STK and SGP4 FAQ

This FAQ discusses the use of the SGP4 propagator within STK 4.4 and STK 5.0. A number of changes have been made since STK 4.3 so we felt a new FAQ was warranted. If you are using STK 4.3 or earlier, please refer to the STK 4.3 SGP4 FAQ.

What is SGP4?

SGP4 is an acronym for Simplified General Perturbations No. 4. The SGP4 propagator is used with two-line mean element (TLE) sets to propagate a satellite's orbit over time. The TLE sets used are maintained and updated in the space catalog, which has been maintained by various military organizations at the Cheyenne Mountain Complex in Colorado Springs, CO, since 1965.

The main product of the space catalog is the maintenance of the orbital element sets. The original analytic theory, Simplified General Perturbations (SGP), was developed by Aeronutronic-Ford. In 1965, Max Lane began developing a slightly different analytic theory. His work, along with contributions by Ken Cranford, resulted in the Simplified General Perturbations Theory No. 4 (SGP4). In the early 1970s, the original SGP analytic theory was replaced by a version of the Air Force General Perturbations Theory No. 4.

The main objective of Lane, Cranford and other scientists of the 14th Aerospace Force was to develop an analytic orbit theory that provided better orbit determinations and predictions for high drag satellites, yet didn't significantly increase computer time requirements. While the new theory was implemented into the Cheyenne Mountain Complex, operational requirements prevented it from being implemented at that time at any of the space surveillance/missile warning sensor sites due to operational issues. To resolve the astrodynamic compatibility issue, pseudo SGP elements were developed to maintain compatibility with the SGP orbital theory.

In the mid- to late 1970s, the SGP4 was modified to address deep space requirements. The incorporation of deep space algorithms into the SGP4 was developed primarily by Air Force Captain Bruce Bowman and Richard Hujsak of the 14th Aerospace Force/Air Defense Command/NORAD. The current SGP4 propagator, then, is really an SGP4/DP4 propagator.

While sensor sites and most military users have changed to SGP4, the practice of providing element set data that can be used in either SGP or SGP4 has been preserved. The primary difference between the two element sets is the formulation of mean motion and the atmospheric drag representation, i.e., the SGP is a Kozai-based theory while SGP4 is a Brouwer-based theory. Due to the operational requirements, the Kozai mean motion is the standard for TLE orbital products. You will normally find a zero (0) for ephemeris type on the first line of the TLE set product but if a two (2) should ever appear, that indicates the mean motion is the Brouwer formulation and doesn't need to be converted for use in SGP4.

What changes were made to SGP4 for STK 4.4 and STK 5.0?

The name of the SGP4 propagator within STK was renamed from MSGP4 to SGP4 in keeping with the commonly accepted terminology outside of STK. In addition, the AGI's former USGov version of the MSGP4 propagator within STK has been incorporated as the baseline SGP4 propagator. As such, the USGov version no longer exists in STK 4.4 or 5.0.

Where did the MSGP4 propagator go?

The SGP4 propagator in STK used to be called MSGP4 (Merged Simplified General Perturbations). The term "merged" refers to the fact that the algorithm used for orbits with periods below approximately 225 minutes is the Simplified General Perturbations (SGP4) propagator and, for orbits with longer periods, the algorithm used is the Simplified Deep Space General Perturbations (SDP4) propagator. Outside of AGI, the term SGP4 is commonly used to mean the combination of SGP4 and SDP4, so AGI has accepted the use of this terminology and eliminated the name MSGP4. All references to MSGP4 have been replaced with SGP4, including Connect commands (although the command syntax remains backwards compatible with the term MSGP4).

What are the different SGP4 implementations?

AGI currently has two implementations of SGP4, the standard version in STK and an interface to the SGP4 implementation developed by Air Force Space Command (AFSPC).

Where did you get the source code?

AGI originally developed SGP4 based off the publicly available algorithms and code documented in the 1980 Space Track Report #3. When implementing the algorithm as described therein, we noted some coding practices that would lead to a variety of errors. The mathematical foundation was correct, but the code as documented in the report was in error. We believe that AFSPC has also identified these issues over the years and have adjusted their code as well (based on various informal conversations that we have had).

Where can I get the source code?

A publicly available version of SGP4 can be found at www.celestrak.com. Another version of the SGP4 source code was on the Internet as part of a NASA web site supporting the SeaWIFS satellite program but has subsequently been removed. A third implementation is available as part of the SPICE library from NASA's Jet Propulsion Labs (JPL).

What changes have you made to SGP4?

AGI has made a number of modifications to the original code as published in Space Track Report #3 to address a number of coding errors and to improve the general robustness. These updates are:

The code was converted from FORTRAN to C.

TLEs by their nature only have a two-digit year in their epoch date. SGP4 assumes that TLEs with a year greater than 50 are assumed to be relative to 2000 and years

less than 50 are relative to 1900. Of course, should SGP4 be around in 2050 we would have to adjust this again.

The original SGP4 propagator used the FK4 theory as part of its baseline coordinate system definition of True Equator, Mean Equinox (TEME). AFSPC subsequently updated their algorithms to use the FK5 theory for defining TEME. AGI accordingly modified the SGP4 propagator as well by updating the Greenwich Hour Angle computation.

TLEs in the 2:1 resonance zone (periods near 12 hours) exposed an error in the original code when calculating the periodic terms for the solar and lunar perturbations. They were initialized once, but then never updated on subsequent calls to the routine. This code change was originally available only in the USGov version of SGP4 in versions prior to STK 4.4. With STK 4.4 and 5.0 this fix is part of the standard implementation.

Added a number of additional error checks for invalid computations. The original Space Track Report #3 code would occasionally crash when propagating under certain circumstances (e.g., eccentricity equal to zero).

Under certain circumstances, the Right Ascension of the Ascending Node (RAAN) would exceed 360 degrees when accounting for solar-lunar perturbations and would have to be adjusted along with additional dependent variables.

When propagating TLEs with very small inclinations (less than 0.06 degrees) SGP4 was incorrectly modifying the perturbed right ascension of the ascending node when perturbations to the mean inclination resulted in a negative inclination. The modification was being made prematurely, before all perturbations had been considered. Using the correction, the resulting ephemeris no longer shows a discontinuity.

We believe that the changes we have made are substantially similar to those in the official SGP4 propagator. Since AFSPC will not release the official version to AGI, we are unable to state with certainty that the results would be the same. A number of end-users who have access to both the STK SGP4 implementation and the official SGP4 from AFSPC have performed internal validation and verification (V & V) efforts for their organizations and they have verbally indicated that any differences are extremely small. We are unable to generate a V&V report due to the unavailability of official executables that we can use to generate test cases for comparison.

How do I run STK 4.4 or 5.0 using the USGov version of the SGP4 propagator?

The USGov version no longer exists in STK 4.4 and STK 5.0.

I've heard that Air Force Space Command has the official version of SGP4? Can I use that with STK?

For the last several years AFSPC has been developing an official, distributable version of SGP4 for use by authorized third parties. This version of SGP4 consists of a documented API and DLL (or shared library) that may be used by a third party application to propagate TLEs. AGI has been working closely with AFSPC/XPYC since June 2000 and has successfully integrated the AFSPC SGP4 propagator with STK. The integration consists of an AGI supplied DLL that acts as a wrapper to the DLL supplied by AFSPC. When STK users use

the SGP4 propagator (provided they have the USGov license) they are offered a choice as to which implementation they want: Standard or AFSPC. This choice is available wherever SGP4 is used within STK, including the STK/Pro and STK/CAT modules.

The AGI integration and testing of the AFSPC propagator was performed using a test library (called the AnPro version) that intentionally corrupts the resulting ephemeris. This has been sufficient to prove that the interface works and we have been able to validate and verify (V&V) our results with test results provided by AFSPC using the same test library. We do not anticipate any problems using the actual library, however we are unable state this with certainty because it is unavailable to AGI.

We have only performed the integration and testing using the Windows DLL implementation of the AFSPC propagator. We understand that several UNIX versions are in the works and will produce STK wrapper routines when they are available.

How do I get the AFSPC propagator?

HQ AFSPC/DOY has been identified as the focal point for obtaining the AFSPC version of SGP4. The POC is Mark Riddle, 719-554-9582. Contact Mark to obtain the necessary paperwork. Currently the process takes somewhere between one to two months. The latest version that we are aware of is 5.2.0.0 released in the May 2003 timeframe. Note that this version is not compatible out of the box with versions of STK prior to 5.0.4 since AFSPC changed the interface. Please contact AGI customer support if you need to run this version with older versions of STK.

How do I run STK using the AFSPC propagator?

To use the AFSPC propagator, contact AGI customer support to obtain a USGOV license key and the file AgAsAFSPCSGP4.dll (AGI's interface dll to the AFSPC dll).

Then contact AFSPC/DOY to obtain the official AFSPC SGP4 DLL (Sgp4Dll.dll) and supporting files (DFORMD.dll) and documentation. No license is required by the AFSPC library itself; however AGI has implemented a licensing policy to prevent unauthorized users from accessing the AFSPC propagator from within STK.

Locate your STK installation directory (typically "C:\Program Files\AGI\STK Software Suite 5.0") and create a directory called Modules at the same directory level as the bin directory. Copy the files AgAsAFSPC_SGP4.dll, Sgp4Dll.dll, and DFORMD.dll files into the Modules directory.

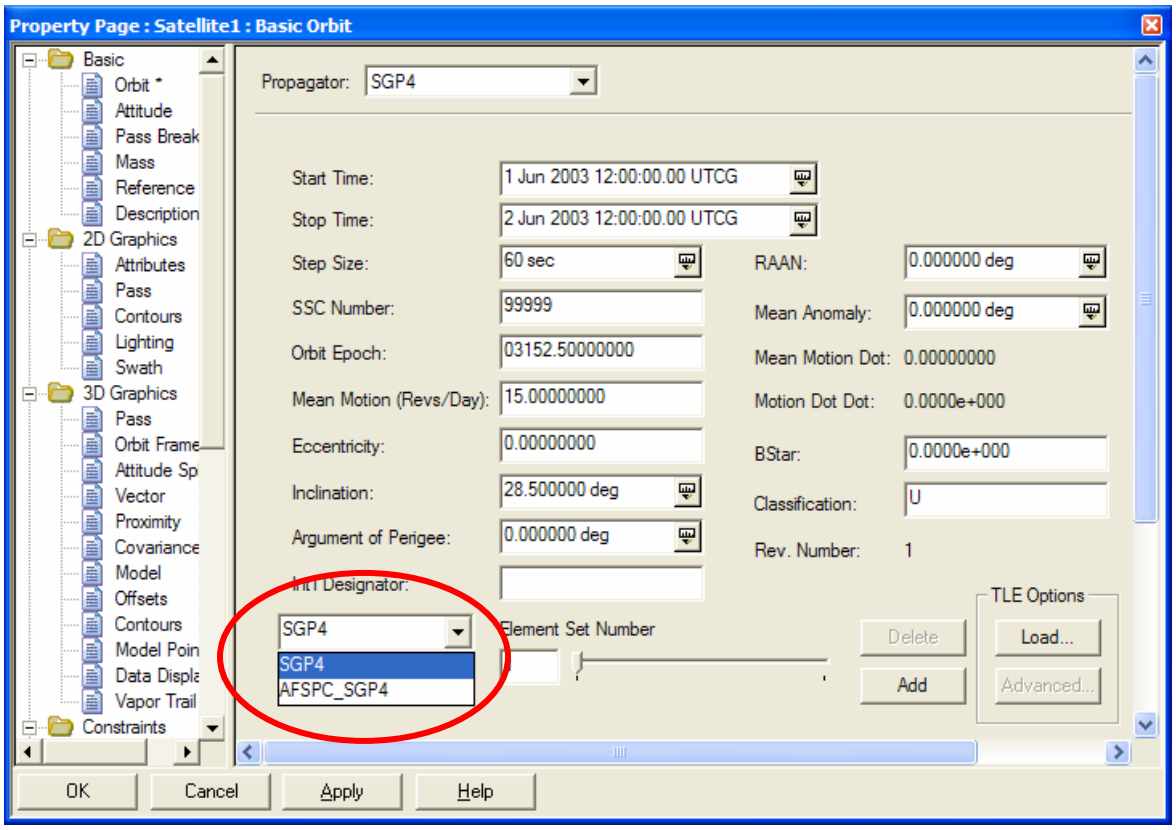
Now start up STK and verify that your USGOV license is valid by displaying the License Manager panel from the Help menu. You should see a license labeled USGOV displayed in the list of licenses. If you do not, you have a licensing problem and should contact customer support.

Now run STK. From the View menu, select the Message Viewer and verify that at start up STK found the extra DLLs. You should see a series of messages saying something similar to the ones below. The first message indicates that STK successfully found the AGI interface DLL and opened it. The next two indicate that the interface DLL successfully opened the AFSPC DLL and queried it for its version information. Your version information may be different (since we do not have the real one to test with).

```
C:\Program Files\AGI\STK Software Suite 5.0\Modules\AgAsAFSPCSGP4.dll Opened
Sgp4Dll version: 5.0.1.
Sgp4Dll:  HQ AFSPC AnPro-IDL DLL BETA Version 5.0.1. expires:        2005.
```

If you do not see these messages, then STK has not been able to successfully configure itself to use the AFSPC SGP4 propagator. Please recheck the first couple of steps and then contact AGI customer support if the problem continues.

Create a scenario and a satellite and set the propagator to SGP4. In the bottom left hand corner of the Orbit tab under the satellite's Basic Properties you should see a combo box displaying the choice of SGP4 versions: SGP4, AFSPC_SGP4. See the figure below for an example. If you do not see this, then contact AGI customer support.



Are there any coordinate system issues when using SGP4?

As a matter of design all SGP4 propagators produce ephemeris in the TEME inertial coordinate system. The date reference for TEME can either be of Epoch (using the time specified as the epoch in the TLE) or of Date (using the time for each point as it is calculated). The documentation in Space Track Report #3 indicates that the official SGP4 implementation uses is TEME of Epoch, but reports from customers using an official version seem to indicate that the output is actually TEME of Date. The difference between using TEME of Epoch and TEME of Date is very small when comparing the results over the time frame that a TLE is typically valid for (typically a week or so).

Based on customer feedback, STK has been configured to treat the output from SGP4 as if were TEME of Date. It may be reconfigured to use TEME of Epoch using a flag within the _Default.ap file to switch the output between TEME of Date and TEME of Epoch. The example below illustrates the use of the flag within the _Default.ap file. Valid values are TEMEOfEpoch or TEMEOfDate. By default, STK is set to assume that the ephemeris is generated in the TEME of Date system.

```
BEGIN SGP4FrameDefinition

    ReferenceFrame      TEMEOfDate

END SGP4FrameDefinition
```

When using external SGP4 propagators like the AFSPC SGP4 implementation, the choice of whether to use TEME of Date or TEME of Epoch is up to the user. However, the user should be aware that if they configure STK to treat it as TEME of Date and then generate ephemeris reports using a TEME of Epoch frame, the results would not be the same when compared to the same ephemeris generated using another application using SGP4. The converse is true as well if STK is configured for TEME of Epoch and the reports are in TEME of Date. The comparisons should be performed using an ephemeris reported in the same coordinate frame as STK is configured for (e.g. report in TEME of Date if configured for TEME of Date, report in TEME of Epoch if configured for TEME of Epoch).

Transformation from the TEME coordinate frame to any other inertial frame is performed by first transforming to the True Equator, True Equinox (TETE) frame by applying the equation of the equinox. STK implements the equation of the equinox using the full definition of nutation as specified by the 1980 IAU Theory of Nutation (see the Explanatory Supplement to the Astronomical Almanac). From TETE, any other frame (e.g. J2000, B1950, Earth Centered Fixed, etc.) may be obtained using standard methods.

I generate ephemeris with SGP4, but my results don't match my other ephemeris I am comparing against? What is the problem?

There are a number of reasons why your results may be different. First and foremost, make sure you are only comparing between two SGP4 propagators. Otherwise you are mixing and matching different theories and force models and will surely get different answers.

The only "truth" model for comparison purposes is the ephemeris generated from the official SGP4 implementation by AFSPC. Unfortunately, public test cases have not been made available by AFSPC. Customers with access to the official SGP4 implementation may generate their own ephemeris. Make sure the ephemeris that you are comparing with came from an up-to-date official version.

Ensure that you are comparing ephemeris using the same coordinate system. As mentioned above, SGP4 produces ephemeris in the TEME of Date coordinate system. However, you may not necessarily be reporting the ephemeris in the TEME of Date coordinate system. STK allows ephemeris to be generated in one system and then converted to any other system (e.g. J2000, Earth Centered Fixed, etc.).

STK differentiates between the time steps used to generate ephemeris and the time steps used for reporting data (including ephemeris). When a report or graph requests data at a particular time step, STK will interpolate as necessary within the available ephemeris to get the desired time. STK performs 5th order Lagrange interpolation in these circumstances to

generate the intermediate points. AGI recommends that users choose a time step that produces at least 50 ephemeris points per orbit in order to ensure accurate interpolation. The default time step of 60 seconds produces approximately 90 points for a LEO orbit – a typical worst-case orbit scenario. However, it is possible for a user to specify a 20-minute time step for ephemeris generation (on the satellite's Orbit panel) and then report the ephemeris at 1-minute results. In this case 19 out of 20 points would be interpolated. For a LEO orbit, these 19 points would be considerably different when compared to those obtained when propagating at 1-minute intervals. The choice of 60 seconds is designed to provide default behavior for a novice user that would keep them out of trouble while allowing an expert user to tailor the time step as they saw fit to reduce the amount of ephemeris that was being held in memory. This issue is also discussed in the on-line help available within STK (press the Help button on a satellite's Orbit panel).

If you still have a difference and don't understand why, contact AGI customer support and we will be happy to discuss it with you and work with you to resolve it.