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The CanX-7 Nanosatellite ADS-B Mission: A Preliminary Assessment

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Abstract

The development of space-based Automatic Dependent Surveillance-Broadcast (ADS-B) will allow surveillance of aircraft in areas not covered by radar or ground-based ADS-B systems. In September 2016, the Canadian Advanced Nanospace eXperiment-7 (CanX-7) satellite was launched into a 690 km sun synchronous orbit with an ADS-B receiver payload. The first phase of ADS-B data collection took place over the North Atlantic between 4 and 31 October. A preliminary assessment of the data indicates that the average ADS-B signal strength is close to the calculated receiver detection threshold of −94.5 ± 0.5 dBm. The pattern of received ADS-B reception appears to be consistent with a signal propagation model developed for the CanX-7 mission. Future work includes the comparison of coincidental flight plan data for the operations area and an analysis of the payload antenna pattern.

Keywords

ADS-B, Space-Based ADS-B, CanX-7, Air Traffic Control

1. Introduction

Automatic Dependent Surveillance-Broadcast (ADS-B) is an air traffic surveillance technology in which aircraft transmit identification, position, velocity and status on 1090 MHz. The transmissions may be received by other aircraft or by ground stations for relay to Air Traffic Services to augment traditional surveillance radars. The ADS-B message is 120-bits in length and broadcast at random intervals between 0.4 and 0.6 seconds with pulse position modulation to help prevent signal collisions between aircraft. Signal power varies between 75 W and 500 W, depending on aircraft category [1]. The vertically polarized ADS-B transmission alternates between top- and bottom-mounted quarter-wave monopole antennas.

Currently only 30% of the Earth is covered by the combination of radar and ADS-B. In the absence of aircraft surveillance, existing air traffic procedures use standardized routes and large inter-aircraft spacing to provide aircraft separation. ADS-B coverage is limited by the placement of ground stations, which cannot be installed in mid-ocean and are difficult to maintain in remote areas. A potential solution for the surveillance of aircraft anywhere in the world is through the monitoring of ADS-B transmissions using orbital platforms. The first space-based ADS-B receiver flew on Proba-V in 2013, followed by the GOMX-1 (2013) and GomX-3 (2015) nanosatellites. The Canadian Advanced Nanospace eXperiment-7 (CanX-7) satellite was launched with an ADS-B receiver in September 2016. In January 2017, the first ten Iridium NEXT satellites carrying hosted ADS-B payloads were placed in low Earth orbit (LEO) as part of a 66-satellite constellation that is projected to provide full Earth coverage for ADS-B signal reception.

The ADS-B payload onboard CanX-7 was developed at the Royal Military College of Canada (RMCC). ADS-B research has been conducted at RMCC since 2009, which includes the first ADS-B receiver in near space and extensive signal propagation modelling [2]-[8]. This paper gives a preliminary assessment of the CanX-7 ADS-B mission. Section 2 describes the satellite and payload parameters; Section 3 outlines the first phase of operations; Section 4 discusses the preliminary findings and Section 5 includes a summary and future work.

2. CanX-7 Satellite and ADS-B Payload

Funded by the Natural Sciences and Engineering Research Council of Canada, Defense Research and Development Canada-Ottawa, COM DEV and the Canadian Space Agency, CanX-7 was developed and built by the University of Toronto Institute of Aerospace Studies-Space Flight Laboratory (UTIAS-SFL). The primary payload consists of four deployable drag sails that will demonstrate passive de-orbiting from LEO. The Inter-Agency Space Debris Coordination Committee recommends de-orbiting of spacecraft in LEO within 25 years of mission completion, which is problematic for small satellites without propulsion systems. The drag sail, with a total area of 4 m^2, is scheduled for activation approximately six months after launch. Deployment of the sail will be captured with onboard cameras. The secondary payload is an ADS-B receiver that will collect transmissions prior to drag sail initiation. Raw ADS-B data will be stored onboard CanX-7 and downlinked later to the UTIAS ground station. Attitude determination is accomplished with a magnetometer, while a set of three magnetic torquers provide 2-axis attitude control by aligning a primary axis with the local magnetic field. Solar cells generate power with a lithium ion battery used for energy storage. Thermal tapes provide passive temperature control for the spacecraft. Table 1 lists specifications of CanX-7, while Figure 1 and Figure 2 show the major components of the satellite.

The ADS-B payload consists of an ADS-B receiver, low-noise preamplifier, payload computer and a microstrip patch antenna. Payload electronics are lo-

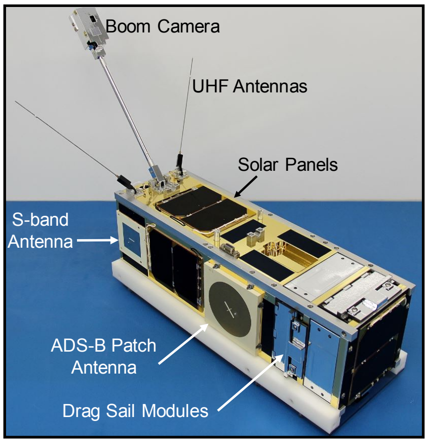

Figure 1. The CanX-7 satellite with major components indicated (Courtesy of UTIAS-SFL).

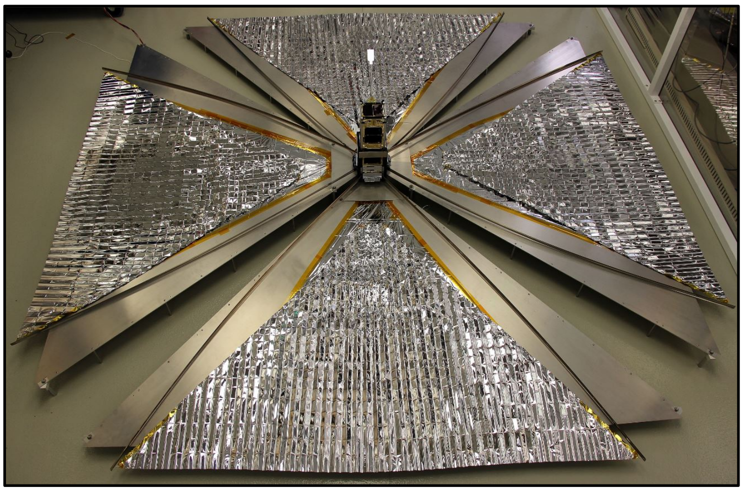

Figure 2. CanX-7 satellite with drag sails deployed (Courtesy of UTIAS-SFL).

Table 1. CanX-7 specifications.

Element	Description
Primary Payload	Drag Sail
Secondary Payload	ADS-B Receiver
Size	10 × 10 × 34 cm
Mass	3.6 kg
Communication Downlink	S-Band
Communication Uplink	UHF
Attitude Determination	Magnetometer
Attitude Control	3 Magnetic Torquers (2-axis)
Primary Power	Solar Cells
Energy Storage	Lithium Ion Batteries
Thermal Control	Passive
Propulsion	None

cated within an aluminum enclosure to reduce electromagnetic interference with other satellite components. The receiver is a commercially available unit (88 mm × 53 mm, 60 g) with a throughput of 1700 messages per second. Upon demodulation, each message is tagged with a Received Signal Strength Indicator (RSSI) value and time of arrival before being saved by the payload computer. ADS-B messages are subsequently transferred to the spacecraft computer for storage and downlink. The right hand circularly polarized conformal antenna is 75 mm in diameter and features a 35 MHz bandwidth, 4.5 dBic gain and a broad uniform main lobe with a half power beam width of 95˚ [9]. A schematic of the ADS-B payload is shown in **Figure 3** [9].

3. ADS-B Operations

CanX-7 was launched into a sun synchronous orbit of 690 km on 28 September 2016, resulting in approximately 15 orbits per day. Following a satellite-commissioning period, the first phase of operations began on 04 October and ended on 31 October. During this time, the ADS-B receiver was activated for 18 minutes in the Northern Hemisphere during each orbit, representing a latitudinal coverage between 12˚N and 78˚N. There were 381 collection periods in which a total of 776,584 call sign, position and velocity messages were received. Status messages were not decoded and are not included here. Overall statistics for the first phase of the mission are shown in **Table 2**.

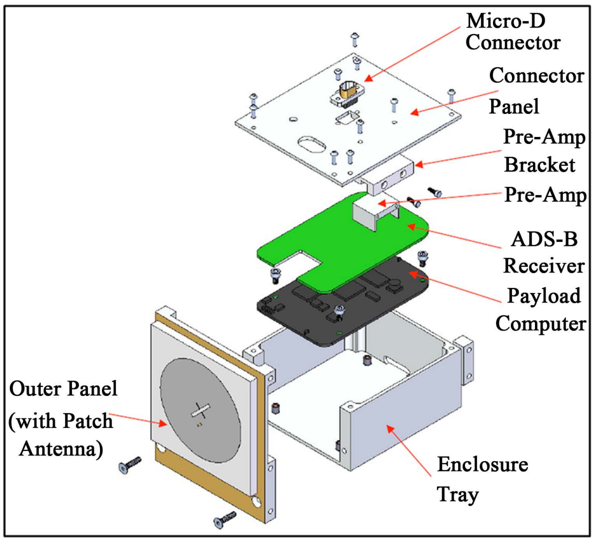

Figure 3. Exploded view of the CanX-7 ADS-B payload.

Table 2. ADS-B mission statistics for the Northern Hemisphere, 4 to 31 October 2016.

Property	Value
Total Collection Periods	381
Total Messages Decoded	776,584
Call Sign Messages	7.9%
Position Messages	46.4%
Velocity Messages	45.7%

Although ADS-B data collection was planned for every orbit, the primary analysis concentrated on the North Atlantic over the Shanwick and Gander Oceanic Control Areas (OCAs). This region was selected for the first phase of the experiment since it is relatively quiet with respect to non-ADS-B 1090 MHz transmissions. Additionally, NAV Canada has access to historical flight plan information for the region. As a result of the sun synchronous nature of the orbit, CanX-7 flew over the operations area at approximately the same local time each day. There were as many as four passes over the operations area per day, but typically a descending pass between 1100 UTC and 1300 UTC and an ascending pass between 2100 UTC and 2300 UTC provided the best coverage. Figure 4 shows the CanX-7 ground track for a 24-hour period, with favorable descending and ascending passes identified. Data provided by NAV Canada indicated that air traffic in the Ganderand Shanwick OCAs experience two peaks every day. As seen in Figure 5 there is a maximum of about 220 aircraft at 0300 UTC representing the eastward flow of aircraft and a similar peak at 1400 UTC representing the westward flow of aircraft [6]. During CanX-7 passage the number of

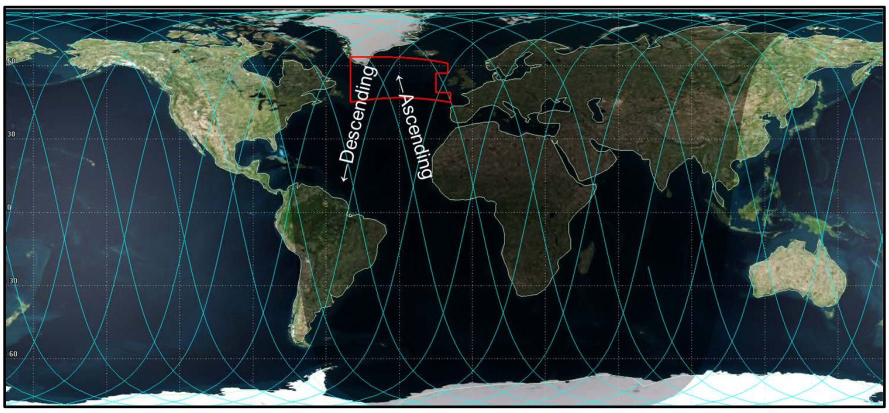

Figure 4. CanX-7 ground track for a typical 24-hour period with descending and ascending passes over the operations area highlighted. The operations area is indicated in red (Satellite Tool Kit Software).

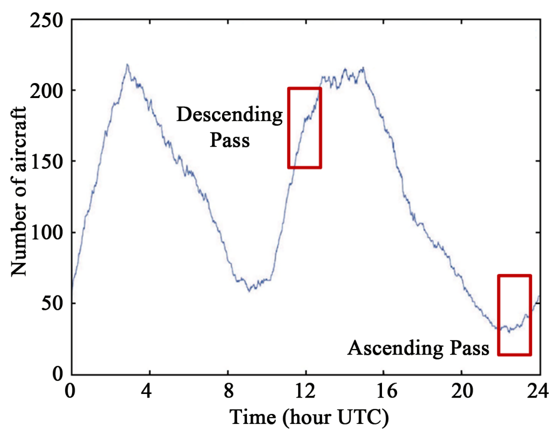

Figure 5. Number of aircraft in the Gander and Shanwick OCAs is shown for a 24-hour period. Expected number of aircraft in the operations area is indicated in the boxed areas for the ascending and descending pass for a typical day.

aircraft expected in the operations area ranges between 150 and 200 aircraft for the descending pass and 50 to 75 for the ascending pass. Data collected over the operations area accounted for approximately 13% of the first phase data.

4. Data Assessment

4.1. Spacecraft Pointing

The magnetic torquer on board CanX-7 aligns the ADS-B antenna Boresight with the local magnetic field. While this is a simple method to achieve Earth pointing objectives in the region, the absolute accuracy and rate of change of rotation as the satellite transits from either the north or south through the operations area is problematic. Travelling at 7.5 km/s it takes the spacecraft approximately five minutes to pass over the operations area. If CanX-7 enters the region from the north on a descending pass the spacecraft begins with a pointing direction closer to nadir than if it enters from the south. The rotation vector during a pass is dependent on local magnetic field conditions and satellite response to changes in the field. Figure 6 shows a sequence of aircraft contacts in

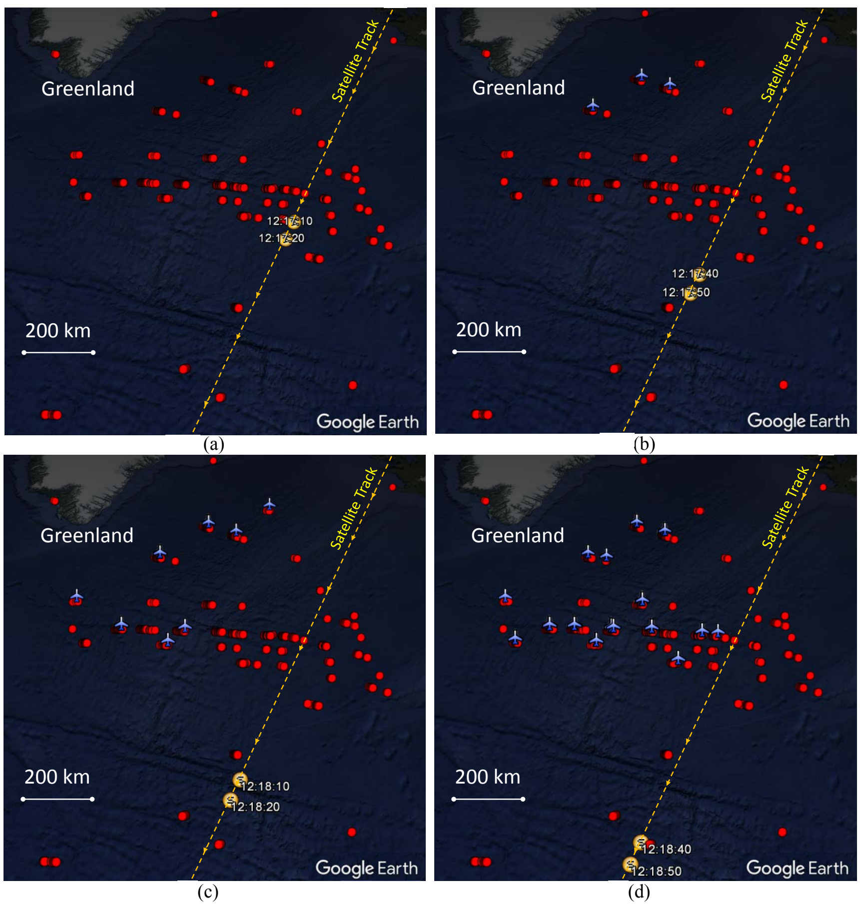

Figure 6. A sequence of four images (a) to (d) is shown as CanX-7, denoted by the orange circle with UTC time, transits southward through the operations area for selected 10-second intervals on 29 October. Red dots represent ADS-B messages received during the entire pass, while aircraft symbols indicate signal reception during the shown 10-second interval. Aircraft symbol does not indicate heading.

the operations area during a descending pass on 29 October. The satellite position is shown in 10-second increments with red dots representing ADS-B messages received during the entire pass, while aircraft symbols indicate signal reception during the shown 10-second interval. In Figure 6(a) the satellite, represented by the orange symbol, did not detect any of the aircraft. As the satellite transits southward in Figures 6(b)-(d), an increasing number of contacts is evident. The sequence, which is typical of the descending passes, implies a bias of the satellite antenna to the northwest because of the pointing vector. Contacts to the east of the satellite track do not appear until the satellite is near the southern boundary of the operations area. Figure 7 shows the local magnetic field for the 29 October descending pass in one-minute increments based on the International Geomagnetic Reference Field (IGRF). The theoretical offset of the nadir point is shown to the northwest of the satellite ground track.

4.2. Signal Levels

ADS-B signals received by the payload are given an integer RSSI value between 0 and 255. The average RSSI value for all signals received was 28, which is close the calculated −94.5 ± 0.5 dBm Minimum Detectable Signal (MDS) of the payload receiver. In accordance with Van Der Pryt and Vincent [8], Figure 8 shows the ADS-B signal propagation model for a satellite altitude of 690 km based on a 500 W transmitter and a typical aircraft antenna radiation pattern for ADS-B transmissions. Taking into account the calculated payload MDS, represented by the dashed line in Figure 8, the model implies that aircraft 5˚ to 8˚ and 42˚ to 60˚ from nadir should be detected. There is a null 0˚ to 5˚ because of the aircraft quarter-wave monopole radiation pattern, while signals between 8˚ and 42˚ are

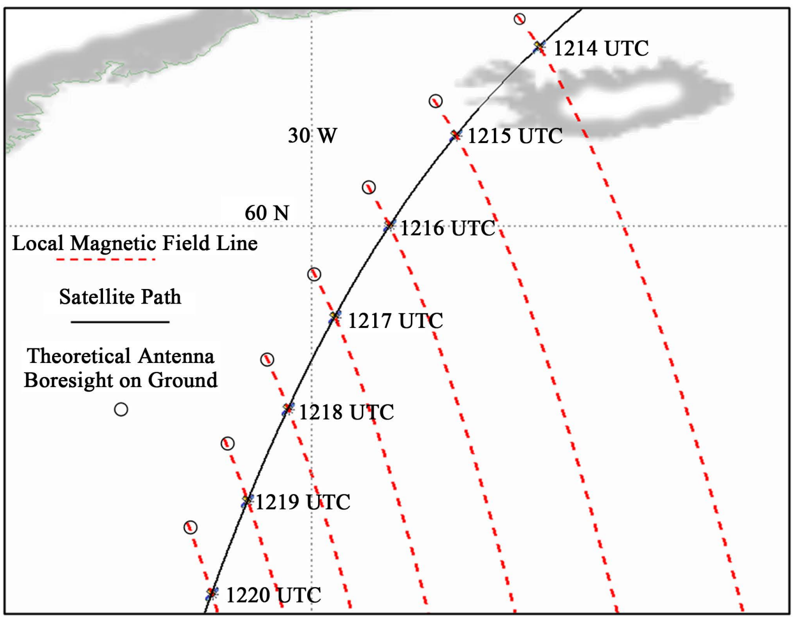

Figure 7. The IGRF local magnetic field is shown in one-minute increments for satellite passage through the operations area for the descending pass on 29 October. The Boresight of the antenna points to the northwest (Satellite Toolkit Software).

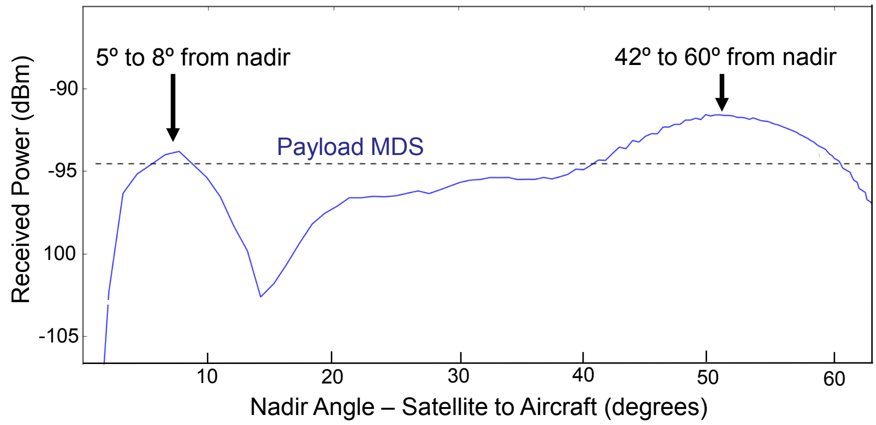

Figure 8. Expected ADS-B signal strength at an altitude of 690 km is shown in relation to degrees from nadir for a 500 W transmitter and a typical aircraft radiation pattern for ADS-B transmissions. The dotted line is the calculated −94.5 ± 0.5 dBm MDS of the ADS-B payload.

predicted to fall below the payload detection threshold.

Spurious contact was observed for all passes. This is likely because signal strength may be near the threshold of payload sensitivity depending on aircraft-satellite orientation. While there are many instances of single message contact in the database, there are also examples of hundreds of messages received from the same aircraft in a single pass. With respect to multiple message contact, the data stream could be near continuous or experience significant intervals between messages. For the descending pass of 29 October (Figure 6) there were 60 different aircraft detected in the operations area, representing 996 position messages. During this pass, there were seven instances of 40 or more position messages received from a single aircraft with a maximum of 106 messages from the same aircraft. Figure 9(a) illustrates the breakdown of the position messages received for each aircraft in the operations areas during the 12 UTC descending pass on 29 October. Figure 9(b) offers a comparison to the 12 UTC descending pass of 16 October to demonstrate the observed consistency between similarly timed passes. The average RSSI value for 40-plus multiple message contact shown in Figure 9(a) and Figure 9(b) is not significantly different from the overall average RSSI value of 28 and remains close the payload MDS. This implies that the disparity between the number and consistency of received signals from individual aircraft may be a function of aircraft antenna radiation pattern rather than transmitter power. For 16 and 29 October, the greatest number of received messages originated from a Boeing 777 (KLM) and a Boeing 767 (Delta) respectively, which could indicate a superior antenna configuration for space-based ADS-B surveillance.

4.3. Signal Propagation Model

The tilt of the antenna boresight as a function of the magnetic field may result in contact at extended ranges from the satellite. Figure 10 shows the beginning (a) and end (b) of a 23 UTC ascending pass on 16 October. During this pass there

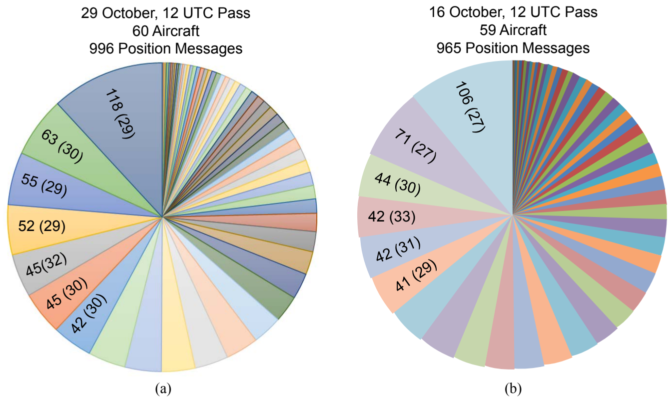

Figure 9. Number of position messages per aircraft is illustrated for 12 UTC descending passes on (a) 29October and (b) 16 October. The integer value of the average RSSI is shown in parenthesis for aircraft with more than 40 position messages.

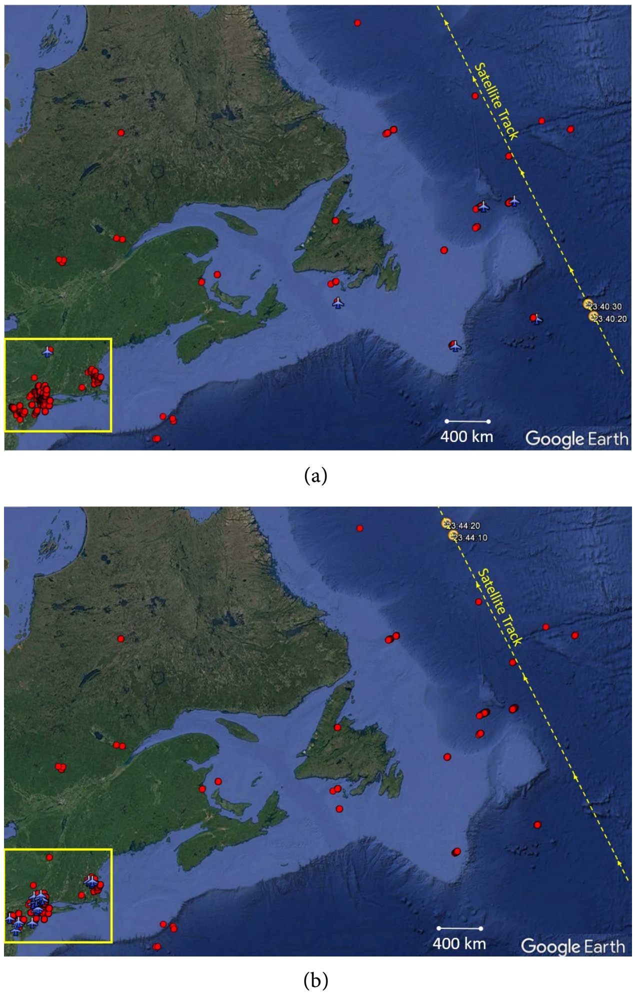

Figure 10. A sequence of two images (a) and (b) is shown as CanX-7, denoted by the orange circle with UTC time, transits northward through the operations area for selected 10-second intervals on 16 October. Red dots represent ADS-B messages received during the entire pass, while aircraft symbols indicate signal reception during the shown 10-second interval. Aircraft detected at extended ranges on the coast are highlighted in the yellow box to the bottom left of each panel. Aircraft symbol does not indicate heading.

are few contacts in the operations area, however a grouping of aircraft are detected on the east coast of North America. The slant range to these aircraft is 2500 to 3000 km. During this timeframe, there is evidence that the payload did not detect a number of aircraft between CanX-7 and the coastal region. Figure 11 shows flights reported during the satellite pass by *Flightradar*24, a flight tracking application that combines data from several sources including ground-based ADS-B and radar. Considering the calculated MDS of the payload, the signal propagation model in Figure 8 predicts the potential of missed contacts in the medium range as suggested by Figure 11.

5. Summary and Future Work

The CanX-7 ADS-B receiver collected data over the Gander and Shanwick OCAs from 4 to 31 October 2016. The average signal strength for 776,584 decoded messages detected was close to the calculated receiver MDS of −94.5 ± 0.5 dBm. ADS-B transmissions appear sporadic at times because the average signal strength is near the threshold of payload sensitivity depending on aircraft-satellite orientation. Aircraft contacts vary from single transmission receptions to hundreds of near continuous messages. The disparity in message reception is likely a function of aircraft antenna radiation pattern since there was no observed increase in power for continuously received messages. The distribution of aircraft contacts, including long-range signal reception, appears consistent with a signal propagation model developed for the CanX-7 mission. Precise mapping of the radiation pattern of the satellite antenna is complicated by the magnetic torquer attitude control method. A complete data analysis will be carried out over the next several months, including a rigorous approach to the satellite pointing characteristics and the comparison of NAV Canada flight data for the operations area.

In November 2016 the polarity of the magnetic torquers of the satellite was reversed to allow the observation of ADS-B transmissions in the southern hemisphere. In December, operations commenced once again in the Northern Hemisphere to collect data over the Polar region. Following a successful software update of the ADS-B receiver, CanX-7 was re-tasked to collect ADS-B data over

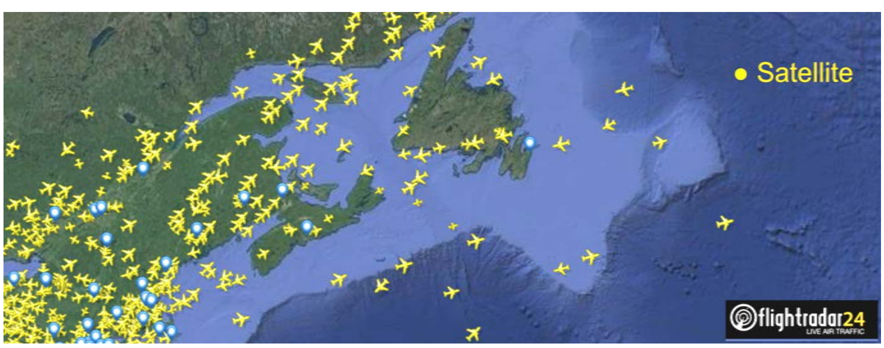

Figure 11. Aircraft reported by flightradar24 during the time of satellite pass at 2342 UTC on 16 Oct. 2016. Some aircraft may not be ADS-B equipped.

high-density air traffic areas. The drag sail is scheduled for deployment at the beginning of May 2017, at which time ADS-B operations shall be terminated.

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