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DRDC Ottawa 9.1m antenna (foreground), 1.2m antenna (inside dome) and the 4.6m antenna (lower left)

LEO DOPPLER CURVES SATELLITE TRACKING AND CHARACTERIZATION

Captain Jean-Francois Guimond, M.Sc.

Space Systems Group
Defence R&D Canada

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DRDC | RDDC

Canada

Background

- DRDC Space Systems Group
  - Core expertise in space surveillance, also known as Space Situational Awareness (SSA)

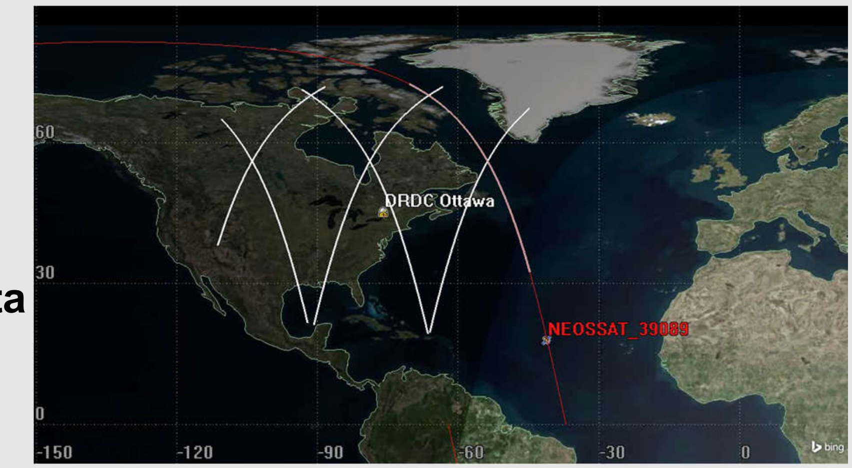
  - Satellite orbit determination from optical astronomical observation
    - Satellite characterization
    - Mission characterization
    - Maneuver detection
    - Anomaly detections

- Currently looking at other parts of the EM spectrum to conduct space surveillance
  - Repurpose the decommissioned 9.1 m satellite ground station at DRDC Ottawa to obtain satellite positional data derived from 1-way Doppler measurements

  - Advantages
    - RF emissions are better immune to weather than optical
    - they also reveal different information
    - instantaneous Assessment of space object status

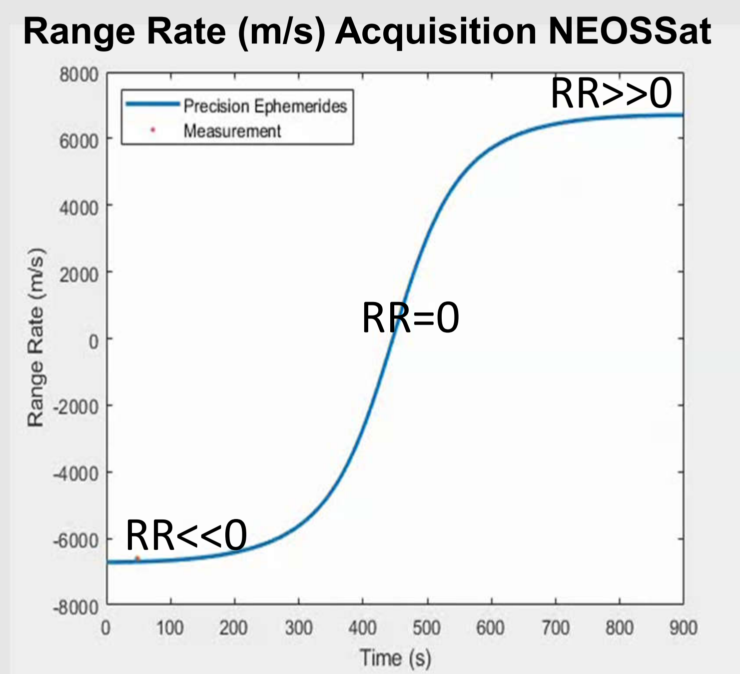
Purpose of this work

- Experiment objective: Estimate orbital position precision from 1-way Doppler from our ground station
- Test subjects used are 4 Canadian LEO satellites
  - NEOSSat
  - M3MSat
  - SCISAT
  - CANX-7
- Present preliminary findings of collected data
  - Doppler, range rate measurements
- Out of scope for experiment:
  - Measurements were not used to update orbital ephemerides of the satellites, this is left for a future experiment



Experimental Setup: System Overview

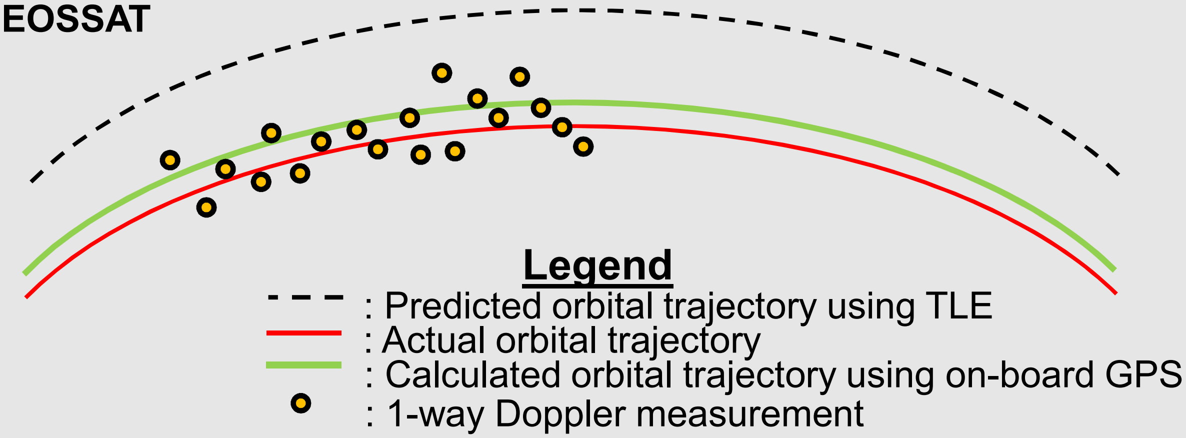
- **Kintech 9.1m antenna delivered in 1991**
  - **Peak Receiving Net Gain of 41.16 dB**
  - **Feed S-Band 2.000 to 2.400 GHz**
  - **High Speed Recorder and Processing Server**



By measuring the apparent frequency during a complete pass we can produce Doppler and range rate curves. This information can then be later used for orbit estimation.

Calibration and Testing

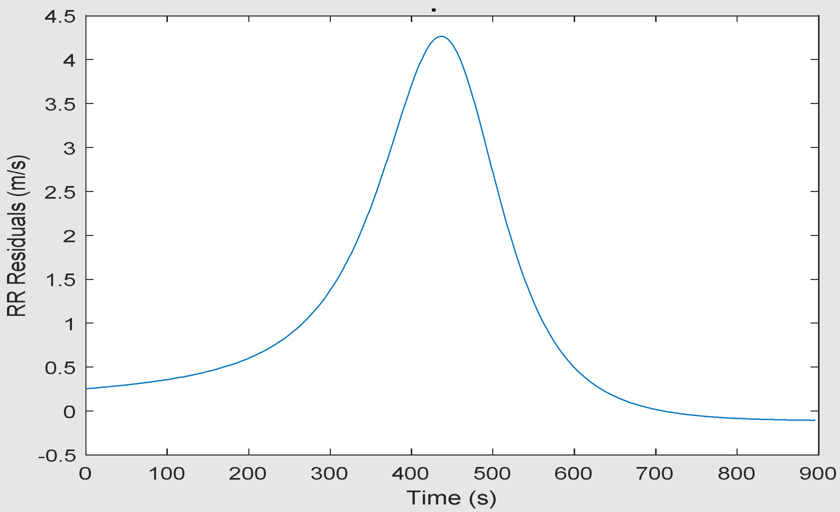
- **NEOSSat provided "ground truth" measurements:**
  - **Precision orbital ephemerides derived from onboard GPS**
- **Comparison measured range rate vs theoretical measurements (Ephemerides)**
  - **Inferred systematic and random errors**
- **Canadian satellites other than NEOSSAT**
  - **TLE**
- **Satellite Passes**
  - **eastern Ontario**
  - **9 to 15 minutes**
  - **complex baseband Samples**
- **Range Rate Predictions**
  - **Systems Tool Kit 11 (Ephemerides and TLE)**
- **Tracking Files**
  - **Standardized Astrodynamics Algorithms (SAA) Library in Matlab**

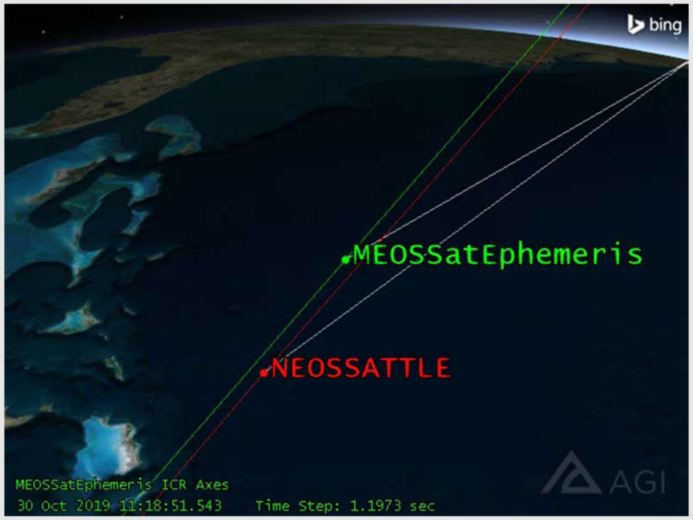


Typical Range Rate Residuals

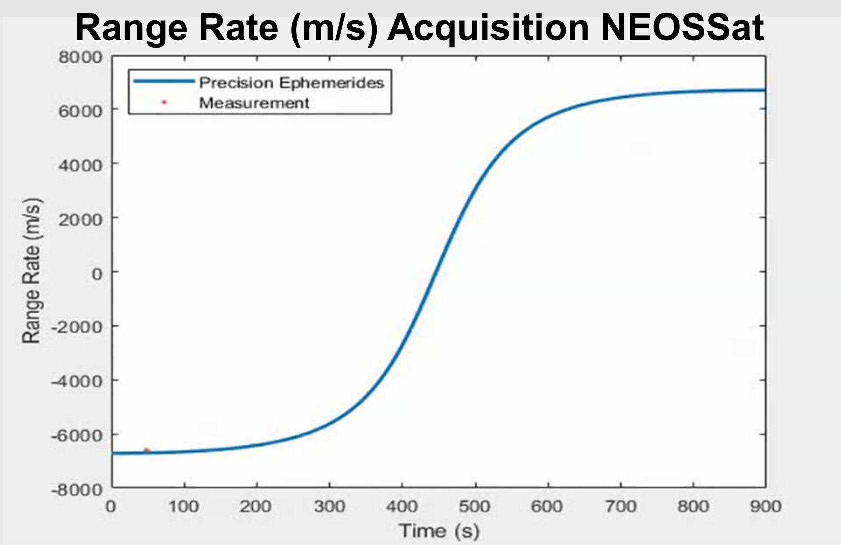
- **Precision Ephemeris Vs TLE**
  - **Precision Ephemeris leading the TLE prediction along its track**
  - **approximately from 100m to 500m**
  - **maximum Error occurs in the middle of the pass**
  - **the error comes from the TLE inaccuracies**

Precision Ephemeris Residuals - Range Rate TLE



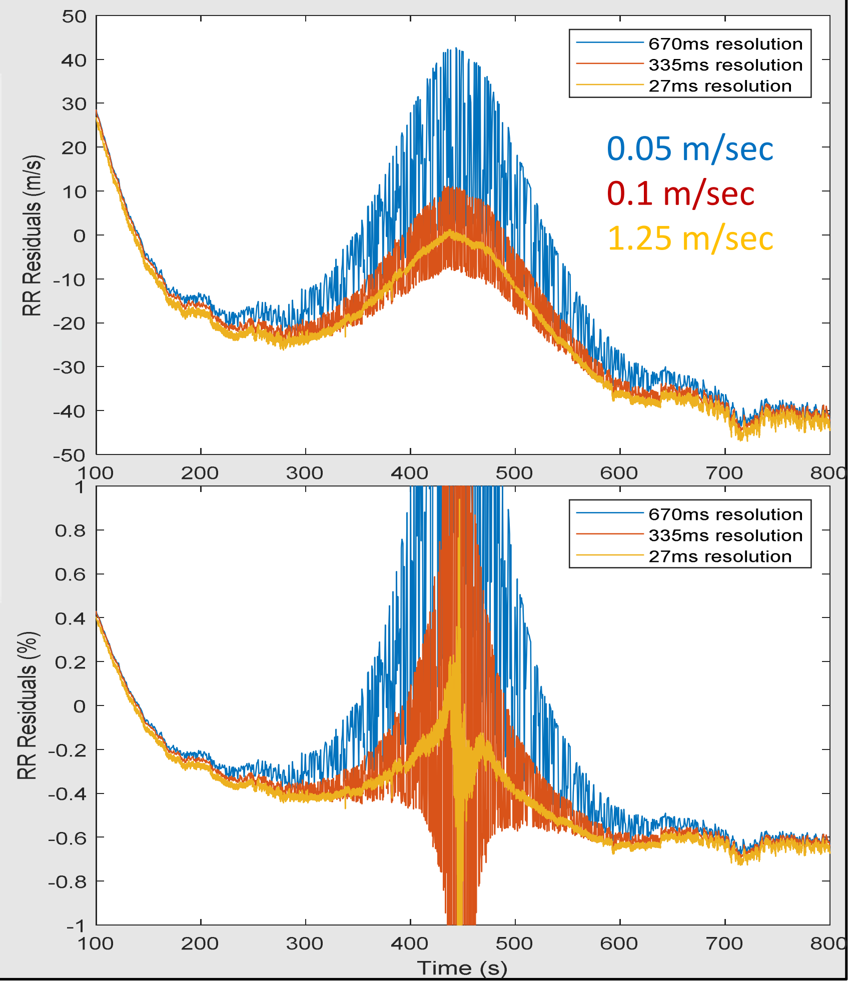


SYSTEMATIC ERROR ANALYSIS BASED ON NEOSSAT PRECISION EPHEMERIDES

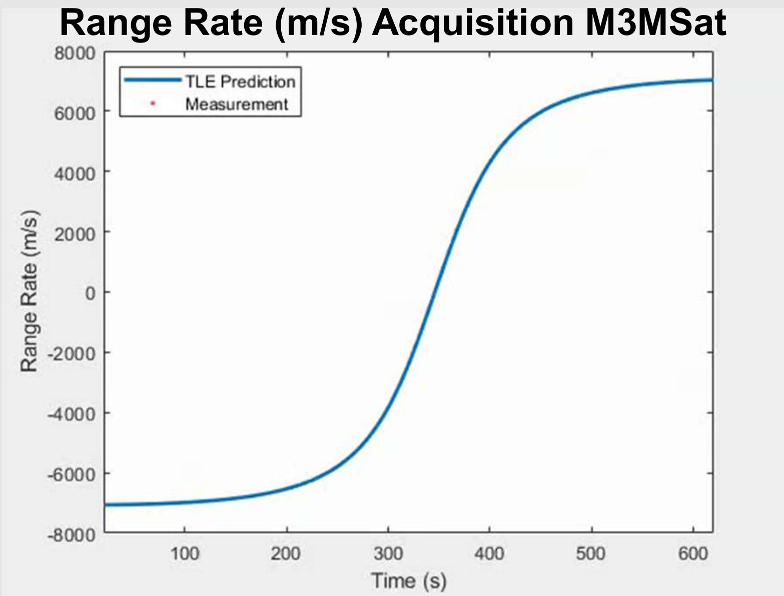


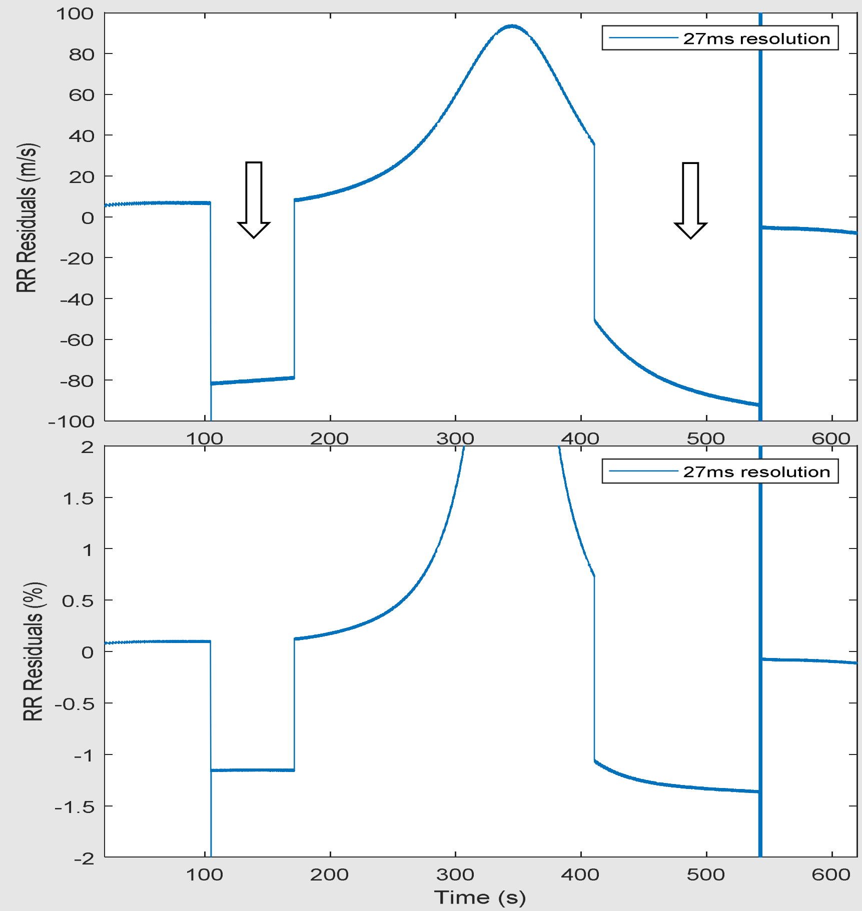
Finer time resolutions reduce
- **fluctuations**

But increase
- **frequency**
- **range rate resolutions**



MEASUREMENTS ON OTHER CANADIAN SATELLITES: M3MSAT

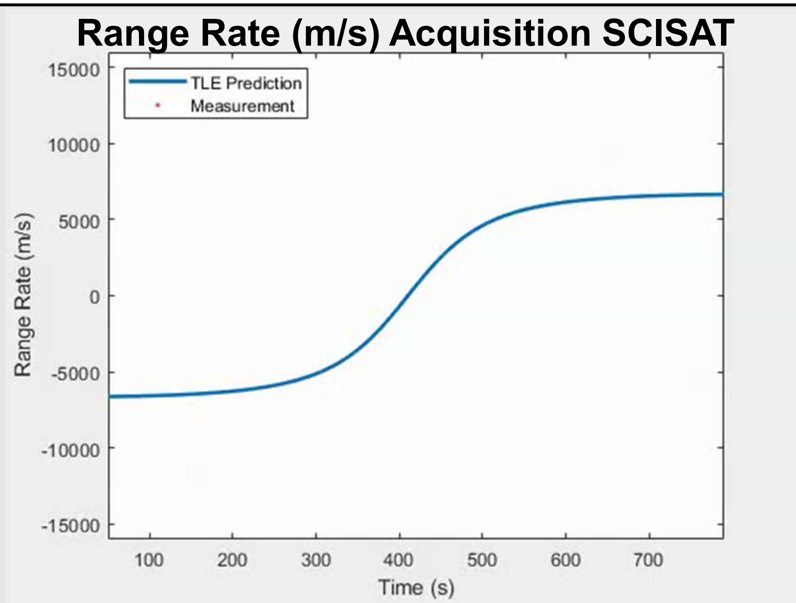


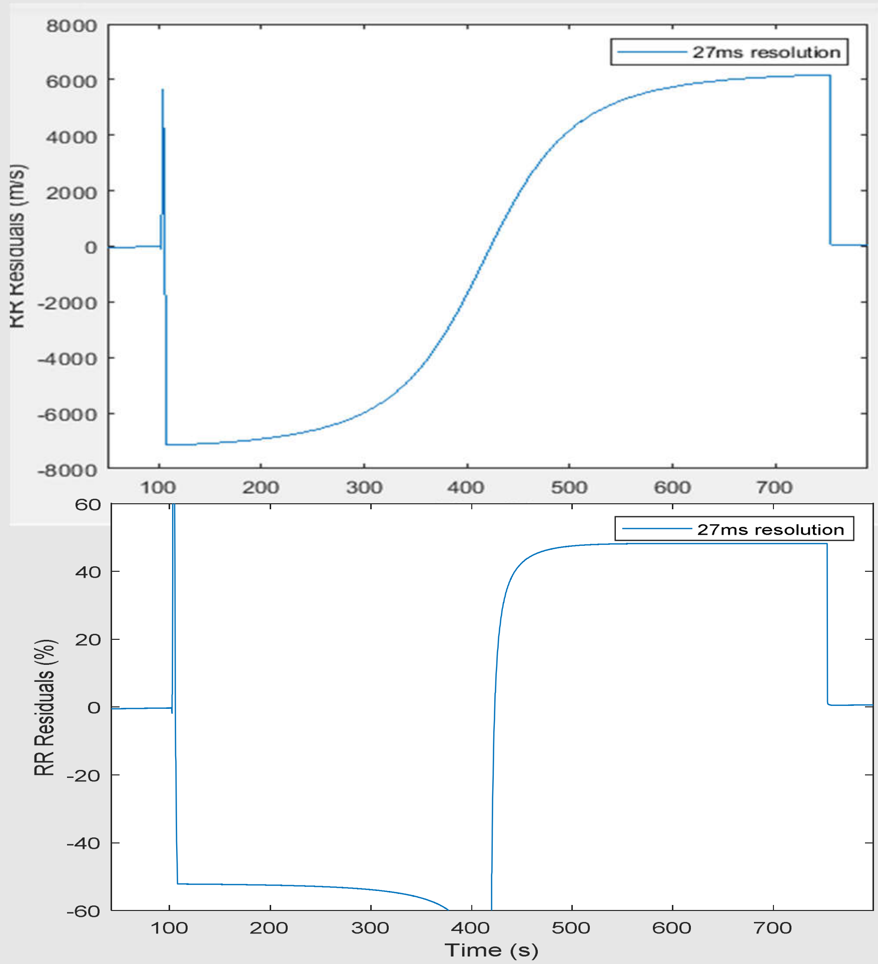


Unlike NEOSSat

- **range rate residuals are smaller beginning and end**
- **more consistent with the expected range rate residuals predicted in NEOSSat case.**

MEASUREMENTS ON OTHER CANADIAN SATELLITES: SCISAT

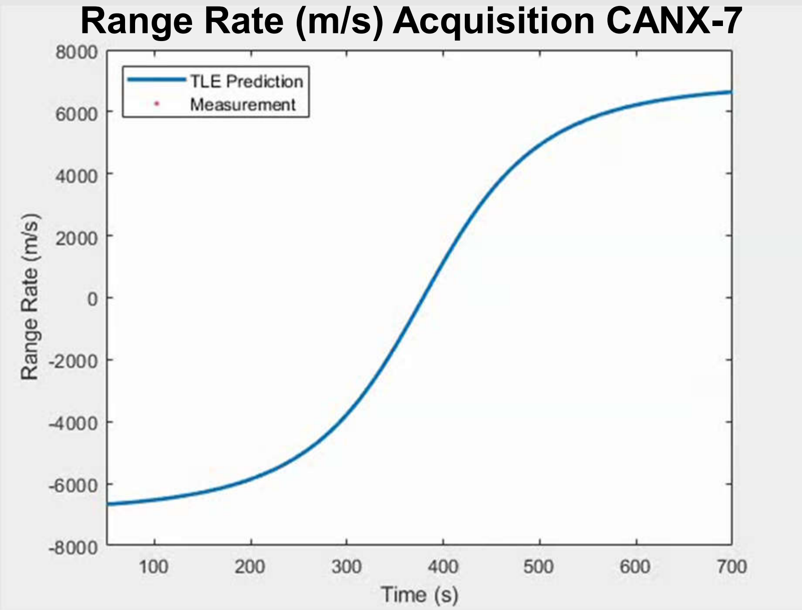




Close to theoretical predictions

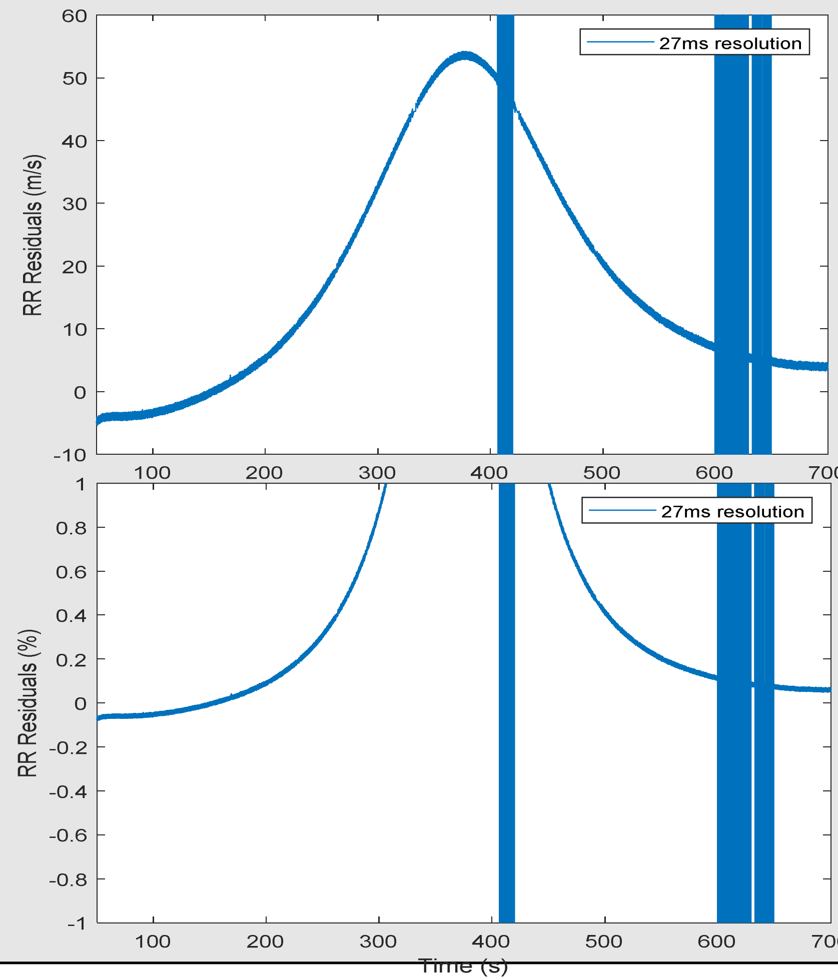
- **beginning and end**

MEASUREMENTS ON OTHER CANADIAN SATELLITES: CANX-7



Shape of the range rate residual curve

- **similar to NEOSSat**
- **peak value 50 m/s**



CONCLUSIONS

- **Despite some technical issues, this work has demonstrated that the 9.1m antenna at DRDC Ottawa now has the capability to perform basic one-way Doppler characterization of LEO satellites.**

- **Findings**
  - **some systematic error was observed and it is not well-characterized at this time**
    - **Hypothesis frequency compensation**
  - **satisfactory range rate residuals were obtained with satellites other than NEOSSat**
  - **M3MSat and CANX-7 had residuals less than 0.1% at the beginning and end of their passes**
  - **suggests that an analysis of the RF front-end, specifics on communications hardware and temporal link budgets may be required**

- **Future work**
  - **involve investigation and correction of the observed systematic error**
  - **development of a method for orbit determination**
  - **data fusion experiments by using a nearby optical tracking sensor**
  - **NEOSSat attitude slew maneuvers**
  - **cooperative tracking of NEOSSat**

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POUR LA DÉFENSE ET LA SÉCURITÉ DU CANADA

LEO DOPPLER CURVES SATELLITE TRACKING AND CHARACTERIZATION

Jean-Francois Guimond MSc. (a), Dr. Simon Henault (b)
(a) Defence R&D Canada Ottawa, Ottawa, ON, jean-francois.guimond@drdc-rddc.gc.ca
(b) Defence R&D Canada Ottawa, Ottawa, ON, simon.henault@drdc-rddc.gc.ca

ABSTRACT

The Space Situational Awareness (SSA) community collects observations of Earth orbiting space objects typically by using radar systems and electro-optical telescopes to maintain the satellite catalog. These sensors work well in their classical orbital measurement role, but do not generally acquire tracking data from the emitted RF spectrum from active satellites. With the increasing number of small satellites in orbit, new techniques to assess the status of orbiting space objects is of interest to help characterize this rapidly expanding class of vehicle.

In this paper, we describe the augmentation of a satellite ground station operated by Defence R&D Canada Ottawa as an S-band SSA sensor for range rate and Radio Frequency (RF) characterization. While ground stations are regularly employed for range rate measurements for satellites they control, the ability to examine RF emissions on commonly used small satellite RF bands is advantageous to the SSA community. It enables the instantaneous assessment of space object status simply by measuring and characterizing their emitted RF energy.

This paper describes characterization measurements of frequencies and Doppler shift on four different Canadian Low Earth Orbit (LEO) small satellites; CANX-7, SCISAT, M3MSat and NEOSSat. We measured the carrier frequency with a 9.1m S-band receiver and recorded passes using a high resolution data recorder. Range rate measurements were collected and compared to their ephemerides data using Satellite Tool Kit. Range rate residuals were calculated to assess the precision of our repurposed system. The results obtained are in accordance with theoretical expectations that were based on ephemeris data and are described in this paper. The characteristics of the received signals are described in addition to potential uses of this data within the SSA community.

INTRODUCTION

The number of LEO satellites in orbit is rapidly expanding. As this proliferation of small satellite technology continues it will be necessary to assess the status and orbital state of this unique class of space object. It is expected that there will be on the order of 12000 objects (>10cm) in the LEO domain by 2030 even in the absence of large constellations [1]. Recognizing that there are a large number of ground stations used for satellite TT&C around the world, we examine how a ground station can be repurposed to perform Space Situational Awareness (SSA) tracking using one-way Doppler measurements on the small satellite class of vehicle. Similar efforts were documented recently by Richmond & al. in [2]. The DRDC Ottawa Defensive Satellite Operation Research Facility (DSORF) team converted a 9.1 meter S-band system developed as a cold backup for the NEOSSat mission as a SSA test and evaluation capability.

This paper summarizes the preliminary findings of the conversion of 9.1m antenna at DRDC Ottawa and Doppler range rate measurements. These measurements were collected on four Low Earth Orbit (LEO) Canadian Satellites: CANX-7, SCISAT, M3MSat and NEOSSat.

DOPPLER AND RANGE RATE THEORY

Throughout this paper we use a classic derivation of the Doppler equation [3]. The one-way Doppler equation for a moving source is described as

$$f_D = \left(1 - \frac{1}{c}\frac{dr}{dt}\right) f_t \qquad (1)$$

where f_t is the known or approximated satellite transmitted frequency, f_D is the apparent measured frequency, c is the speed of light, and $\frac{dr}{dt}$ is the range rate in meters/second which is the derivative of the range r with respect to time between the satellite and the fixed receiving station on the ground. Solving for the range rate,

$$\frac{dr}{dt} = c\left(1 - \frac{f_D}{f_t}\right) \quad .$$

As the satellite approaches, the frequency appears higher than the actual transmission frequency because $\frac{dr}{dt}$ is negative. As the satellite moves away from the observer, the frequency appears to be lower because $\frac{dr}{dt}$ is positive. At the zenith (inflexion point), the received frequency is equal to the actual transmission frequency therefore $\frac{dr}{dt}$ is 0. By measuring the apparent frequency during a complete pass we can produce Doppler and range rate curves. This information can then be later used for orbit estimation processes.

SYSTEM OVERVIEW

The DRDC DSORF consists of 9.1m, 1.2m and 4.6m S, X and C-band systems mounted on altitude-azimuth pedestals (see Figure 1). The 9.1 meter system uses a Kintect 9.1m Antenna Pedestal system delivered in 1991 [4]. The antenna can slew at a rate of 5 degrees per second in azimuth and elevation. It has a tracking resolution of 0.012 degrees and is controlled by an antenna control system (ACS) that was designed and installed by Intertronic Antennas in 2012. It consists of updated motors and belt drive, and a drive panel controlled through *Human Machine Interface* (HMI) software. It can be synchronized to an SNTP server and uses the MODBUS TCP/IP, i.e. industrial Ethernet protocol to communicate between the antenna and the control computer located in a nearby building.

Figure 1. DRDC Ottawa DSORF with 9.1m antenna (foreground), 1.2m antenna (inside dome) and the 4.6m antenna (lower left)

The feed of the 9.1m S-band antenna is located at the focal point of the paraboloid. The feed consist of an arrangement of bandpass filters, low-noise amplifiers (LNA), couplers and relays. It can receive between 2000 to 2400 MHz, has a peak receiving net gain of 41.16 dB, and a sensitivity of 20.02 dB/K. The entire system was converted to S-band one way Doppler system over a period 7 months, where all the networks, secondary equipment, control systems and the antenna were tested, verified, synchronized, calibrated, and tested. Data recording uses a D-TA 2300S high speed recorder and processing server that enables high-rate continuous recording of data of sensor interface, data transfer and playback features. The downconverter is a Novella D492 S-Band to VHF synthesized downconverter covering S-Band from 1750 MHz to 2950 MHz with an output of 70 MHz with a usable bandwidth of +/- 20 MHz. Our team measured the signal using the 9.1m S-band antenna and feed after downconversion to the 70 MHz intermediate frequency. The signal was fed to the RF recorder and a spectrum analyser. This setup permitted us to verify the reception of the signal in real-time in both the recorder and the spectrum analyser.

CALIBRATION AND TESTING

SSA sensors typically require some form of calibration to assess their sensitivity and accuracy. For the repurposed 9.1m, NEOSSat daily precision orbital ephemerides produced using onboard GPS measurements were made available by DRDC Ottawa. By comparing measured range rate from the 9.1m against theoretical measurements, systematic and random errors could be inferred by taking residuals between the measured and theoretical values. After the calibration process using NEOSSat, additional Canadian satellites would be characterized, however no precision orbital ephemerides are available.

A measurement campaign was established to track small satellites flying in characteristic, polar Sun-synchronous orbits used by small satellites. The Canadian satellites tracked were: NEOSSat, CANX-7, M3MSat and SCISAT. All of which are S-band satellites transmitting in the 2000-2400 MHz range. Satellite details are compounded in Table 1.

Table 1 – Objects observed by DRDC

Satellite Name	NORAD ID	Int'l Code	Perigee	Apogee	Inclination	Period	Semi major Axis	RCS
NEOSSat	39089	2013-009D	775.2 km	792.6 km	98.5°	100.6 min	7154 km	0.5655 m^2
M3MSat	41605	2016-040G	500.1 km	518.4 km	97.3°	94.7 min	6880 km	unknown
CANX-7	41778	2016-059F	628.9 km	667.9 km	98.3°	97.5 min	7019 km	unknown
SCISAT	27858	2003-036A	639.8 km	650.4 km	73.9°	97.5 min	7016 km	0.7229 m^2

Note:Data taken from NYO2.com website NYO2.COM

The Near Earth Object Surveillance Satellite (NEOSSat) is a Canadian microsatellite equipped with a visible light telescope and is used for space-based SSA experimentation. NEOSSat is the first space telescope designed to search for hazardous Earth-crossing asteroids [5]. The Maritime Monitoring and Messaging Microsatellite (M3MSat) is a remote sensing satellite that receives and locates Automated Information System (AIS) signals transmitted by vessels [6]. The Canadian Advanced Nano Space eXperiment 7 (CanX-7) is a deorbiting nanosatellite demonstration mission of the University of Toronto Institute for Aerospace Studies/Space Flight Laboratory (UTIAS/SFL). This mission was developed to validate a de-orbit drag sail [7]. SCISAT is a relatively small Canadian satellite (150 kg) designed to make observations of the earth atmosphere [8].

The satellite passes were acquired over Eastern Ontario and consisted of passes having different elevations and azimuths, as shown in Figure 2. These passes were visible to the 9.1m S-band antenna for approximately 9 to 15 minutes, depending on the satellite altitude and pass elevation. The DRDC DSORF is located at a latitude of 45.3497°, a longitude of 75.8903^0, and an altitude of 79.2 m above sea level with the 9.1m S-band pedestal axes intersection being 9.76 m above the ground. The tracking was done with the HMI software provided with the antenna control system. The resolution is one second between points and uses interpolation in horizon coordinate system. The interpolation method used in the controller requires position, time and velocity at which the antenna must pass through the time tagged positions to maintain pointing toward the targeted satellite. This is done by differentiating the positions and times of the preceding and following points [9].

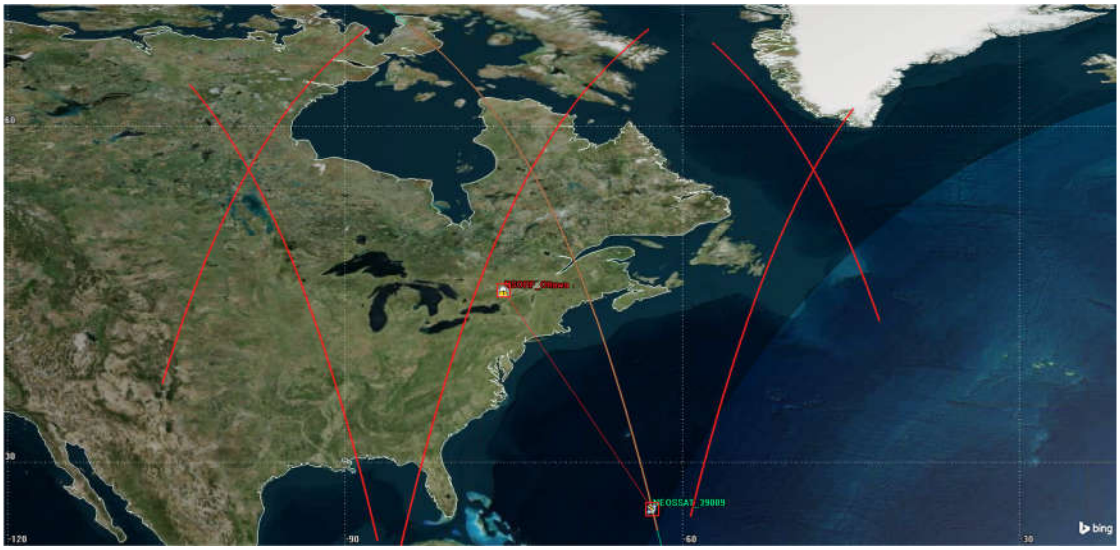


Figure 2. Orbital passes of NEOSSat (Red) relative to the DSORF sensor. The line from NEOSSat to the DSORF signifies the satellite is in view of the DSORF

All range rate predictions were generated with the help of Satellite Tool Kit 11 and the tracking files were generated with the Standardized Astrodynamics Algorithms Library- SSA Version 7.8 27 March 2017 [10] . This Dynamic Link Library/Shared Object was called from Matlab Scripts developed by the team. The tracking files where generated with Matlab and loaded through the HMI software.

During each satellite pass, complex baseband samples were recorded at a rate consistent with the downlink signal used by the satellite. For NEOSSat, CANX-7 and M3MSat, a sampling rate of 3.125 MHz was used, while a sampling rate of 6.25 MHz was used for SCISAT. The raw samples were processed using Matlab. Short-time discrete Fourier transforms were generated in order to estimate the Doppler frequency shifts by locating the discrete frequency points having maximum magnitude at various instants of time. Since the signals transmitted by the satellites were generally modulated and the carrier was suppressed, an additional step was required before conversion of the time series to the frequency domain to recover the carrier. This involved raising the time-domain signals to the second, fourth and eight powers to attempt the fast recovery of the carrier frequency depending on whether the signal was modulated using binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) or 8-PSK respectively.

Both the RF downconverter and the data recorder were synchronized to a GPS time and frequency reference. However, no absolute time stamps were provided by the recorder and a rather crude time alignment had to be made using time tags found on files generated by the recorder. It is assumed that each recording of a pass started at the top of a GPS second by triggering on the one pulse per second (1 PPS) input signal, as is the case for several RF recorder of this type. Then the time correction was assumed to be an integer number of seconds. It was found that frequency corrections also had to be made on the order of several kilohertz, indicating that satellites may have large carrier frequency deviations.

TYPICAL RANGE RATE ERROR MEASUREMENT

Before delving into measurements, it can be insightful to predict the kind of error that should be measured in practice when comparing range rate measurements with predictions that are based on standard two-line element (TLE) sets. Using precision ephemerides for NEOSSat that were derived from its on-board GPS as truth data and standard TLE sets, the range rate residuals on a pass on 30 October 2019 are plotted in Figure 3. It is observed that the maximum error occurs in the middle of the pass, as the satellite reaches its highest elevation.

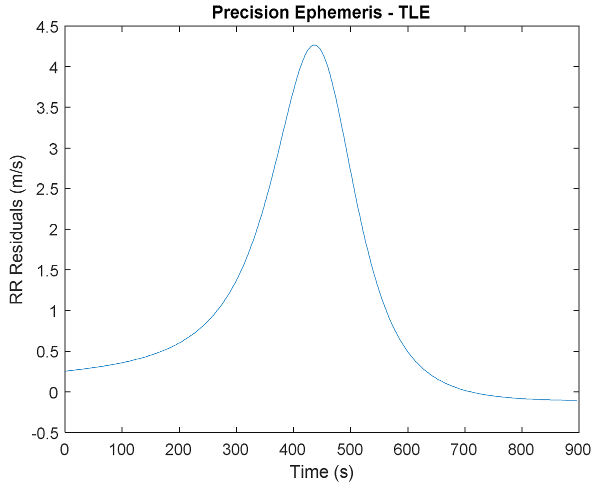


Figure 3. Typical range rate estimation error during a pass. This was generated using predicted range rate by precision ephemerides and regular TLEs for NEOSSat on 30 October 2019

SYSTEMATIC ERROR ANALYSIS BASED ON NEOSSAT PRECISION EPHEMERIDES

NEOSSat was tracked on more than 10 opportunities i.e. passes and frequency measurements collected. These measurements were then converted to range rate and compared to reference ephemeris pseudo-measurements generated by importing NEOSSat's precision ephemeris into STK and generating truth range rate measurements for comparison. Residuals were calculated by

$$\Delta_{RR}(t) = RR_{mea}(t) - RR_{Ephe}(t) \tag{3}$$

where RR_{Ephe} is the range rate given by the reference NEOSSat ephemerides, and RR_{mea} is the range rate derived from the measured frequency emitted by the satellite. Figure 4 shows a comparison of the measured range rate with the predicted one for a NEOSSat pass on 30 October 2019. The two curves are seen to be in very good agreement over the entire pass, showing small differences at the beginning and end of the pass. Note that at the time of these measurements, synchronization of the data recorder was not setup correctly. Since the precision ephemerides were assumed to give the truth data, the two curves were aligned at the inflexion point corresponding to the point of highest elevation of the satellite.

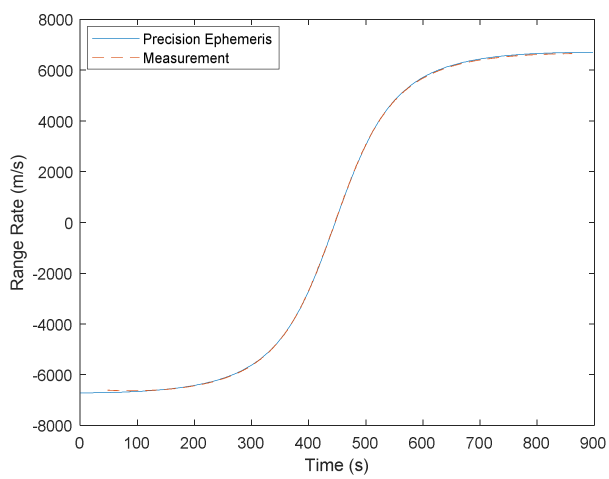


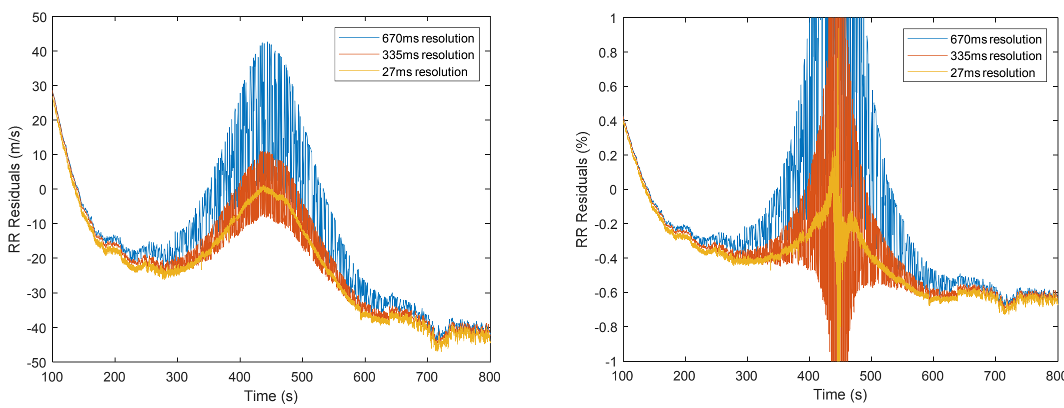
Figure 4. Comparison of measured range rate and predicted range rate based on precision ephemeris data for a NEOSSat pass on 30 October 2019.

The difference between the two curves is plotted in Figure 5. The measured curve of Figure 4 was obtained using a time sampling resolution of 670 ms. Over this period, all available samples were used for Doppler estimation and the satellite was assumed to be stationary. For this reason, significant fluctuations occur in the middle of the pass where the range rate changes more rapidly. Finer time resolutions reduce these fluctuations, as demonstrated in Figure 5, at the expense of coarser frequency and range rate resolutions. The range rate resolution is given by:

$$\Delta RR_{Res} = \frac{c}{k f_t \Delta t} \tag{4}$$

where Δt is the time resolution and k is the exponent used on the raw time series to test various PSK modulations. In the results shown in Figures 4-5, the modulation is QPSK and k=4. The range rate resolutions are therefore 0.05, 0.1 and 1.25 m/s for the three time resolutions shown in Figure 5.

The range rate residuals are also evaluated relative to the measured range rate in Figure 5(b). Since the range rate is very small in the middle of the pass, the relative range rate residual percentage has a very large magnitude, although the corresponding absolute range rate residual of Figure (a) can be small, which is expected. Other than this special case, the relative range rate residual is smaller than 1%. Assuming that the precision ephemerides give the true range rate data, these residuals constitute the systematic errors that need to be investigated further to improve future range rate measurements.



(a) (b)

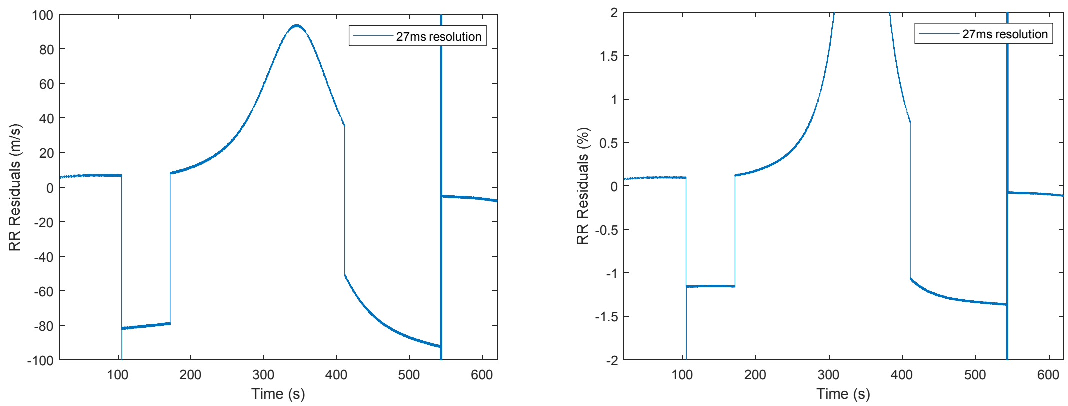
Figure 5. Range rate residuals against precision ephemeris prediction for a NEOSSat pass on 30 October 2019 in (a) meters per second and (b) percent for various time resolutions.

MEASUREMENTS ON OTHER CANADIAN SATELLITES

Other Canadian satellites, M3MSat, SCISAT and CANX-7, were tracked during this measurement campaign. Precision ephemerides were not available for these three satellites, and the measured range rate is therefore compared to the most recent TLE available during the pass.

M3MSat

Measurements on M3MSat were performed on more than 10 occasions throughout 2019-2020, and one of these passes is shown in Figure 6. In Figure 6(a), we can see a range rate residual curve having a similar shape as that of Figure 3, but with approximately 20 times the peak residual peak value. Two sudden transitions are observed at approximately 100 and 400 seconds having durations of one and two minutes respectively, where the range rate residuals increase to approximately -80 m/s. These are still under investigation and could be due to a front-end malfunction. Note that these transmissions were in a different mode where the signal-to-noise ratio was very weak. Unlike NEOSSat in Figure 5, we note that the range rate residuals are smaller at the beginning and end of the pass. This is more consistent with the expected range rate residuals predicted in Figure 3.

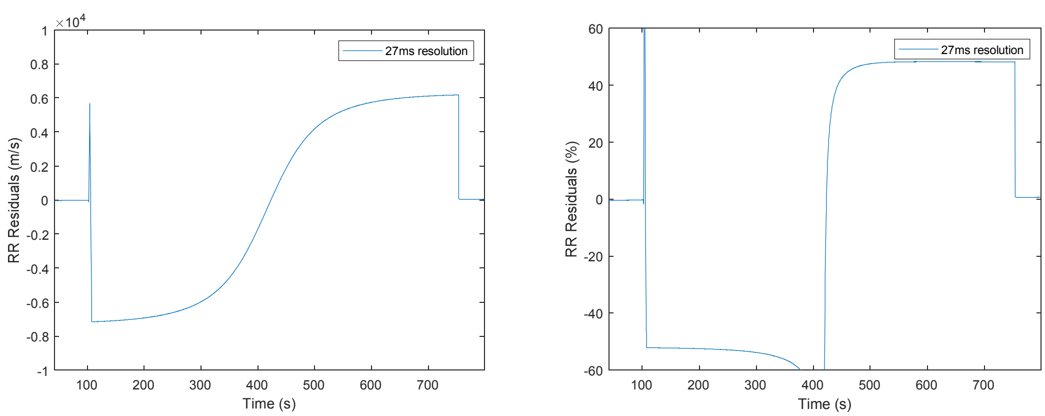


(a) (b)

Figure 6. Range rate residuals against TLE prediction for an M3MSat pass on 6 January 2020 in (a) meters per second and (b) percent for a 27 ms time resolution.

SCISAT

The measurements for SCISAT were performed on more than 8 occasions throughout 2019-2020, and one of these passes is shown in Figure 7. In this figure, we see that the satellite is close to theoretical predictions only at the beginning and end of the pass. Changes in its frequency, possibly by locking on to its ground station reference frequency, is likely why the range rate is not consistent during the entire pass. In particular, the additional Doppler shift from the ground station to the satellite may be contributing to approximately double the range rate measurement, leading to a range rate residual close to 50%.

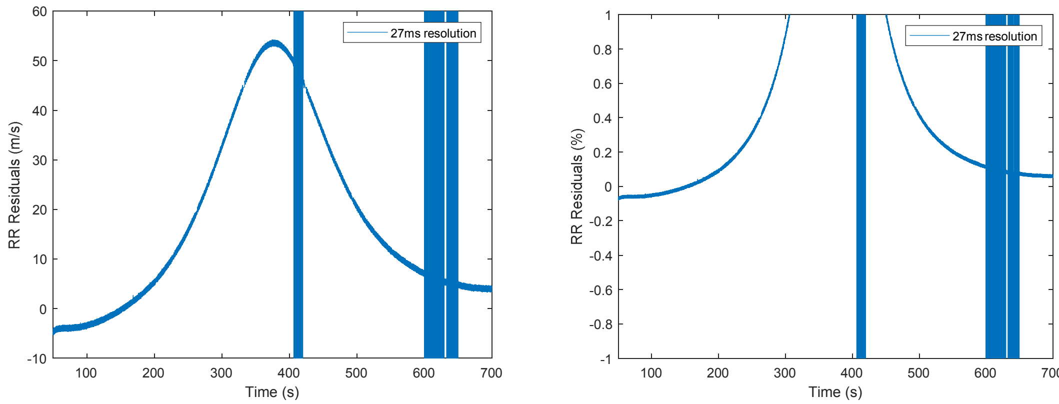


(a) (b)

Figure 7. Range rate residuals against TLE prediction for a SCISAT pass on 9 January 2020 in (a) meters per second and (b) percent for a 27 ms time resolution.

CANX-7

The measurements for CANX-7 were performed on more than 7 occasions throughout 2019-2020, and one of the passes is shown in Figure 8. The shape of the range rate residual curve in Figure 8(a) is similar to that of Figure 3, with a peak value of approximately 50 m/s. The beginning and end of the pass have residuals like those of M3MSat in Figure 6 and are less than 5 m/s and 0.1%. The vertical bands in the two plots indicate a change in modulation or the interruption of the transmission.



(b) (b)

Figure 8. Range rate residuals against TLE prediction for a CANX-7 pass on 7 January 2020 in (a) meters per second and (b) percent for a 27 ms time resolution.

DISCUSSION & CONCLUSIONS

In this study, the first steps toward the repurposing of a ground station to passively characterize the S-band RF emissions from small satellites is detailed. A calibration campaign was performed by monitoring the S-band transmissions from NEOSSat during passes over eastern Canada. Some systematic error was observed by comparing measurements against precision ephemeris-generated pseudo-measurements and is not well-characterized at this time. Interestingly, we noted that more satisfactory range rate residuals were obtained with satellites other than NEOSSat despite the absence of precision ephemerides. M3MSat and CANX-7 had residuals less than 0.1% at the beginning and end of their passes. One commonality of these two satellites is that they use carrier frequencies higher than NEOSSat and SCISAT, i.e. 2237.5 and 2234.4 MHz instead of 2232 MHz. This suggests that an analysis of the RF front-end may be required in future work when converting the 9.1m for SSA sensing. Another issue is time and frequency synchronization. For all passes, carrier frequency corrections had to be made on the order of several kilohertz. With respect to time synchronization, the current recording system does not provide accurate timestamps. This forced us to align the Doppler shift curves using the operating system file timestamps assuming that the recording truly started at the top of a second.

Despite these initial technical issues, this paper has demonstrated that the DSORF now has the capability to perform basic one-way Doppler characterization of LEO satellites. This has potential applications in SSA such as orbit determination, maneuver detection, satellite status characterization and anomaly detection. Future work by our team will involve investigation and correction of the observed systematic error. Data fusion experiments by using a nearby optical tracking sensor are also planned. Cooperative tracking of NEOSSat is also planned. NEOSSat will perform attitude slew maneuvers during passes visible to the DSORF to characterize attitude maneuvers using NEOSSat's emitted RF energy.

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