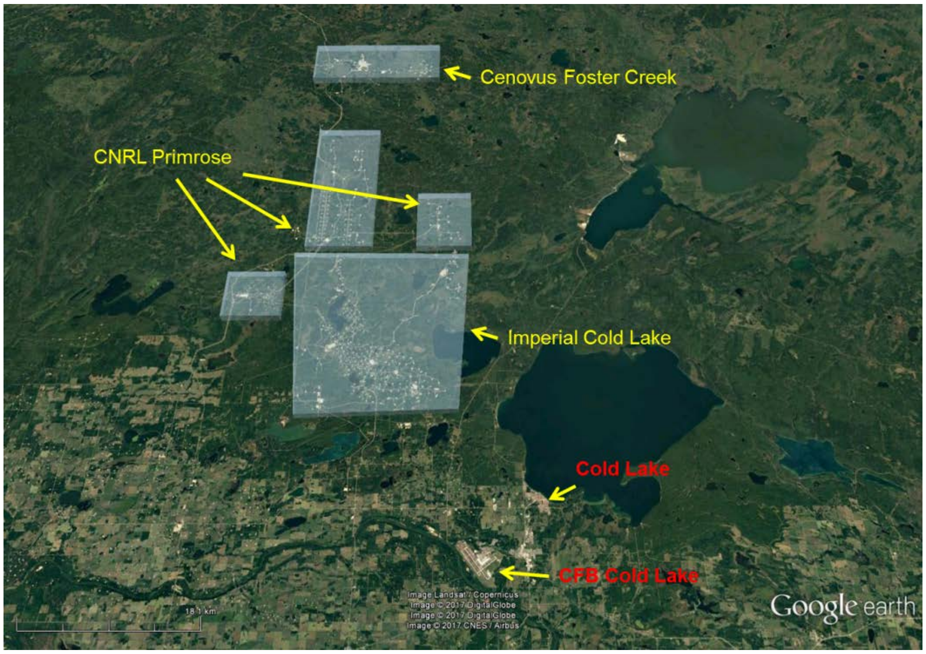

Figure 3. Major in-situ oil sands facilities near Cold Lake. The aircraft will be flown over these facilities to determine air emissions.

1.3. CHOPS Region

Specific CHOPS production facilities in regions between Cold Lake and Lloydminster will be defined for aircraft measurements. These facilities will likely be grouped into approximately 5x5 km^2 sections or larger for which the aircraft will be conducting measurements. The coordinates of these regions or facilities will be determined using the IHS database after consultation with Environmental Protection Branch of ECCC.

1.4. Scotford Upgrader

A specific flight is planned for making measurements over the Shell Scotford upgrading facility in Fort Saskatchewan.

2. Airborne Measurements

Instruments on the NRC Convair-580 aircraft will provide measurements of gases, particles, and meteorology. Table 4 gives the specific types of measurements and instruments. Measurements highlighted in yellow are new additions to the original instrumentation package from the 2013 aircraft study in the oil sands, and allow expanded characterization of the pollutant mix from the oil sands development. The increased measurements are a result of improved instrument designs, smaller packaging, and improved calibration procedures

Table 3. Planned measurements on the NRC Convair-580 for the 2018 aircraft study.

Measurement	Component	Instrument	Time Resolution	Type
Gases	SO_2	TECO 43i	continuous 1 sec	online
	NO	TECO 42i	continuous 1 sec	online
	NO_2	TECO 42i + photolytic converter	continuous 1 sec	online
	NO_y	TECO 42i + molybdenum	continuous 1 sec	online

		converter		
	O_3	TECO 42i + NO titration	continuous 1 sec	online
	CO	Picarro CRDS	continuous 1 sec	online
	CO_2	Picarro CRDS	continuous 1 sec	online
	CH_4	Picarro CRDS	continuous 1 sec	online
	VOC+OVOC (20+ compounds)	Ionicon PTR-TOF-MS	continuous 5 sec	online
	VOC (100+ compounds)	In-house automated canister system + auxiliary manual canister sampling	discrete 20 sec sampling intervals	sampling + lab analysis
	NH_3	LGR CRDS	continuous 1 sec	online
	Acids	Aerodyne CIMS	continuous 1 sec	online
	Glyoxal, epoxides	same CIMS instrument as above	continuous 1 sec	online
	H_2O_2, CH_3OOH	same CIMS instrument as above	continuous 1 sec	online
	N_2O_5, HCN, orgNO_3, HCl	same CIMS instrument as above	continuous 1 sec	online
	Elemental Hg	Tekran	continuous 2.5 min	online
	Total Hydrocarbon	Picarro CRDS + catalytic converter	continuous 5 sec	online
	IVOCs-SVOCs	In-house automated cartridge system	discrete 30 min sampling intervals	sampling + lab analysis
Particles	Number size distribution 0.05-1 um	DMT UHSAS	continuous 1 sec	online
	Number size distribution 0.3-20 um	DMT FSSP 300	continuous 1 sec	online
	Total number concentration	TSI CPC 3775	continuous 1 sec	online
	Black carbon mass conc and size distribution	DMT SP2	continuous 1 sec	online
	Chemical composition and size distribution	Aerodyne HR-ToF-AMS	continuous 10 sec	online
	Speciated chemical composition	Aerodyne CIMS + electrospray inlet (EESI)	continuous 1 sec	online
	Speciated chemical composition	In-house filterpack sampling	discrete 60 min sampling intervals	sampling + lab analysis
	Scattering at 3 wavelengths	TSI Nethphelometer	continuous 1 sec	online
	Absorption at 3 wavelengths	NOAA CLAP	continuous 1 sec	online

	Aerosol Optical Depth (AOD)	Sunphotometer (from NASA AMES)	continuous 1 sec	online
Meteorology	3-d Wind, T, RH, P	Rosemount 858 probe, Edgetch hygrometer, DigiQuartz sensor	continuous 1 sec	online
	Positioning, inertia	GPS, Honeywell inertial instrument	continuous 1 sec	online
Other	video recording of flight underpath		continuous 1 sec	
	cabin air quality		continuous	

3. Flight Designs

Specific flight patterns will be used to address: (1) emission rate characterization; (2) transport and transformation; (3) deposition; and (4) satellite retrieval validation. Flight patterns will generally follow the same approach used in the 2013 aircraft study in the oil sands region. These are briefly described here.

3.1. Emission Flights

Emission characterization will be based on a top down mass balance approach, using **TERRA** that was successfully applied to the 2013 aircraft measurements (Gordon et al., 2015; Li et al., 2017; Liggio et al., 2017a,b). This method is based on mass balance of a pollutant within an air volume that can be measured with an aircraft. Similar aircraft top down methodologies for determining emissions have also been used by other research groups.

In most cases, the aircraft will be flown along a polygon (mostly four sided) around a specific facility, at different altitudes from 150 meters up to above mixed layer height. The polygons at all flight altitudes can then be stacked to create a virtual box-like shape surrounding a facility. Fluxes across all walls of the box, including through the top, are calculated using measurements. The divergence in the in- and out-fluxes from the box is the emission rate.

The polygons will be mostly four sided for the larger oil sands facilities, as shown in Figures 1 to 3. Over small facilities, or components of a facility (such as a mine face or a tailing pond), cylindrical flights are planned, down to a minimum of approximately 5 km diameter. Over a regional scale, integrated emission rates may be obtained from single screen flights, during which the aircraft will be flown on the same flight tracks but at different altitudes to create virtual screens of pollutant concentrations (Baray et al., 2017). Results from all types of flights will be analyzed for emissions from the enclosures or from the screens using the **TERRA** tool.

3.2. Transformation Flights

Pollutants, once emitted into the atmosphere, undergo atmospheric transport, transformation, and deposition. The 2013 aircraft study demonstrated that such processes are important for the formation of secondary organic aerosols (Liggio et al., 2106), organic acids (Liggio et al., 2017a), and HNCO (Liggio et al., 2017b). During transformation flights an air pollutant plume from a specific oil sands facility (or a group of facilities) will be sampled successively at different atmospheric transport times, in a lagrangian experimental design. Hence, the transformation of the primary pollutants within the same plume parcel over time can be determined. The plume measurements will be conducted at specific times starting from either the source when a single source can be identified, or at a distance away from a group of sources (Liggio et al., 2016), with flight tracks perpendicular to the plume axis at different altitudes thus creating virtual screens. Such screens of pollutant concentrations along with wind measurements will allow the atmospheric transfer rates of air pollutants to be determined at different times. Formation rates of second pollutants can be determined from differences in the atmospheric transfer rates, as clearly demonstrated by Liggio et al. (2016, 2017a,b); similarly, the decaying rates for the primary pollutants can be determined using the same approach.

A software tool (**OnTheFly**) has been developed at ECCC to assist guiding the flights during lagrangian experiments. While the results from the 2013 lagrangian experiments were satisfactory and eventually led to important findings and publications, they relied on impromptu decisions by the flight director to guide the flight pattern, thus were restricted in spatial and temporal scopes for the flights. The **OnTheFly** tool will automate the task of determining the waypoints for the flights and thus providing guidance for the flights, while also providing scenario analysis tools for alternative flight designs in real time for different spatial and temporal scopes for the lagrangian experiments. Thus, it is anticipated that the new lagrangian experiments will allow the temporal/spatial scopes of transformation processes to be expanded compared to the 2013 study.

3.3. Deposition Flights

Deposition of atmospheric pollutants is driven by two processes, dry and wet. While wet deposition can be directly measured when precipitation occurs and is sampled for chemical analyses, dry deposition is always inferred from limited measured or modelled dry deposition velocities. Furthermore, dry deposition fluxes determined this way have high uncertainties especially when applied to large geographic regions. Despite these uncertainties, numerical air quality models rely on the inferred dry deposition velocities to predict the fates of air pollutants. There is a need for observation based dry deposition fluxes across large geographic regions that can be used to evaluate model performance in predicting dry deposition.

Based on a few selected flights during the 2013 aircraft study a methodology has been demonstrated that uses an extension of TERRA to compute a mass balance approach to estimate the dry deposition fluxes of atmospheric Sulphur and Nitrogen over large geographic regions upward of 10^4 km^2 (Hayden et al., 2017). A similar approach will be used in the 2018 aircraft study, with increased emphasis on deposition flux determination across different spatial scales downwind of the oil sands facilities. Again, the **OnTheFly** tool will be used to guide the flight pattern to achieve the mass balance measurements over different spatial and temporal scales.

3.4. Satellite Data Product Validation Flights

Satellite retrieval products can provide long term observation records of air pollutants over much of the oil sands region (McLinden et al., 2012). During the 2013 study, a component was built into the aircraft measurement plan to provide data to validate available satellite data products on NH_3, CH_3OH, HCOOH, and CO (Shephard et al., 2015).

Newly available satellite data products include those from the following existing satellites: TropOMI, VIIRS, MODIS, GOSAT, and OCO_2/OCO_3. The TROPOMI is a newly launched satellite and it is likely that this project will provide the first validation measurements. Geographic information on satellite pixel footprints for each of the above satellites for the oil sands region will be prepared in advance of the aircraft study, together with their overpass times. Under clear sky conditions, which are required for the satellite data validation flights, the aircraft will be flown over selected satellite pixel locations for deep vertical profile flights. Approximately 15 minutes before the satellite overpass, the aircraft will start to ascend from approximately 150 m above ground level to approximately the maximum aircraft altitude of 6500 m on a spiral pattern that covers a specific satellite pixel corners, thus obtaining vertical profiles of the pollutants. The aircraft will reach the maximum altitude while the satellite flies over the pixel location. After the satellite overpass, the aircraft will start descend toward 150 m altitude in approximately 15 minutes, thus obtaining a second vertical profiles down to the minimum altitude of 150 m. Therefore, two vertical profiles for each measured pollutant will have been created that encapsulates the satellite overpass.

4. Flight Planning

As noted above, flights will be conducted in virtual box and virtual screen patterns to allow mass balance determination of pollutant fluxes, which further allows emission rates, transformation rates, and deposition rates to be determined. Detailed flight planning will focus on the most efficient use of aircraft flight time, e.g., to achieve multiple objectives during any flight such as measuring to satisfy the needs for both satellite validation and emission determination. The details are given in a separate flight planning document.

5. Forecasting for Flight Planning

Flight plans are highly dependent on meteorology. The success of each flight depends on appropriate meteorological conditions. For example, during the emission flights, a consistent wind field, with consistently moderate wind speeds during flight around a facility, is essential. Divergence, especially in the vertical, can lead to biased results and increased uncertainties for the final emission rates.

Following the practice of the 2013 airborne study, detailed meteorological and air quality forecasts will be provided to the aircraft flight planners. The forecasters will provide detailed 3-hourly forecasts of meteorology over the oil sands region, including vertical structures of the atmosphere in the region. This forecast will be an enhanced version of the public forecast, and will be based on ECCC's GEM forecasting model. Furthermore, air quality forecast will be made at the same time intervals to provide guidance in terms of plume positions and directions from the oil sands region. The air quality forecast will be based on the GEM-MACH model driven by the GEM meteorology.

6. Data Quality Assurance, Quality Control, and Delivery

There will be a strong emphasis on data quality assurance (QA) and data quality control (QC), following the protocols at ECCC for air quality studies (Sukloff et al., 2006). There is a sequence of QA activities and documentations for each measurement to assure that the measurements will be conducted in accordance with the project plan to meet the objectives. For each measurement or group of measurements, a standard operating procedure (SOP) is required from the principal investigator(s). This is followed by a QA plan for such measurement that will precede the start of the measurements and will be completed after the measurement is completed. QA activities include standard certification where possible or in-house standard preparation, instrument preparation and calibration under normal operating conditions, inlet characterization, instrument optimization for the ambient conditions for sampling, and activities assuring capturing of data. Most of the activities will be carried out prior to and during the field deployment. Software tools, developed at ECCC, will aid these processes; the **QPLogger** captures the data and stores them in a relational database, while the **QPMonitor** allows realtime monitoring of measurements and allows capturing of metadata and flagging information.

Data QC activities will be carried out during and after the field measurements are completed. Pre-, during- and post-project calibration of instruments will be performed. Raw data will be processed into ambient air concentrations or equivalent for the measured pollutants. Instrument background shifts if any will be corrected. Backgrounds or blanks will be subtracted from the measurement results. Detection limits, accuracies, and precisions for the measurements will be determined and defined. Data will be validated using a standard set of flags, user defined flags, and field/laboratory notes. The final data sets will be converted to the ECCC NATChem Data Exchange Standard (DES) format, which will also include metadata. The finalized data in the NATChem DES format will be posted on ECCC publicly accessible web sites.

7. Field Measurement Periods

The aircraft measurements will be conducted over two periods to investigate the seasonal differences in emissions, transformation, and deposition. In addition, satellite validation is also envisioned for the two different seasons when ground conditions are not the same. The first measurement period will be from April 3rd to 20th, 2018. The second measurement period will be from May 28th to July 6th, 2018. The operational base will be at the Fort McMurray airport.

8. Coordination with Partners

The ECCC flight planning will be coordinated with the AEP-NOAA aircraft measurement study on GHGs in the oil sands region. For example, AEP-NOAA flight crews are expected to attend the ECCC flight weather and air quality forecasting. Under appropriate meteorological conditions, AEP-NOAA aircraft flights and ECCC flights will be coordinated over certain oil sands facilities, so that joint flights with NOAA aircraft are discussed and executed. Results from the coordinated flights will be used to complement each other or to inter-compare.

ECCC flights will also be coordinated with planned measurements of CH_4 at ground level and low level Unmanned Aerial Vehicle (UAV) flights at CNRL Horizon facility. The CNRL study focuses on quantifying emissions of CH_4 from area fugitive sources (tailings pond and mine face). Through detailed coordination, the ECCC aircraft measurements and the CNRL ground level measurements can be complementary to each other. Furthermore, coordinated calibration of instruments used in the aircraft ground measurements provides an opportunity to eliminate potential biases in the measurements. Advanced and on the day notice will be provided to CNRL for the flight planning over the CNRL Horizon facility.

Finally, ECCC flight plans will be communicated to, and coordinated with, COSIA for distribution to all industry partners. Flight planning-forecasting (1 and 2 days before) and flight decisions (day of) will be communicated to COSIA for distribution. This will provide lead-time of flight activities to industry partners. ECCC will be providing a wish list of activities that they would like to see industry partners' document during times that flights are conducted near selected facilities. Subsequent analysis and interpretation of the aircraft data could be significantly enhanced by knowledge of industry activities.

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Oil Sands Monitoring 2018 Aircraft Campaign

Flight Plans and Operations

1. Project Objectives

An aircraft campaign will be conducted in 2018 to study air pollutant emissions from oil sands activities and their subsequent transformation and fate in northern Alberta. This report provides comprehensive documentation on the flight plans and operations that support this campaign. Additional flights may be conducted, depending on funding and measurement conditions, to investigate emissions from other sources as described in Appendix A. Environment and Climate Change Canada (ECCC) is working collaboratively with the National Research Council of Canada (NRC) under an approved Memorandum of Agreement. NRC owns and operates a Convair-580 research aircraft that will be used in this study and has been used in multiple, successful air quality research projects, most recently in 2013 in the Alberta oil sands region. The project objectives contribute to the Oil Sands Monitoring (OSM) plan that ultimately seeks to understand the cumulative impact of oil sands emissions on ecosystems.

The specific aircraft campaign objectives are:

- To characterize and quantify emission rates of air pollutants from oil sands surface mining and oil sands in-situ mining
- To study the transformation of pollutants under different seasonal and oxidative regimes
- To characterize and quantify deposition fluxes of sulphur and nitrogen on a spatial scale of 10^4 km^2
- To evaluate and improve model capabilities
- To evaluate and validate satellite remote sensing retrievals

Should have a flight coordination section where joint flights with NOAA are discussed, and where industry is provided advanced and on the day of notice of flights over their facilities.

2. Regions of Interest

The aircraft will be based out of Fort McMurray, Alberta with flights being conducted in several different regions of Alberta including the Fort McMurray region, the Conklin/Christina Lake region, the Cold Lake region and the Cold Heavy Oil Production with Sand (CHOPS) region. Figure 1 shows a broad overview of mining facilities in these regions. Depending on suitable sampling conditions, flights may also take place in the surrounding provinces of BC, NWT and Saskatchewan.

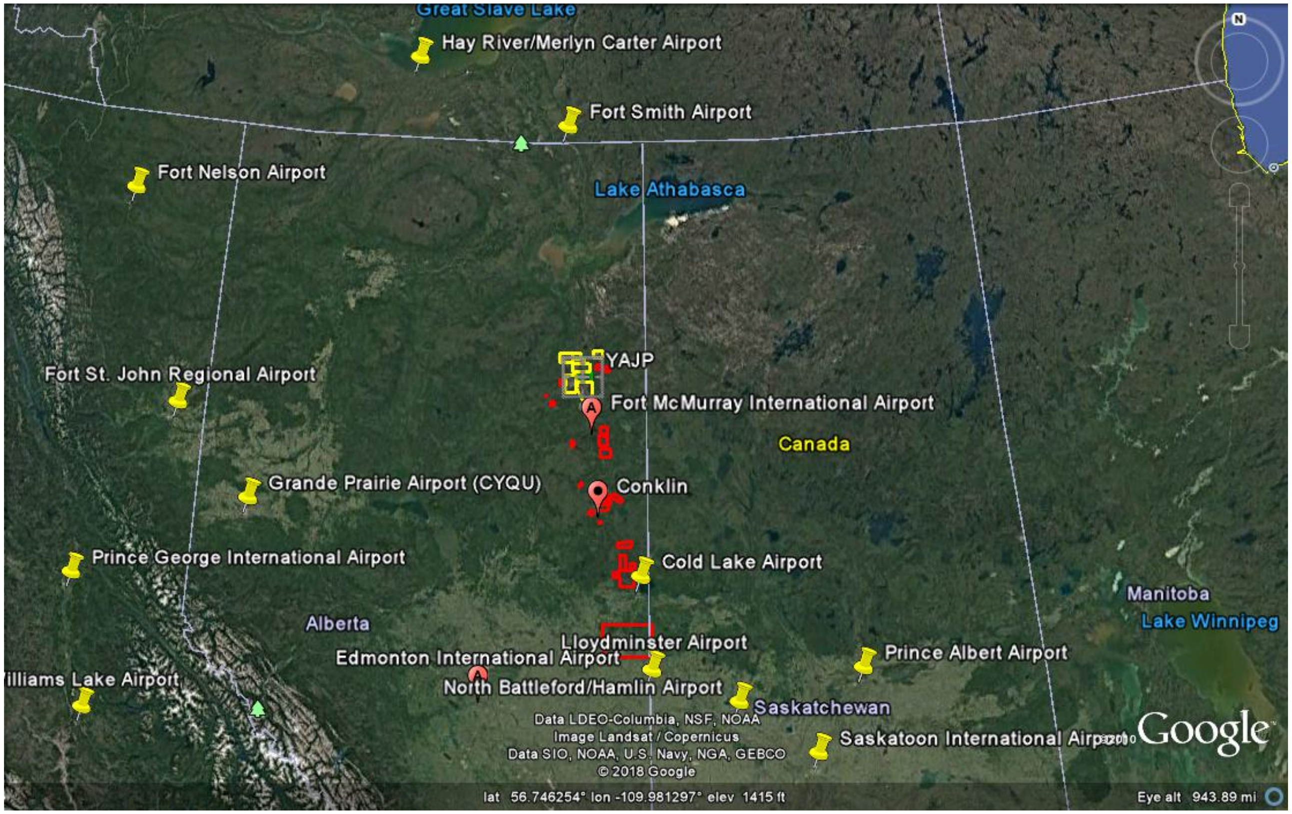


Figure 1. Map overview of regions of interest. Yellow boxes = surface mines; red boxes = in-situ mines.

3. Emissions Flights

Pollutant emission rates will be quantified for activities associated with surface mining and in-situ mining. Flights will be flown in a box-like pattern that encompasses the emissions area and at multiple altitudes. Flight tracks encompassing each facility will include a number of altitudes ranging from 350 masl (~150 magl) to above the mixed layer. In addition, densely gridded tracks may be flown over selected facilities at one or two altitudes to characterize the major sources within the facility.

3.1 Surface Mines

Emissions from **s**even surface mines in the Fort McMurray region will be studied as identified in Table 1. Estimated waypoints for the box corners are in Table 1 and the flight tracks (yellow) are shown for the Fort McMurray region in Figure 2. In Table 1 estimated times are shown to complete an entire box (first value) and the estimated time to fly a grid (second value). The box time estimates accounts for 10 vertical altitudes and the grid time estimate is based on one altitude with 2 km spacing.

		North East		North West		South East		South West		Angle Screen or Centre Point		North-South Screen	West-East Screen	Box Time/Grid Time
		Lat N	*Lon W*	*Lat N*	*Lon W*	*Lat N*	*Lon W*	*Lat N*	*Lon W*	*Lat N*	*Lon W*	*Km*	*Km*	*hours*
Fort McMurray Region														
Syncrude Mildred Lake	**SML**	57.148	-111.566	57.148	-111.814	56.931	-111.566	56.931	-111.814			24	15	2.46/0.6
Suncor Millenium and Steepbank	**SUN**	57.055	-111.208	57.057	-111.550	56.832	-111.208	56.831	-111.406	56.981	-111.550	25	21	2.90/0.8
CNRL Horizon	**CNRL-H**	57.400	-111.657	57.400	-111.970	57.304	-111.657	57.304	-111.970			11	17	1.77/0.3
CNRL Muskeg River/Jackpine	**CNRL-MJ**	57.293	-111.276	57.293	-111.647	57.191	-111.276	57.191	-111.621			10	23	2.10/0.5
Imperial KearlOil Sands	**IKOS**	57.440	-110.988	57.440	-111.189	57.362	-110.973	57.366	-111.189			9	13	1.40/0.18
Syncrude Aurora	**SAR**	57.363	-111.005	57.350	-111.581	57.295	-111.431	57.295	-111.589			7	15	1.40/0.2
Suncor Fort Hill	**SFH**	57.401	-111.496	57.401	-111.656	57.357	-111.496	57.357	-111.656			7	12	1.20/0.15
York Athabasca Jack Pine	**YAJP**	57.173	-111.232	57.182	-111.531	57.060	-111.225	57.065	-111.548	57.122	-111.426	13	18	1.96/0.38

Table 1. Estimated waypoints, screen lengths and times for box emission flights around the surface mines (yellow) and the tower site (green) in the Fort McMurray region.

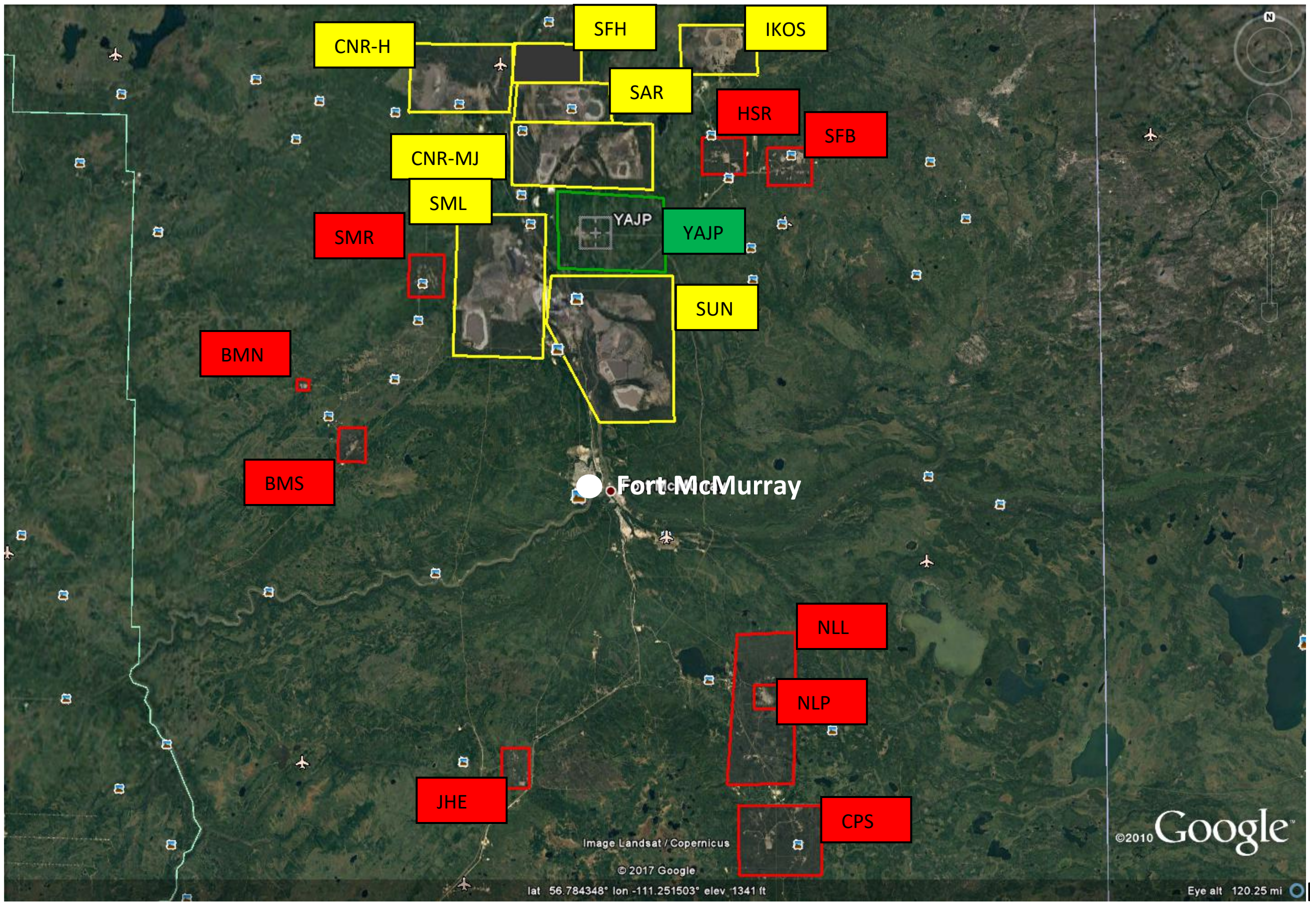


Figure 1. Box flight patterns around the surface mining facilities (yellow), in-situ mining facilities (red) and the tower site (green) in the Fort McMurray region.

3.2 In-Situ Mines

In-situ mines that are being considered for emissions quantitation are grouped by region including the Fort McMurray region, the Conklin/Christina Lake region and the Cold Lake region. Estimated waypoints for the box corners and flight times are in Table 4 for all the in-situ mines in these regions. The box time estimates accounts for 7 vertical altitudes and the grid time estimate is based on one altitude with 2 km spacing. Flight tracks are shown in red for the Fort McMurray in-situ mines in Figure 1, for the Conklin/Christina Lake in-situ mines in Figure 2 and for the Cold Lake region in-situ mines in Figure 3. The CHOPS region, shown in Figure 3, will likely be divided into 5x5 km^2 sectors to target groupings of faciltiies. Additionally, a specific flight is planned for making measurements over the Shell Scotford upgrading facility in Fort Saskatchewan. Also shown in Table 4 is a ranking based on the sixteen highest bitumen production rates (according to average monthly crude bitumen production rates) for Alberta in-situ mines (data from Alberta Energy Regulator). The ranking is used to identify, prioritize and optimize flights around these facilities.

		North East		**North West**		**South East**		**South West**		**North-South Screen**	**West-East Screen**	**Box Time/Grid Time**	**Production Rate Ranking**
		Lat N	***Lon W***	***Lat N***	***Lon W***	***Lat N***	***Lon W***	***Lat N***	***Lon W***	***Km***	***km***	***hours***	
Fort McMurray Region													
Suncor Firebag	**SFB**	57.250	-110.816	57.250	-110.941	57.193	-110.816	57.193	-110.941	6	7.5	0.6/0.1	1
Suncor Mackay River	**SMR**	57.085	-111.860	57.085	-111.949	57.021	-111.852	57.021	-111.949	7	6	0.6/0.06	10
Husky Sunrise	**HSR**	57.267	-111.004	57.267	-111.124	57.210	-111.004	57.210	-111.124	6	7	0.6/0.06	11
Brion Energy Mackay River south	**BMS**	56.819	-112.064	56.819	-112.140	56.767	-112.064	56.767	-112.140	5.5	4	0.4/0.03	No report
Brion Energy Mackay River north	**BMN**	56.891	-112.225	56.891	-112.260	56.875	-112.225	56.875	-112.260	1.7	2	0.2/0.005	No report
Nexen Long Lake	**NLL**	56.511	-110.866	56.508	-111.027	56.279	-110.872	56.279	-111.055	26	10.5	1.6/0.6	13
Nexen Long Lake Plant	**NLP**	56.430	-110.915	56.430	-110.982	56.395	-110.915	56.395	-110.982	3	4	0.3/0.015	?
ConocoPhilips-Surmont	**CPS**	56.246	-110.794	56.246	-111.024	56.140	-110.794	56.140	-111.022	11	14	1.1/0.24	8
JACOS Hanginstone Expansion	**JHE**	56.333	-111.601	56.333	-111.676	56.272	-111.601	56.272	-111.676	7	5	0.53/0.05	Very small
Conklin/Christina Lake Region													
Cenovus-Christina Lake	**CCL**	55.599	-110.790	55.599	-110.926	55.563	-110.790	55.563	-110.928	4	9	0.6/0.07	3
Cenovus	**CNL**	55.678	-110.821	55.678	-110.919	55.636	-110.821	55.636	-110.919	4.6	6	0.5/0.05	?

Narrows Lake													
MEG-Christina Lake	**MCL**	55.623	-110.541	55.694	-110.723	55.582	-110.607	55.649	-110.782	14	6	0.9/0.19	6
Devon-Jackfish	**DJF**	55.554	-110.861	55.554	-111.071	55.495	-110.861	55.495	-111.071	6.5	13	0.9/0.15	5
CNRL-Kirby Expansion south	**CKS**	55.352	-111.000	55.352	-111.056	55.331	-111.000	55.331	-111.056	2	3.6	0.3/0.19	?
CNRL Kirby Expansion north	**CKN**	55.484	-111.182	55.484	-111.263	55.437	-111.182	55.438	-111.263	5	5	0.4/0.03	9
Statoil Leismer	**STL**	55.810	-111.426	55.837	-111.455	55.774	-111.468	55.782	-111.501	6.4	3	0.4/0.03	15
Cold Lake Region													
Imperial Cold Lake	**ICL**	54.745	-110.294	54.748	-110.637	54.555	-110.314	54.549	-110.601	22	22	1.9/0.77	2
CNRL Primrose facility 1	**CN1**	54.723	-110.650	54.723	-110.746	54.665	-110.650	54.665	-110.761	6.5	7	0.6/0.06	7 – probably this
CNRL Primrose facility 2	**CN2**	54.938	-110.485	54.938	-110.619	54.757	-110.485	54.757	-110.619	20	8	1.2/0.37	?
CNRL Primrose facility 3	**CN3**	54.834	-110.288	54.834	-110.397	54.757	-110.288	54.757	-110.397	8.5	7	0.7/0.09	?
Cenovus Foster Creek	**CFC**	55.099	-110.358	55.099	-110.651	55.035	-110.358	55.035	-110.651	7	19	1.2/0.3	4
	CHOPS	54.078	-109.951	54.078	-110.97	53.675	-109.951	53.675	-110.970	45	67	5.0/5	

Table 4. Estimated waypoints, screen lengths and times for box emission flights around in-situ mines (red) and a bitumen production rate ranking.

- Where is CNRL Britnell geographically located? Ranked 12
- Where is Husky Tucker Lake? Ranked 16

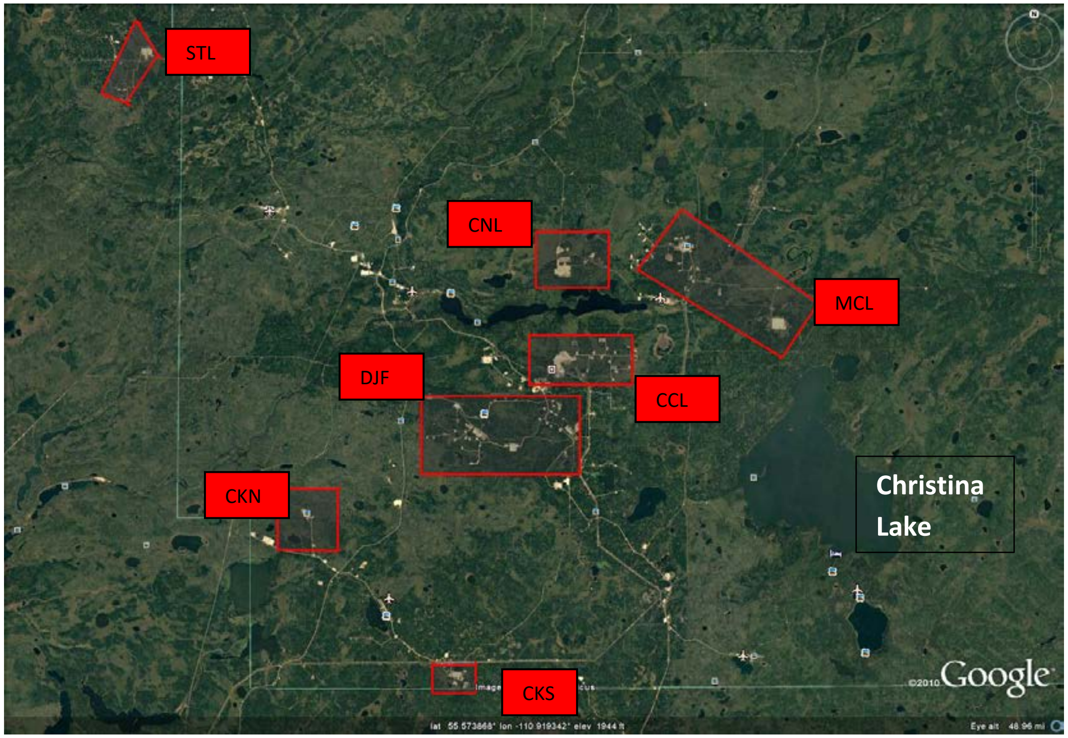


Figure 2. Box flight patterns around in-situ mining facilities in the Conklin/Christina Lake region (red).

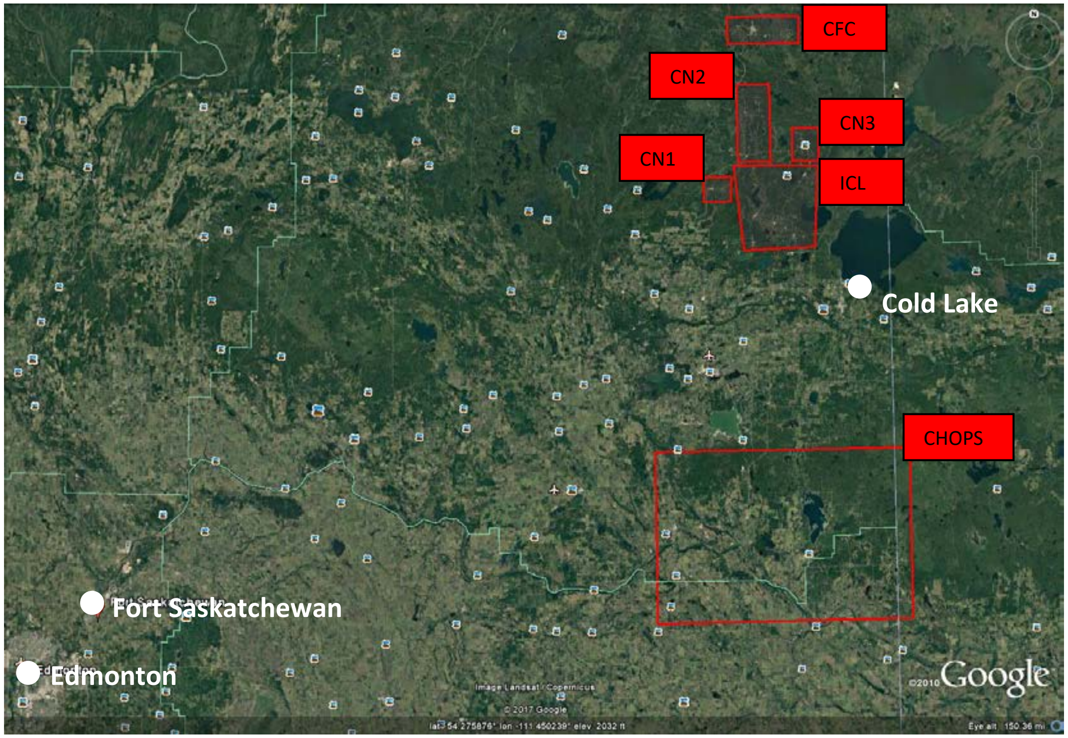


Figure 3. Box flight patterns around in-situ mining facilities in the Cold Lake region (red).

3.3 Upgrader facilility

A specific flight is planned for making measurements over the Shell Scotford upgrading facility in Fort Saskatchewan (Figure 3).

4. Transformation and Deposition Flights

4.1 Lagrangian Flights

Flights that address transformation and deposition of pollutants emitted from oil sands activities and forest firest will be conducted in a Lagrangian pattern in which the same plume will be repeatedly sampled along the plume axis. Flight tracks will be designed to intercept the plume at increasing distances away from the sources. At each intercept flight tracks will be flown at multiple altitudes to create virtual screens to capture the entire plume. Figure 4 illustrates the flight tracks and virtual screens for a Lagrangian flight during the 2013 aircraft study.

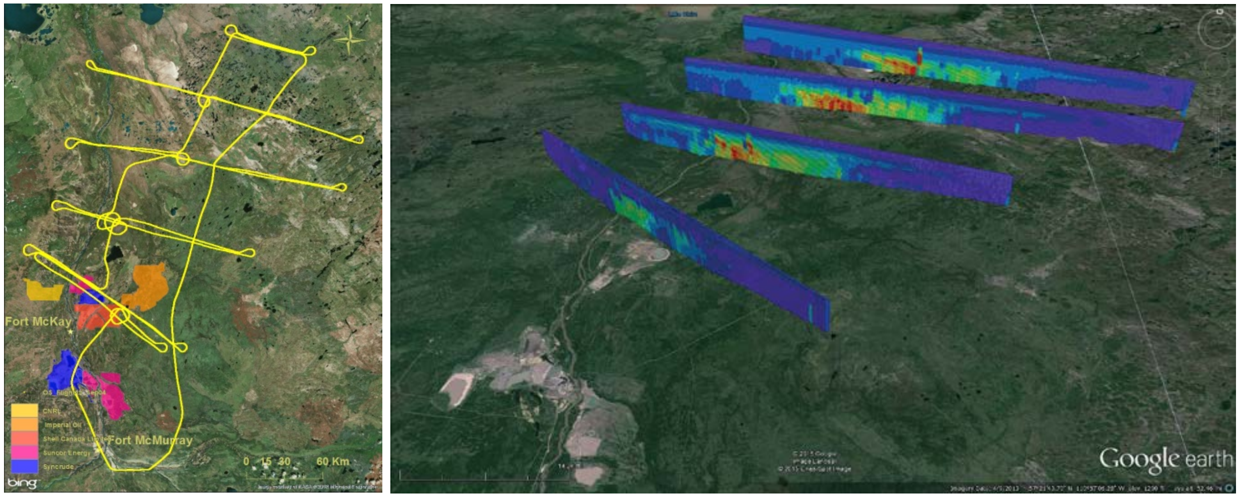


Figure 4. Lagrangian flight pattern for transformation/deposition flights showing a) flight tracks and b)kriged flight data to create virtual flux screens.

4.2 OnTheFly

A newly developed program at ECCC, OnTheFly, has been developed to assist with the determination of the waypoints for the transformation/deposition flights. Using a gaussian plume distribution, the program calculates the interception of the plume with realtime in-flight wind data. The program will be used during pre-flight planning to determine the optimum number of downwind flight screens, number of altitudes, and distance between flight screens based on current and forecasted meteorology. Waypoints will be identified and communicated to the pilots. The program will also be used in-flight to further optimize the waypoints using realtime wind data to track the plume in a Lagrangian manner. The program interface is shown in Figure 5.

4.3 Flux Tower Site

During the aircraft study, measurements on a 30-m flux tower will provide data below the lowest aircraft flight altitude. The flux tower will be set up and operated by York University (Prof. Mark Gordon) and is located at the York Athabasca Jack Pine (YAJP) site at 57.1226 N, -111.4266 W. The tower will support multiple profile measurements at various heights as shown in Table 5. In order to relate the aircraft measurements to the tower measurements, a potential flight track is to fly a box/screen pattern around the YAJP site. Waypoints for this flight track are provided in Table 4 and illustrated in Figure 2, green box.

Measurement	Instrument	Period	Meas. Height (m)
Wind, turbulence	ATI Vx	From July 2017	4.0
	ATI V		9.0
	ATI A		31.4
CO_2 and H_2O	Licor LI-7500	From July 2017	4.0
	Licor LI-7500RS		31.4
O_3	2B Model 205	June 2018	2.0
	2B Model 205		6.3
	2B Model 205		Variable heights
Dust (PM1, 2.5, 10)	TSI Dustrax	June 2018	2.0
	TSI Dustrax		16.6
SW and LW	CNR2	From July 2017	31.4
PAR	Licor, LI-190	From July 2017	2.0
	Licor, LI-190		9.0
	Licor, LI-190		31.4
UV	CUV5L	From July 2017	2.0 m or variable heights
Sub-micron aerosols	UHSAS	June 2018	Sample line to 31.4
BC aerosols	SP2	June 2018	Sample line to 31.4
SO_2	TECO?	June 2018	Sample line to 31.4
NO_x	TECO?	June 2018	Sample line to 31.4

Table 5. Planned profile measurements on the 30-m flux-tower at the YAJP site.

5. Satellite Validation

There are a number of satellites/instruments in orbit that are relevant for comparison with the 2018 aircraft study and a summary is provided in Table 6. Priority instruments for data validation are highlighted in green. Unlike during the 2013 aircraft study, spatial resolution is full coverage and there are overpasses everday so the primary consideration is overpass time. Many of the box and transformation flights are considered useful for validation. The following are criteria identified for optimal satellite validation:

- Particulate matter (ie. AOD satellites) are the top priority

- GOES-R satellite measurements are useful throughout the day
- Flights that incorporate 10-15 km diameter spirals (to fill in pixels) and transects to cover multiple pixels are useful
- Ideally there is <20% cloud fraction
- Ideal to collect aircraft data under cloud-free conditions over mixed snow/snow-free surface

Satellite	**Instrument**	**Measurements**	**Overpass time (LT)**			**Spatial resolution (km)**
			March 15	April 20	June 29	
Sentinel – 5p(launched Oct 2017)	TropOMI	NO2, SO2,HCHO, CO, CH4, AOD	17:35	19:46	19:53	7x7 nadir; 7x17 wings
NPP, JPSS1 (launched Nov 2017)	CriS	NH3	17:32	19:43	19:50	14
	OMPS	SO2				15
	VIIRS	AOD				3
GOES-R (launched Nov 2016)	ABI	AOD	Half-hourly (TBC)	Half-hourly (TBC)	Half-hourly (TBC)	2
Aqua	MODIS	AOD	18:01	20:56	20:14	3 (?)
Aura	OMI	NO2, SO2, HCHO	18:08	20:09	20:09	13x24
MetOp-A/B	IASI	CO, NH3	20:55		20:30	12
Terra	MODIS	AOD	16:17	19:03	18:26	3
	MOPITT	CO				22

Table 6. Summary of satellites/instruments in orbit that are relevant for comparison with the 2018 aircraft study. Priority satellites for comparisons are highlighted in green.

6. Schedule

A significant amount of work has already taken place over the past 6 months in the planning and identification of the aircraft measurement payload, design and fabrication work, instrument improvements and testing, and technical support activities. Intensive work on the installation and integration of measurement systems will start early February and continue to near the end of March. The week of March 19 is planned for test flights with last week set aside for final preparations. The aircraft will be based at the Fort McMurray airport (56.653 N, -111.226 W) and operated out of the Golosky hangar as was done in the 2013 campaign. A small team will organize and prepare the hangar space for our operations during the last week of March and pack up after the conclusion of the study.

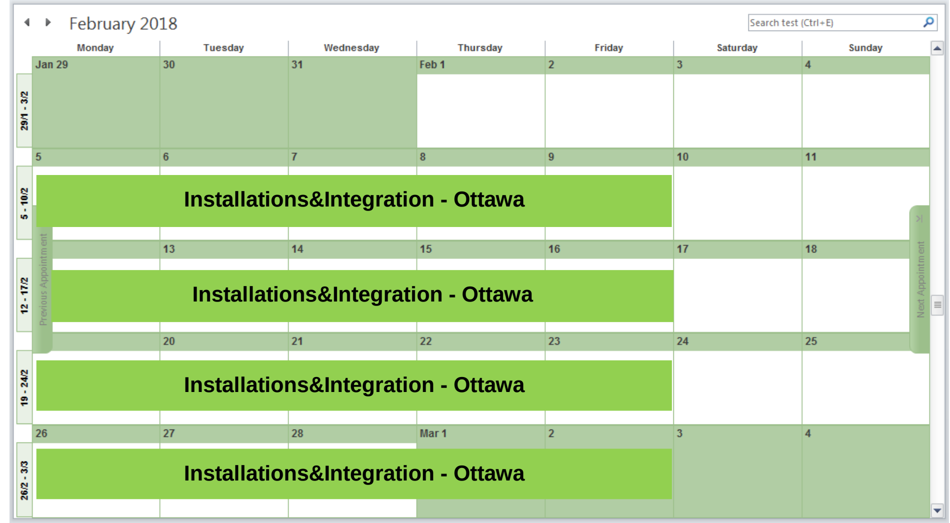
The project will take place during two phases for a total of 9 project weeks in the field. The schedule with relevant project activities from January to July is shown in Figure 5.

<u>Phase 1</u>:
3 weeks, ~25 flight hours
Tues April 3 – Convair departs Ottawa and arrives in Fort McMurray. First science flight Thurs Apr 5.
Friday Apr 20 – Convair departs Fort McMurray and arrives in Kelowna. Last science flight Thurs Apr 19.

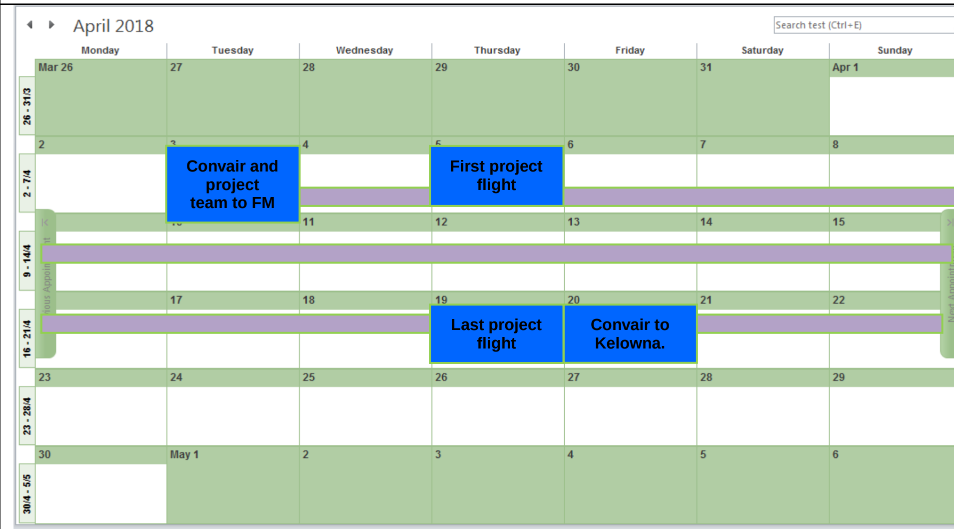
<u>Phase 2</u>:
6 weeks, ~80 flight hours
Mon May 28 – Convair departs Ottawa and arrives in Fort McMurray. First science flight Wed May 30.
Fri July 6 – Convair departs Fort McMurray and arrives in Ottawa. Last science flight Thurs July 5.

After the conclusion of the first phase, the Convair will fly to Kelowna for some pre-planned engine maintenance which will take an estimated 7-10 days. Prior to the aircraft departure, all measurement systems will be powered off and remain off during this maintenance. After the maintenance is completed, the Convair will fly to Ottawa for some further regular maintenance until departure for the second phase. Power to measurements systems will be available.


January 2018
Convair grounded
Scouting trip – Fort McMurray


February 2018
Installations&Integration - Ottawa
Installations&Integration - Ottawa
Installations&Integration - Ottawa
Installations&Integration - Ottawa


March 2018
Installations&Integration - Ottawa
Test flights - Ottawa
Final preparations - Ottawa
Hangar set up – Fort McMurray


April 2018
Convair and project team to FM
First project flight
Last project flight
Convair to Kelowna.

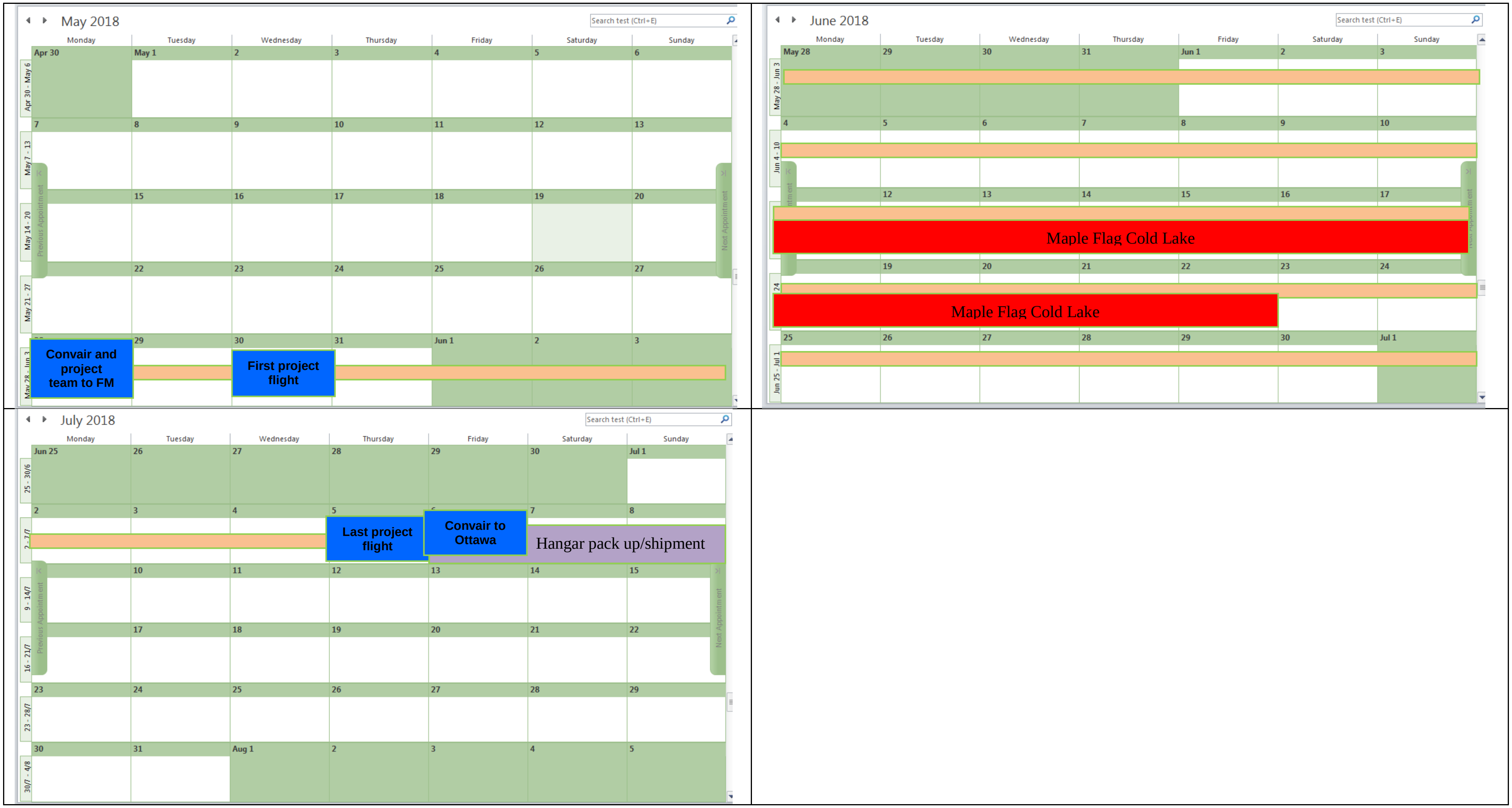


Figure 5. Month by month schedule of project activities from January to July.

7. **Flight hours and optimization**

The current, planned distribution of flight hours is shown in Table 7. There are a total of 105 science hours allocated for the OS project over the two phases. Depending on funding, consideration has been given for an additional 35 for potential flights targeting forest fire emissions and emissions related to hydraulic fracturing activities. Compared to the 2013 aircraft study, an increased proportion of flight hours will be devoted to transformation/deposition flights with the understanding that meteorology during the study will predominantly dictate the relative allocation of flight hours to each of the project objectives.

Objective	Time period	Hours (#)
Emissions/satellite validation	April 2018 – 3 weeks	25
Transformation/deposition, emissions, satellite/model validation	June/July 2018 – 5 weeks	80
Forest fires	June/July 2018	10
Fracking	June/July 2018	25
Total science hours		***140***
Test flights – pre April study	March 2018	10
Transit flights – April study	April/April 2018	15
Test flights – pre June study	May 2018	5
Transit flights	May/July 2018	15
Total non-science hours		***45***
TOTAL hours		**185**

Table 7. Distribution of flights hours for the 2018 aircraft study.

Optimization

Of the 105 science flight hours, 50 flight hours will be allocated to measuring emissions and 55 hours will be allocated to studying transformation and deposition. The design of these flights will also provide data sufficient for satellite validation and model comparisons. It is anticipated that the aircraft will fly at the same selected altitudes for both the emissions and transformation/deposition flights as indicated below, and that the number of altitude levels chosen will be dependent on the height of the boundary layer and the selected number of horizontal cross sections (for transformation/deposition flights).

Altitudes

1. 500’ (152 m)
2. 750’ (228 m)
3. 1000’ (305 m)
4. 1250’ (381 m)

5. 1500’ (457 m)
6. 1750’ (533 m)
7. 2000’ (610 m)
8. 2250’ (685 m)
9. 2500 (762 m)
10. 3000’ (914 m)

Phase 1

- Estimated 5 5-hr flights (25 hours)
- Focus on surface mines and one tranformation/deposition flight
- Anticipate 7 altitude levels around each facility (depending on mixed layer height)
- If poor weather, consider other locations outside of the FMM region

Sites	Winds	Hours
CNRL-H + SML	North, south and west winds; NOT east winds	3.0
SUN + grid	south and east winds; maybe north; NOT west winds	3.6
SFH + SAR + CNRL-ML + IKOS OR SAR + CNR-ML + IKOS	north	4.3
SML + grid for satellite validation	South and west winds; NOT east winds	3.0
Deposition	Westerly	5.0
		~25 hours (20 Emissions, 5 T&D)

Phase 2

- Estimated 6 Emissions flights (30 hrs) and 10 Transformation/Deposition flights (50 hrs) for a total of 80 flight hours
- Anticipate 10 levels around the larger surface mining facilities and ~7 levels around in-situ mining facilities
- Selected flights to include grid tops
- 16 in-situ facilities have been ranked, based on highest production rates
    - assumption is that higher production rates result in higher emission rates
    - if emission rates are above the reporting threshold for a facility then we can compare with our measurements
    - if you know the emission rate and production volume, then it’s possible to derive emission factors

Sites	Winds	Hours
SML (+grid) + SMR + YAJP	southwest	4.1
CNRL-H + CNRL-ML + SAR	West, east, ?? difficult	5.2
IKOS + SFB + HSR + SFH + SAR	East, south, north	5.2

SUN + YAJP	Southwest	4-5
CCL + MCL + DJF + CKN (Conklin/Christina Lake region)	Any wind direction ?	4.1 (2.8 mission + 1.3 transit to/from = 4.1hrs). No stop to refuel.
ICL + CN1(?) + CFC (Cold Lake region)	Any wind direction ?	5.1 (3.6 mission +1.5 transit to/from=5.1hrs) Stop to refuel in Cold Lake before/after mission
Transformation/Deposition		5 hours/flight * 10 flights = 50
		~80 hours (30 Emissions, 50 T&D)

8. Hangar operations

- Aircraft parked outside
- Heater available for April time period
- Designated hangar space
- VOC module analyses, 24 hr/7 day operation, LN2/GC set up, extra power being installed
- VOC basket can shipment out only to Ottawa for analysis
- Security overnight due to 24 hr power
-

9. Aircraft payload

A comprehensive suite of atmospheric measurements will be made including gases, aerosol physics and chemical composition and meteorology. The complete planned instrumentation package is shown in Table 8. Measurements will be conducted during daytime hours and in-cloud free conditions that span a range of 150 to 6000 magl in altitude. Most of the flights will take place within and just above the boundary layer. with occasional vertical spirals/ascents reaching no more than 6000 magl in order to provide comparison data for satellite retrieval products.

Instrument	Manufacturer	Measurement
Particles		
UHSAS	DMT	Particle number 50nm-2um
SP2	DMT	black carbon
CPC 3775	TSI	particle number (10nm - 2.5um?)
CAPS	Aerodyne	extinction
HR-ToF-AMS	Aerodyne	particle chemistry and size distributions (SO_4^{2-}, NO_3^-, NH_4^+, org)
CIMS + electrospray inlet	Aerodyne	particle chemistry
FSSP300	DMT/PMS	size distribution (0.3-20 um)
PCASP	DMT/PMS	size distribution (50nm - 2um)
sun photometer	from NASA-AMES	aerosol optical depth, O3, H2O
filter packs	filter packs	coarse particle chemistry
nephelometer	DMT	scattering
CLAP	DMT	absorption
Meteorology		
Rosemount 858 probe, Edgetech hygrometer, DigiQuartz sensor	NRC	winds, temperatures, RH, pressure
GPS and Honeywell inertial measurement unit	NRC	altitude, position
Other		
Video cameras	NRC	videos
Cabin Air Quality	NRC	various

Instrument	Manufacturer	Measurement
Gases		
TECO 42i+photolytic converter	CD NOVA	NO2
TECO 42i	CD NOVA	NO
TECO 42i+molybdenum external converter	CD NOVA	NOy
TECO43i	CD NOVA	SO2
TECO 42i	CD NOVA	O3
CRD	Picarro	CO, CO2, CH4
Total Hydrocarbons	Picarro	Total Hydrocarbons
PTR-ToF MS	Ionicon	VOCs
canisters	in-house	VOCs
CIMS	Aerodyne	acids, glyoxal, HNO3, N2O5, IEPOX, MAE, H2O2, methylH2O2,
Isopark	LGR	NH3
Tekran	Tekran	Hg
Cartridges	in-house	IVOCs

Table 8. Instrumentation and measurements planned on the NRC Convair-580 for the 2018 aircraft study.

10. Flight Operations

Flight Operations in the Fort McMurray area are planned to be very similar to those conducted in 2013. The aircraft will operate to/from CYMM (Fort McMurray) airport and fly predominately under visual flight conditions. Higher altitude missions for sampling above 12,500 ft MSL will entail an IFR clearance. All the procedures and frequencies are well known and understood, including the Oil Sands ATF frequency with procedures laid out in the Canadian Flight Supplement publication planning section, carried onboard NRC aircraft.

Flight in proximity to the four main airfields of the oil sands region – Firebag, Albian, Mildred Lake, and Horizon - have published frequencies that will be monitored and/or contacted with the aircraft's intentions during flight as appropriate for safe flight. The Convair TCAS system provides alerts regarding the location of other aircraft as they are mandated to "squawk" their position through a transponder and the TCAS monitors those signals, with a clear display to the pilots.

In the research area, low level unmanned vehicles (UAVs) are limited to 400 ft AGL and below, and their operations must be communicated through NOTAMs with time and location information which are checked prior to any flights. Given these tools, deconfliction from air traffic and UAVs is not a concern. Although there is a concentration of air traffic in the area of Fort McMurrary, it is far less than that normally experienced by NRC pilots during science flights in the Toronto or Ottawa area.

Establishing appropriate minimum flight altitudes will be in accordance with previous science flights and normal NRC procedures. Over non-built up areas, flight is permitted down to a minimum of 500 ft clear of any person, vessel, vehicle or structure as per the Canadian Aviation Regulations (CAR 602.14). This can be a slant distance, although it is easiest to apply it as a minimum operating altitude in the vertical.   Therefore flight tracks will be planned at not below 500 ft AGL (above any structure). Over flat terrain devoid of any person, vessel, vehicle or structure the aircraft can be comfortably (and legally) flown down to 250 ft AGL for limited additional sampling should it be needed.

Over built up areas such as the towns of Mildred Lake, Fort MacKay, and Bitumount the minimum altitude is 1000 ft AGL on a track within 2000 ft of these towns. Direct overflight of major industry infrastructure and work camp trailers should be included as a built up area for planning purposes. In that regard, the southern track of the SAJ box, the eastern track of the SML box, the western track of the SUN box, and the eastern track of the SNR box described below in this document are approximately 1 nm (6080 ft) laterally from the town of Fort MacKay, Mildred Lake (2), and Bitumount respectively. These are the only lines that are in close proximity to any built up areas – but the tracks are acceptable as planned. Should it be evident on the first flight in any area that areas have become more broadly built up, the lines can be easily adjusted in real time to provide legal and safe clearance from built up areas.

The same regulations and procedures will apply for forest fire and fracking flights as per the campaign in 2013. As these areas are often in somewhat more populated areas (fracking in particular), it is expected that a mix of minimum altitudes of 500 ft AGL and 1000 ft AGL (above obstacles) will apply depending on the working area. Separation from other air traffic will be over local common frequencies and through visual de-confliction as per normal operations.

Contact has been made with the Transport Canada office in Calgary and further discussions will proceed with Edmonton office to avoid any confusion on their part as to the procedures being followed. NRC has not had any issues with Transport Canada in regards to low flying in the past.

The Canadian Air Forces Base at Cold Lake has restricted air space in the vicinity of the Cold Lake airport. It is very likely we will be able to fly in areas of the range on weekends, but weekdays are TBD. During the second phase, Maple Flag will take place out of Cold Lake and during this time period we would only be able to fly in the range areas on weekends.

Each flight will be approximatley 4-5 hours in duration depending on the flight objectives. The average aircraft speed is expected to be ~88 m/s in the project area.

Pilots and scientists will be communicating on an ongoing basis as to weather conditions, aircraft operational issues, flight considerations and instrumentation issues. Air quality and meteorology forecasts will provided each evening and each morning to the research team with subsequent flight planning discussions. A final decision will be made each morning as to whether a flight(s) will be conducted (or not), the flight tracks identified and waypoints communicated to the pilots. Decisions to fly a particular flight mission will largley depend on the meteorology; for example the wind direction is particlarly important in order to capture the emissions from a single facility or a sub-component of a single facility.

11. In-field Forecasts

At the field hotel, a conference room will be arranged for forecast meetings, data management activities and study meetings. Meteorological and air quality forecasts will be provided every evening (~8pm LT) with one meteorologist and one air quality scientist on-site to prepare and deliver the forecasts to the flight planners and scientists. Through discussion decisions will be made as to the flight plan for the following day. A brief forecast (~15 min) the following morning (~8am LT). As in the 2013 study, the forecasts will provide guidance in the determination of flight type and specific flight tracks. Waypoints will be communicated to the pilots.

Other Important Notes

1. need to be strategic about taking canister measurements
    a. need more background/out of plume cans
    b. different plumes need separate can samples
2. cartridge and filterpack sampling for IVOCs and PM
    a. want as a function of downwind distance, how to deploy?
    b. Need to keep track of cartridges/filters in-flight, may want to re-sample
    c. Need background samples
3. Hg measurements – 2 min time resolution, is this a factor in sampling strategy

Appendix A.

Additional flights may be conducted, depending on funding and measurement conditions, to investigate emissions from other sources. The objectives would be to 1. characterize and quantify emission rates of air pollutants from hydraulic fracturing activities; and 2. to study the evolution of primary pollutants emitted from wild forest fires as they chemically and physically transform downwind.

Hydraulic fracturing

Flights to measure emissions from hydraulic fracturing are being considered in northeastern BC, the Grand Prairie region or the Saskatchewan Bakken fields.

Forest Fires

Flights to measure emissions from forest fires would occur within a radius of XX km from the Fort McMurray home base.

Forest Fires

Emissions from forest fires will be made if there is a forest fire that is close enough to our home base, the weather conditions are suitable and it is safe to conduct the flights. This depends on if the location of the fire is suitable either for a transit to/from Fort McMurray within the same day or logistics are feasible for an overnight stay. The flights will be conducted in a Lagrangian manner as described above.

4. How far upwind/downwind from forest fires do we need to be?
5. Airports in 'area' that can accommodate the Convair for refuelling and continuous power
6. Refuelling and overnight options would require an additional NRC tech on board (plus power cart?)
7. Overnight power to support instruments?
8. Overnight hotel options
9. Want to sample a variety of forest fires (flaming, smoldering), but also near source and increasing distance downwind of source
10. Do we want to consider forest fire plumes that originate outside Canada (e.g. Siberia, US)
11. Number of hours transit, number of hours science measurements
12. Meteorology
13. Priority compared to OS flights at that point in the study
14. How are we going to know where the fires are

Hydraulic fracturing

Measurements of emissions from hydraulic facturing are being considered in three locations: the Grande Prairie (GPR) region, the Bakken region (B??) in southern Saskatchewan and northeast British Columbia (???). Estimated waypoints for the box corners and flight times are in Table A1 and the flight tracks (brown) are shown in Figure A1.

Very detailed horizontal legs at one altitude.

	North East		North West		South East		South West		North-South Screen	West-East Screen	Box Time/Grid Time
	Lat	*Lon*	*Lat*	*Lon*	*Lat*	*Lon*	*Lat*	*Lon*	*Km*	*km*	*hh:mm*
GPR	55.850	-118.617	55.850	-119.983	55.433	-118.617	55.433	-119.983	46	86	**8.3/15**
B??											
???											

Table A1. Estimated waypoints, screen lengths and times for box emission flights around in-situ mines (red).

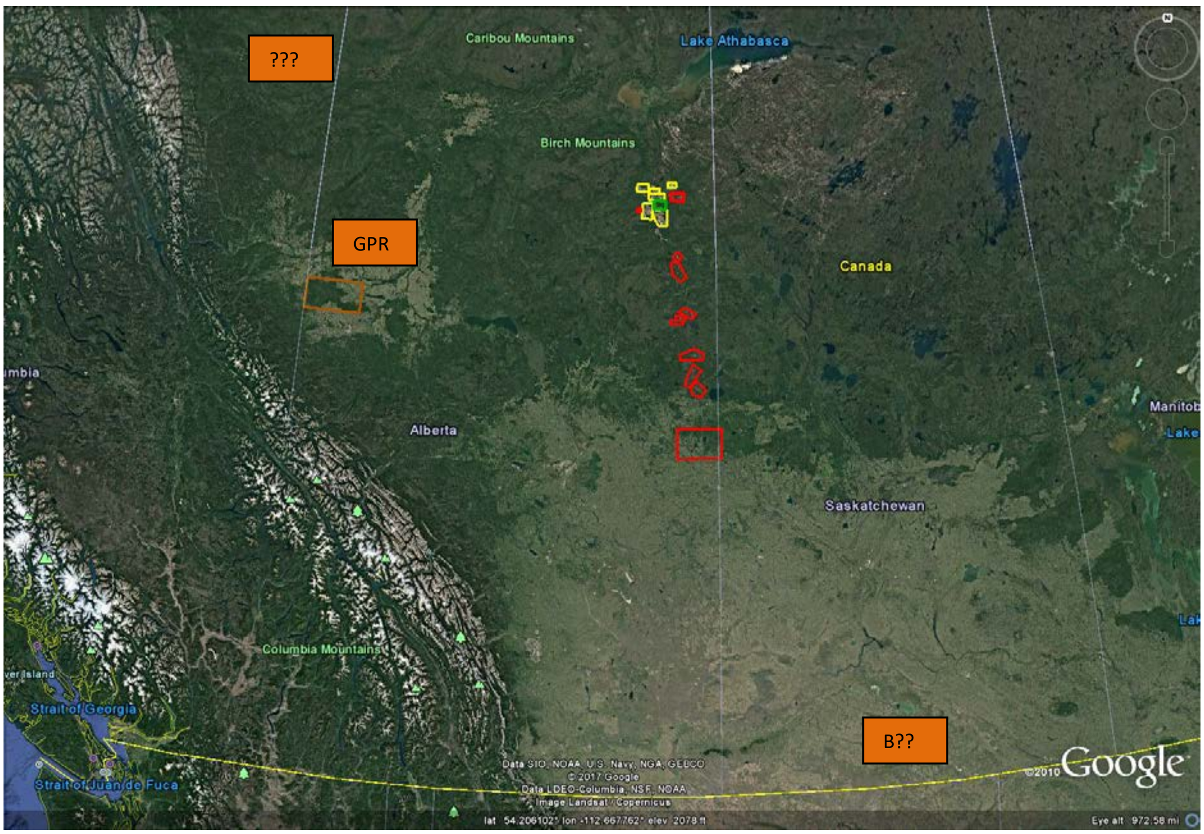


Figure A1. Box flight patterns around hydraulic fracturing facilities (brown).