The Canadian Space Agency (CSA) is a government organization committed to promoting the development and application of space knowledge for the social and economic benefit of Canadians and humanity. The Telemetry, Tracking and Control (TT&C) team within the CSA is responsible for ensuring clear and uninterrupted communication between satellites, both Canadian and European, and ground stations. The team also maintains and upgrades the communication equipment and software at Canadian ground stations. Until recently, TT&C used a commercially written Simplified General Perturbations Satellite Orbit Model 4 (SGP4) propagator to predict the position of satellites, as shown in Figure 1. This aspect of tracking allows for the proper orientation of the communications antenna, known as the antenna pointing angle. However, the SGP4 propagator program had several shortcomings in addition to being out of date with current satellite tracking software requirements. Ilia B. Baranov, a University of Waterloo co-op student, was hired to develop an updated in-house version of the propagator software, based on existing source code.

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Canadian Space Agency Propagation Software Development

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| **Figure 1: 2D projection of two satellite passes simulated using SGP4** |

# CSA Background

The Canadian Space Agency (CSA) is a government organization charged with the peaceful, beneficial use of space knowledge and technologies as well as with ensuring the proper distribution of funds associated with space research, engineering and public education. The Agency was established in March 1989 by the [Canadian Space Agency Act](http://en.wikipedia.org/wiki/Canadian_Space_Agency_Act) and sanctioned in December 1990. CSA headquarters is located at [John H. Chapman Space Centre](http://en.wikipedia.org/wiki/John_H._Chapman_Space_Centre) in [Saint-Hubert, Quebec](http://en.wikipedia.org/wiki/Saint-Hubert,_Quebec). The Telemetry, Tracking & Control (TT&C) team is a subdivision of the Satellite Operations department, and its role is to ensure effective communication between satellites and Canadian ground stations. Telemetry tasks involve the acquisition and analysis of data sent from a satellite pertaining to its physical state, such as orientation, system health, and so on. Tracking refers to locating and predicting the position of a satellite using real-time ranging and mathematical models, respectively. Lastly, Control tasks consist of transmitting commands back to the satellite, such as orientation commands, orbital changes and so on.

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| **Figure 2: Region of Visibility [1]** |

Efficient tracking of satellites as they orbit in space is crucial for effective communication as it allows for the proper orientation of the communications antenna, known as the antenna pointing angle, as shown in Figure 2. This pointing angle is very important to TT&C because it has the largest effect on signal strength, thus it must be extremely accurate in order to provide the highest signal-to-noise ratio. The prediction of satellite location in three-dimensional space is used to generate the pointing angles for the antenna. The TT&C team uses a wide range of software and hardware equipment to enable effective communications. The hardware includes: the main antenna, signal modulation and demodulation equipment, and so on. The TT&C also used a commercial orbital prediction program, the Simplified General Perturbations Satellite Orbit Model 4 (SGP4) propagator, which was written as an ActiveX™library. This software had several limitations and could not meet the current requirements of the propagation program, which led TT&C engineers to consider development of a new in-house, updated propagation software program that would satisfy needs for accurate and reliable orbital prediction.

# Satellite Communication and the Role of SGP4

Satellite orbital propagation is based on Keplerian orbit elements, as shown in Figure 3. These orbit characteristics define the orbital orientation, shape, and speed of orbit as well as the last known position of the satellite [2]. These can be used to generate a rough estimation of a satellite’s position; however, such predictions will fail to reflect reality for extended periods due to orbital disturbances, known as perturbations, such as atmospheric drag and lunar gravitational pull. The need for accurate orbital prediction at the dawn of the space age led to the development of the Simplified General Perturbations model in 1970 [2]. This model was later improved with the advent of the Simplified General Perturbations model 4 (SGP4) in 1980. Although this new model is thought to be as close as possible to orbital models currently used by NORAD, the North American Aerospace Defense Command [2], several limitations must be overcome to obtain an operationally reliable orbital propagation model.

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| **Figure 3 - Keplerian orbit elements, the**[**orbital plane**](http://en.wikipedia.org/wiki/Orbital_plane_(astronomy))**(yellow) intersects a reference plane (gray). For earth-orbiting satellites, the reference plane is usually the Earth's equatorial plane [1].** |

The basic form of SGP4 propagation uses an input file known as the Two Line Elements (TLE). These two lines contain the Keplerian elements information pertaining to the satellite, along with identification and time data. This format was specified by NORAD and continues to be used today. The details pertaining to the exact format are presented in Appendix A. An example is presented in Figure 4.



**Figure 4: Sample TLE for Radarsat-1**

Once this data is entered into the program, the program is expected to provide the XYZ coordinate and velocity of the satellite for any point in time. In the case of NORAD standard SGP4 propagation, the reference frame for these coordinates is Earth Centered Inertial, True Equator Mean Equinox of the epoch (ECI TEME) [3]. Earth Centered Inertial indicates that the coordinates system has (0,0,0) located at the center of the earth and that this coordinate system does not rotate with the earth. True Equator Mean Equinox of the epoch indicates that the coordinates system is oriented such that the Z-axis is pointed from the center of the earth to true north at the epoch time. In addition, the X-axis is pointed from the center of the earth to the point where the earth’s equator intersects the earth’s orbital plane around the sun, at the epoch time. For the last two axes, it is important to specify at what epoch, or time, the coordinate system is generated, because the earth “wobbles” in its orbit, which will shift this reference frame. This wobble is known as nutation. Lastly, the Y-Axis completes the coordinate system and is oriented in the orthogonal direction to the other two axes, following a right hand rule [4], shown in Figure 5.

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| **Figure 5: ECI TEME Reference Frame [1]** |

This data is then used to generate other relevant output, including velocity, antenna angles, latitude, longitude, altitude, and so on. The output format for Pass List and Full Data/Visible Data propagation modes are presented in Appendix B.

# Problem description

TT&C engineers noticed several shortcomings within their existing SGP4 propagator software, written as an ActiveX™ library. One of the primary problems was that the source code for the library was unavailable, which restricted the team from customizing the software, adding key new features, to meet the needs of the TT&C division. In addition, the library was a purchased product, leading to recurring licensing fees for the department. Furthermore, the code did not respond well to being called by multiple programs at the same time. Lastly, the code was outdated and did not reflect the changes suggested by Revisiting Spacetrack Report #3 [2], which outlines the most current standards and formats for propagator software code. Therefore, the team decided to develop a new in-house orbital modeling software package based on the source code and findings in the report. During the validation process, prediction results generated by the new propagator program, to be named IVB SGP4, were compared to results obtained from both ActiveX™ (the original SGP4 program) and STK™. STK™ is a professional propagation program that is used by the CSA planning department. Lastly, the output was verified with real world pointing angles recorded during a physical pass.

The new program was required provide an open source, higher accuracy solution to orbital prediction and antenna tracking. It was also required to have the ability to provide multiple forms of output that are custom tailored to the needs of TT&C, which would allow it to be used in station automation. Station automation is a proposal to convert most of the current manual satellite communication operations to computer-controlled systems. This will free human resources for other, non-repetitive tasks. Therefore, IVB SGP4 will play an important role in upgrading current systems and planning for future station automation. After implementation and testing, the new program will replace currently used, commercially purchased libraries that are expensive and to some extent outdated.

**References**

[1] Ilia V. Baranov, “SGP4 Propagation Program Design and Validation”, 1A Work Term Report, Department of Electrical and Software Engineering, University of Waterloo, Waterloo, ON Canada, April 13, 2009

[2] Vallado, David A., Paul Crawford, Richard Hujsak, and Kelso, T. S., "Revisiting Spacetrack Report #3," AIAA/AAS Astrodynamics Specialist Conference, Keystone, CO, Aug 2006.

[3] Kelso, T. S., "Orbital Coordinate Systems, Part I.," Satellite Times, vol. 2, no. 1, pp. 80-81, Sept 1995.

[4] <http://www.sedsystems.ca/ttc_systems>

**Appendix A – TLE Format**

I represents integer.

C represents character

+ represents either a + or – sign

Each data entry is separated by a space

Unneeded characters are replaced by spaces, unneeded integers are replaced by zeros.

**Table 2: TLE Data format**



**Table 3: TLE Line 1 details**



**Table 4: TLE Line 2 details**



**Appendix B - Output Format**

**Pass List Format**

In pass list format, the total string length, including the return character, is 89 characters.

The data is divided into 8 sections separated by spaces.

1. Pass ID – string generated by concatenating the year, month, calendar day, hour, minute and second. The resulting string is always 14 characters long, with each data value occupying 2 spaces with the exception of the year, which occupies 4. Values less than 10 are left padded with zeros.

Example: 20090221101724

1. AOS Azimuth – string representing the Azimuth pointing angle for the station at AOS. String is always 7 characters and is left padded with zeros.

Example: 110.297

1. Orbit Number – string representing the orbit number for the current pass. String is always 7 characters and is left padded with zeros. Please note this value may not be accurate for Radarsat-1.

Example: 0069418

1. Direction – compass direction indicating whether the satellite is heading North or South during the pass. Can only have values “NORTH” and “SOUTH”, both 5 characters long.
2. AOS Time – string representing the time at which AOS is predicted. String is 17 characters long and each entry is left padded with zeros. Data given in the format: [Year]-[day of year]-[hour]:[minute]:[second]. Accurate to the second.

Example: 2009-051-20:29:20

1. LOS Time – string representing the time at which LOS is predicted. Identical format and content to AOS time.
2. Duration – string representing the total visible duration of the pass as a time value. Time is given in the format: [minutes]:[seconds]. The string is 7 characters long and each entry is left padded with zeros.

Example: 0012:04

1. Max Elevation – string representing predicted maximum elevation in degrees. String is 6 characters long and is left padded with zeros.

Example: 08.084

**Table 5: Example Pass List Strings**

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**Full Data/ Visible Data Format**

In Full Data or Visible Data format, the total string length, including the return character,

is 173 characters. The data is divided into 15 sections separated by spaces. However, the

first section contains a space. This was done to maintain compatibility with existing

software.

1. Timestamp – string representation of the time at which the data point is predicted. The format is as follows: [year]-[day of year]\_[hour]:[minute]:[second].[millisecond]. The underscore in the string represents a space. The string is 22 characters long and each entry is left padded with zeros. Example: 2009-057 20:53:16.000
2. X position – string representing the x position of the satellite in kilometers in ECI TEME reference frame. The string occupies 11 characters and is left padded with spaces. Example: 3017.854
3. Y position – identical in formatting to the X position.
4. Z position – identical in formatting to the X position.
5. X velocity – string representing current X velocity of the satellite in kilometers/second in ECI TEME reference frame. The string occupies 11 characters and is left padded with spaces.

Example: -0.473

1. Y velocity – identical in formatting to the X velocity.
2. Z velocity – identical in formatting to the X velocity.
3. Azimuth angle – string representing azimuth angle in degrees from the station coordinates to the satellite. The string occupies 11 characters and is left padded with spaces. Example: 124.172
4. Elevation angle – string representing elevation angle in degrees from the station coordinates to the satellite. The string occupies 11 characters and is left padded with spaces. Example: 0.030
5. Range – string representing range in kilometers from the antenna to the satellite. The string occupies 14 characters, has 6 decimal places, and is left padded with spaces.

Example: 3260.011543

1. Range Rate – string representing rate of change of range in kilometers/second. The string occupies 14 characters, has 6 decimal places, and is left padded with spaces. Example: -5.703276
2. Visible value – string representing whether or not the satellite is visible from the station. 1 is output if visible, 0 otherwise. The string occupies 2 characters and is left padded with a space. If propagator is used in visible only mode, value will always be 1.
3. Latitude – string representing the current latitude of the satellite, if projected onto a flat earth map, in degrees. The string occupies 11 characters and is left padded with spaces. Example: 28.057
4. Longitude - string representing the current longitude of the satellite, format identical to latitude.
5. Altitude – string representing the current altitude in kilometers above the reference geoid.

**Table 6: Example Full Data/Visible Data Strings**

