A Comparison of Satellite Conjunction Analysis Screening Tools

Eric R. George*

The Aerospace Corporation, Colorado Springs, CO, 80916

Dr. Seth Harvey†

Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, NM,

Abstract

Satellite collision avoidance analysis has received increased attention primarily due to the Iridium-COSMOS collision of February 2009, including consideration by the US Air Force of regular "all vs all" collision avoidance screening of the entire space catalog. Traditionally this type of analysis has been limited by computational resources. This analysis considers the accuracy and completeness of results achieved by six conjunction analysis screening tools in development or use in a variety of commercial and government settings. The focus of this research is large scale conjunction screening with a primary test case of a 7 day, 11K object computation producing on the order of 100K results. The focus of this analysis is on the completeness and correctness of the results. The time and computational resources required to perform the analysis is not considered at this time.

1. Introduction

This paper presents analysis that quantitatively compared six satellite collision analysis tools. To accomplish the collision tools analysis we considered we considered the data set described below. The primary objective of our analysis is to detect all conjunctions between all objects in the public space catalog with a minimum range of less than 10 Km for the 7 day period beginning at 2009-02-10 16:00:00 UTC. The TLE (Two Line Element) catalog used consists of the latest element set (TLE) for each object which received an update within the 14 days preceding the start of the analysis window. There are 11,807 objects in the resulting catalog. All TLE data were obtained from the public Space-Track website‡ and are available from the author upon request. Table 1 describes the composition of space object catalog used in this paper.

Table 1 Composition of the GP Study Catalog

Orbit Class	Semi-Major Axis (Km)	Eccentricity	Number of Objects
Low Earth Orbit (LEO)	$a < 8{,}500$	$e < 0.5$	9,024 - 76.4%
Highly Eccentric Orbit (HEO)	$a \geq 8{,}500$	$e \geq 0.5$	1,225 - 10.4%
Geosynchronous (GEO)	$40{,}000 \leq a \leq 45{,}000$	$e \leq 0.1$	961 - 8.1%
Medium Earth Orbit (MEO)	$23{,}000 \leq a \leq 29{,}000$	$e \leq 0.1$	209 - 1.8%
OTHER	Everything Else		388 - 3.3%
		Total	**11,807**

Conjunction analysis (CA) screening is the process by which conjunctions between orbiting objects are identified. There are two definitions of a conjunction in common use:

* Senior Project Engineer, eric.r.george@aero.org
† Aerospace Engineer, seth.harvey@kirtland.af.mil
‡ http://www.space-track.org

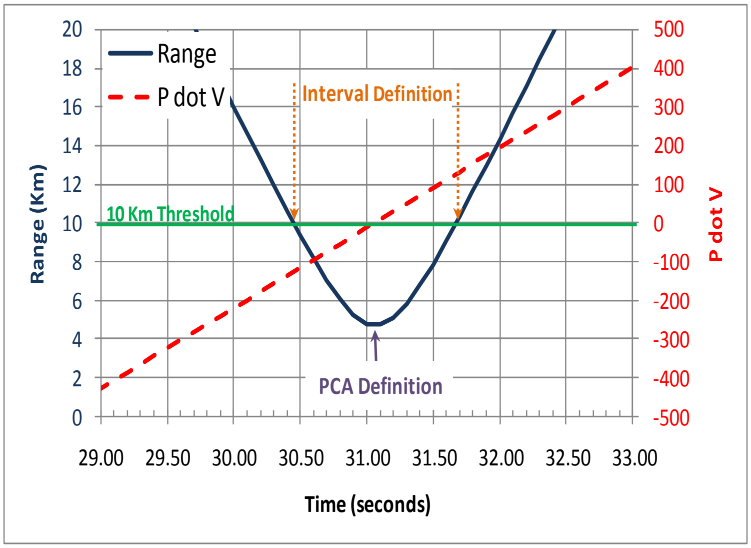
Definition 1 – Point of Closest Approach (PCA) A conjunction is defined as a local minimum of the range between two space objects such that the range is less than or equal to the screening threshold. This minimum corresponds to the root of the dot product of the relative position and velocity vectors.

The PCA definition of a conjunction will exclude instances where the point of closest approach occurs outside of the analysis time frame, even if the range is less than the threshold during the analysis timeframe.

Definition 2 – Conjunction Interval A conjunction is defined as the time interval during which the range between two objects is less than the screening threshold.

The Interval definition of a conjunction may lump together many local minima for closely spaced objects where the local maxima of the range doesn't exceed the screening threshold.

Figure 1 Conjunction Illustration



2. Analysis Tools

This section describes the conjunction analysis (CA) tools considered in this paper.

CAOS-D

CAOS-D (Continuous Anomalous Orbital Situation Discriminator)[1] is an extensible framework developed by Abernathy[*] and Surka[†] that provides a comprehensive conjunction analysis solution. CAOS-D provides the ability for new CA algorithms and approaches to be easily integrated and evaluated against other approaches in a net-centric environment. CAOS-D is implemented in Java and runs on multi-core Linux platforms using externally generated ephemeris data.

CSieve

CSieve (Conjunction Sieve) is a tool developed by the author at The Aerospace Corporation beginning in 2003. The CSieve tool is written in C++ and designed to operate on Linux cluster computers or on large multi-core Linux systems. This high performance computing capability, combined with an innovative screening algorithm inspired

[*] Software Engineer, Intelligent Software Solutions, Inc.
[†] Engineer, Data Fusion & Neural Networks

by Healy[2], greatly enhances the speed, capacity and scalability of the tool. CSieve uses TLE data and/or externally generated ephemeris data.

COMBO

COMBO (Computation Of Miss Between Orbits) is a standard US Air Force CA tool. Version 5.4.2 for Unix from Air Force Space Command's Astrodynamic Standards was tested. This version of COMBO is not used in operations. The COMBO results are available in an FOUO (For Official Use Only) addendum to qualified persons upon request.

SOAP

The Aerospace Corporation's SOAP[3] (Satellite Orbit Analysis Program) is a 3D orbit analysis and visualization tool. Version 13.1.4 for Linux was tested. The SOAP conjunction analysis function does not have the capacity to perform the large scale screenings that are the subject of this analysis. It is therefore used as a verification tool where each conjunction found by the other tools was examined by SOAP to confirm the conjunction.

STK Advanced CAT

STK Advanced CAT (Conjunction Analysis Tools) is an add-on module for the STK (Satellite Tool Kit) product from Analytical Graphics Inc. (AGI). Version 9 was tested with TLE data on a WindowsXP platform. Advanced CAT has several "pre-filters" available in the configuration. The default values and on/off status of these filters were accepted for the initial analysis. The impact of these filters is explored in the results section.

ShadowCAT

ShadowCAT is a tool being developed by AGI expressly for the all vs all CA problem. It performs an ephemeris based analysis on a single multi-core computer. The author was given access to this system via a web interface from AGI's Colorado Springs facility while the program was administered and run at their Pennsylvania facility. The specification and generation of the required ephemeris was performed by AGI personnel.

3. Analysis

All of the tools were configured and run by the authors, with the exception of CAOS-D, which was run by Mr. Derek Surka and ShadowCAT which was run by AGI personnel. In these cases a file containing the raw TLE data was provided, along with the analysis parameters. No results from other tools were provided. Tool configuration was based on the available documentation and conversations with the developers or organizations associated with the product.

The goal of the study was to perform a single seven day all vs all analysis run with each tool. When attempting to perform the seven day all vs all analysis with STK Advanced CAT, the program consistently crashed during report generation. This problem was encountered on a system with 8GB of RAM - the largest Windows system available to the author at the time. The time span of the analysis or number of primary objects had to be reduced in order to obtain results. In order to achieve the study's 7 day duration, several 24 hour duration all vs all analysis runs were concatenated.

4. Results

In order to eliminate problems comparing results near the edge of the screening radius, screening was performed with a 10 Km range, but results were only compared for conjunctions with a range of less then 9 Km. This eliminated problems such as one tool identifying a conjunction with a miss distance of 9.999 Km and another tool not identifying it because it found a miss distance of 10.001. A 1 Km offset was initially chosen and the maximum range difference table (Table 10) suggests that this was a very conservative choice.

In examining the results it became apparent that conjunction definitions varied between the tools, as Advanced CAT and ShadowCAT returned several Interval type conjunctions where the PCA was located outside of the analysis window. CAOS-D and CSieve did not return these events. CSieve has since been modified to include these events. Conversely, both STK tools only returned the overall minima for a low relative velocity case involving ISS (25544) and SOYUZ-TMA-13 (33399) which had 12 local minima. AGI has since modified ShadowCAT to display the local minima. This behavior is summarized in Table 2.

Table 2 Conjunctions types reported by each tool.

	CAOS-D	CSieve	Advanced CAT	ShadowCAT
PCA Conjunctions	✓	✓		✓*
Interval Conjunctions		✓*	✓	✓

* Feature added post analysis

All of the tools which identified Interval conjunctions with PCA outside of the analysis window returned identical results. Similarly, those tools that identified the 13 local minima PCA type events within the conjunction interval all found the same events. Therefore, from this point forward the analysis will focus on event types found by all tools. Table 3 presents the total number of conjunctions with a miss distance <= 9.0 Km found by each tool. It excludes interval events where the PCA is outside of the analysis timeframe, and events with multiple local minima within a conjunction interval are treated as a single event.

Table 3 Conjunctions of less than 9.0 Km found by each tool

Analysis Tool	Conjunctions Found
CAOS-D	116,746
CSieve	116,746
SOAP*	116,746
STK Advanced CAT	116,713
STK ShadowCAT	116,745

* used only in a confirmation role, not as a search tool.

The SOAP tool was used to confirm conjunctions found by the other tools by analyzing the two objects involved in each conjunction for a 20 minute window centered on the reported TCA. The presence of a PCA within ±300 seconds of the reported TCA was considered a "confirmed" event. This analysis confirmed all of the conjunctions found by all of the tools. The differences in TCA and range are included in the range and time comparisons below.

The results from each analysis are then matched to every other analysis using a time window of ±300 seconds.

Table 4 Summary of Matching Results for Default Configurations

		Conjunctions Found By…			
		CAOS-D	CSieve	ShadowCAT	STK Advanced CAT
Which Were Missed By …	CAOS-D	N/A	0	0	0
	CSieve	0	N/A	0	0
	ShadowCAT	1	1	N/A	1
	STK Advanced CAT*	33	33	32	N/A

* With default filter configuration

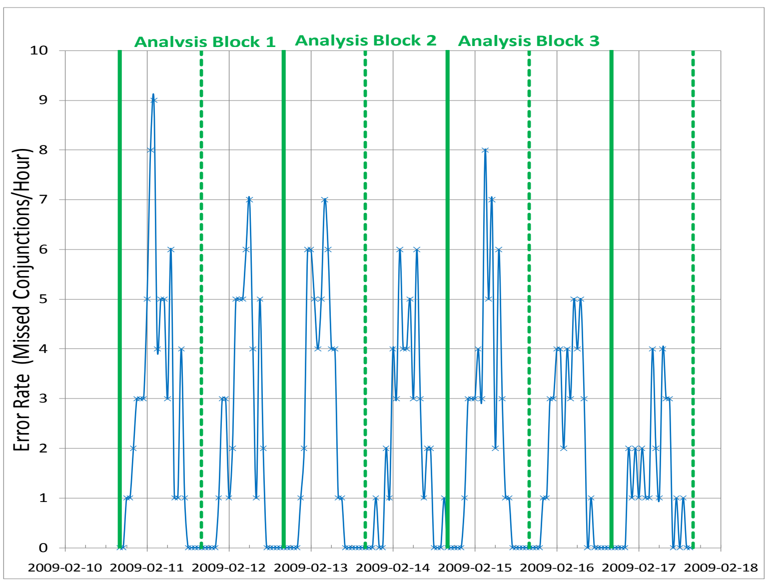
Table 4 summarizes the completeness of the result sets. Tables 9 through 12 examine the accuracy of the results. CAOS-D and CSieve both find all of the same conjunctions, which were also confirmed by SOAP. This result set is a superset of the results from all of the other tools.

Examination of Missed Conjunctions

STK Advanced CAT

There was a significant time component to the STK Advanced CAT errors. Expanding the analysis window from 24 to 48 hours greatly increased the number of missed conjunctions, from 33 for the compiled 24 hour blocks to 326 when analyzed with 48 hour blocks. Figure 2 shows the error rate of the 48 hour block analysis as a function of time. Note that the error rate goes to zero at the ends and center of each block. This may suggest a filter initiation issue where the filter is initialized at the center and each end of the analysis window, where the error rate goes to zero.

Figure 2 Periodic Nature of the STK Error Rate



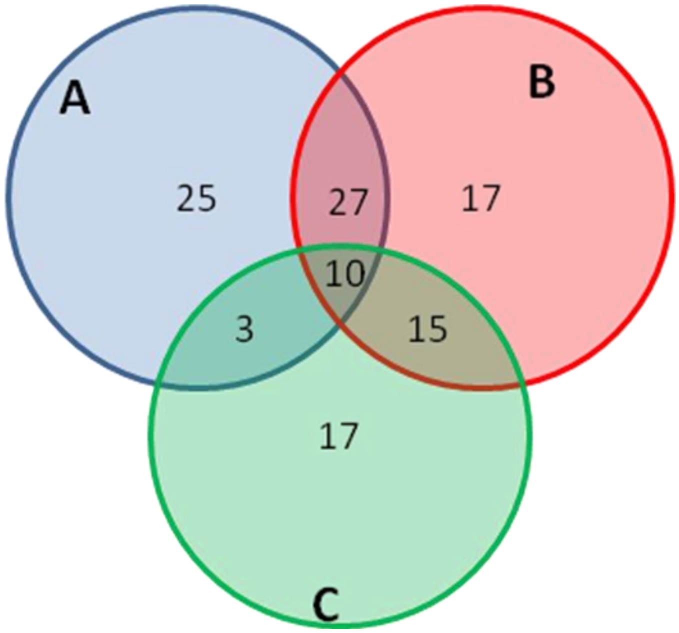
It was also found that the STK Advanced CAT errors depend strongly on the analysis start time, in addition to the time span. This was illustrated by conducting three 48 hour all vs all analysis with start times staggered by 6 hours each as shown in Table 5.

Table 5 Staggered STK Advanced CAT 48 Hour Analysis

Analysis Name	Start Time	Stop Time	Missed Conjunctions
A	2009-02-10 16:00:00	2009-02-12 16:00:00	65
B	2009-02-10 22:00:00	2009-02-12 22:00:00	69
C	2009-02-11 04:00:00	2009-02-13 04:00:00	45

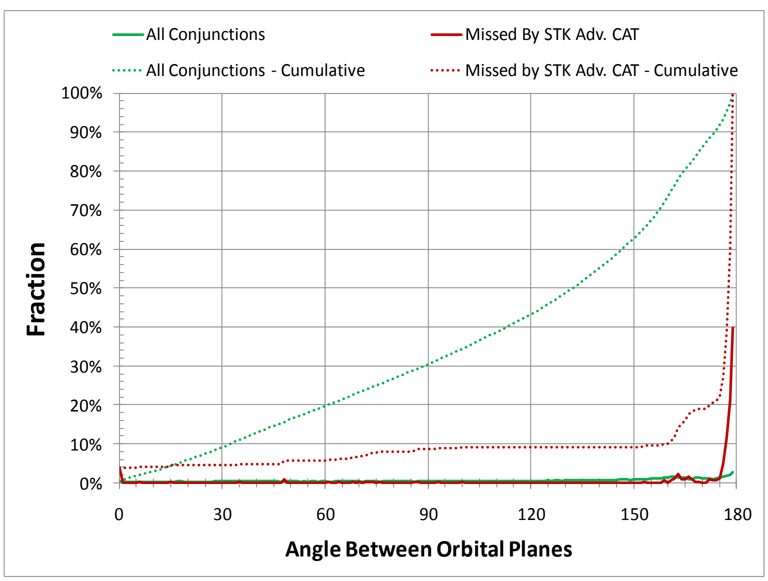
The “Missed Conjunctions” column in Table 5 refers to conjunctions found by CSieve and CAOS-D but missed by the respective STK analysis for the common 36 hour period of 2009-02-11 04:00:00 to 2009-02-12 16:00:00. STK Advanced CAT did not miss a common set of conjunctions across this period. In fact, only 10 of the 147 distinct conjunctions were missed by all three of the analysis, as illustrated in Figure 3. This analysis demonstrates that these errors could have been easily found without reference to external data.

Figure 3 Missed Conjunctions for Staggered STK Advanced CAT Analysis



The conjunctions missed by the STK Advanced CAT – 48 Hour analysis are highly correlated to the angle between the orbital planes of the conjuncting objects. In Figure 4, 0° corresponds to co-planar orbits with the objects traveling in the same direction. 180° corresponds to co-planar orbits with objects traveling in opposite directions, i.e. head on. 79% of all of the conjunctions missed by this analysis had plane angles between 175° and 180° while this same plane angle range accounts for only 9% of all conjunctions found.

Figure 4 Correlation of Conjunctions Missed by Advanced CAT to Plane Angle



The evidence in Figure 2 and conversations with AGI personel suggested investigation of the STK Advanced CAT filter settings. There are 4 filters available under the "Advanced" section of the Advanced CAT configuration.

Table 6 Default Configuration for STK Advanced CAT Filters

Filter	Use	Pad
Out Of Date TLE		2.592×10^{-6} seconds
Apogee/Perigee	X	30 Km
Orbit Path	X	30 Km
Time	X	30 Km

An analysis was constructed using the 519 unique objects involved in conjunctions missed by the STK Advanced CAT 48 hour analysis as primary objects versus the full 11,807 catalog for the period 2009-02-10 16:00:00 to 2011-02-12 16:00:00. This analysis was exercised for several filter settings, however the only improvement was seen by disabling or greatly increasing the size of the path filter as shown in Table 7.

Table 7 STK Advanced CAT Path Filter Impact

	Filter			
Configuration	Apogee/Perigee	Orbit Path	Time	Missed Conjunctions
Default	30 Km	30 Km	30 Km	104
Increased Path Filter	30 Km	60 Km	30 Km	11
No Path Filter	30 Km	Disabled	30 Km	0

It is clear that use of the orbit path filter or the default path filter pad value of 30 Km is responsible for potentially all of the missed conjunctions in this analysis. Disabling the Orbit Path filter had a significant negative impact on the analysis run time.

ShadowCAT

ShadowCAT missed one event. The missed conjunction is a high relative velocity event between LEO satellites with a miss distance of 3.5 km and a plane angle of 178° which occurs 9.5 seconds before the end of the analysis window. Another ShadowCAT analysis with the start time shifted to the right found this conjunction correctly to within 1e-4 seconds. ShadowCAT uses an externally generated ephemeris and the location of this event near the edge of the analysis window may indicate a problem with the ephemeris interpolation near the ends of the analysis window (Runge's Phenomenon[4]).

Range and Time Comparison for Matched Conjunctions

The comparison of conjunction range and time was influenced by three factors. The first was the propagator used, either integrated into the tool, or to generate the ephemeris data used by the tool. The second was the root finder used to find the minimum range – specifically the convergence criteria. And finally the ephemeris step size and interpolation technique for tools using ephemeris data. While running all of the tools from a common ephemeris would help minimize some of these problems, it raises other issues such as differing ephemeris step size and span for each tool, and practical problems with the availability of computing resources with adequate memory for an analysis of this scope.

Table 8 describes the propagation algorithms and methods available for each tool. Where both integrated propagation and ephemeris interpolation are available, the technique used is denoted with the boxed checkmark (☑).

Table 8 Propagation Details

	Propagator	Integrated Propagator	Ephemeris Interpolation
CAOS-D	Java port of Vallado[5]		✓
CSieve	Vallado[5]	☑	✓
SOAP	Vallado[5]	☑	✓
Advanced CAT	AGI SGP4 Propagator, 2008-11-03*	☑	✓
ShadowCAT	AGI SGP4 Propagator, 2008-11-03		✓

* STK Advance CAT can also use the Astro Standard SGP4 propagator via an AFSPC provided DLL

All of the result sets were compared to every other result set for the conjunctions which were matched (Table 4). Table 9 through Table 12 present the maximum and average differences of the results. These differences are rounded to the lowest output precision available from any of the tools (10^{-4} Km for range and 10^{-3} seconds for time of closest approach (TCA)).

Table 9 Maximum Range Difference in Meters

Tool	CSieve	ShadowCAT	SOAP	STK Advanced CAT
CAOS-D	1	48.7	1	1.6
CSieve		48.7	0.1	1.6
ShadowCAT			48.6	48.7
SOAP				1.5

Table 10 Average Range Difference in Meters

Tool	CSieve	ShadowCAT	SOAP	STK Advanced CAT
CAOS-D	0.0	0.0	0.0	0.0
CSieve		0.0	0.0	0.0
ShadowCAT			0.0	0.0
SOAP				0.0

ShadowCAT has a total of 16 events with a max range difference of greater than 10 meters with respect to the other tools in the study, including Advanced CAT. The ShadowCAT average range difference numbers are in line with the rest of the tools and it uses the same propagator as Advance CAT. This may suggest some outlier interpolation results.

Table 11 Maximum TCA Difference in Seconds

Tool	CSieve	ShadowCAT	SOAP	STK Advanced CAT
CAOS-D	0.043	163.3	0.003	159.8
CSieve		163.3	0.043	159.8
ShadowCAT			163.3	3.663
SOAP				159.8

The large TCA difference between the STK tools and the rest of the tools all occur for co-located geosynchronous satellites with very low relative velocity, and therefore, a very flat range vs time slope. In this situation, small changes in the convergence criteria of the root finding algorithm can have a large impact on the TCA determination.

Table 12 Average TCA Difference in Seconds

Tool	CSieve	ShadowCAT	SOAP	STK Advanced CAT
CAOS-D	0.001	0.005	0.001	0.005
CSieve		0.005	0.000	0.005
ShadowCAT			0.005	0.001
SOAP				0.005

Conclusion

Five conjunction analysis screening tools from four organizations were successfully exercised for a 7 day all vs all analysis. Analysis of the results from the COMBO screening tool are available as an FOUO addendum. Two of the tools (CAOS-D, CSieve) found 116,746 conjunctions with a range of less than 9 Km. These results were a superset of the results returned by the rest of the tools, excluding SOAP, which was not used in a search mode. Several differences in the identification of conjunctions were noted, divided here into differences in definition and errors.

Two different definitions of conjunction were found to be in use by the tools. Table 2 summarizes conjunction definition by tool. The small number of events impacted by this difference in definition were examined, and found to be consistently identified by the tools sharing the same conjunction definition. The remainder of the analysis then focused on the common conjunctions for both definitions.

Several errors in the identification of these conjunctions were also discovered. STK Advanced CAT was found to have significant errors when the Orbit Path filter was left in its default configuration. These errors were highly correlated with the length of the analysis run and the conjunction approach angle. When this filter was disabled, all conjunctions were found.

Conversations with Johnson[*] and Coppola[†] emphasized that Advanced CAT is not designed for the all vs all problem and recommended splitting the problem into smaller N vs. All or N vs. M problems. Dividing the analysis in this manner was found to be impractical due to the number of analysis run which would have to be manually configured and executed via the STK graphical user interface. Testing was done with several N vs all subsets of the problem for the full 7 day analysis while exploring the filter selection issue. These results were consistent with the all vs all results of shorter duration, with the exception that the Orbit Path filter problem is much more pronounced for the longer analysis length.

The STK ShadowCAT analysis had a single error in identification. The location of the event relative to the time bounds of the analysis suggests that this may have been due to an error in the ephemeris interpolation.

The consistency of the conjunction range and TCA was examined for all matching conjunctions. Overall, the level of agreement between the tools is remarkable, given the differences in propagators and techniques in use and the use of an intermediate ephemeris generation step by some tools. Larger differences in TCA determination by the STK tools may be related to convergence criteria for low relative velocity co-located GEO satellites.

[*] Vice President of Engineering, Analytical Graphics, Inc.
[†] Senior Astrodynamicist, Analytical Graphics, Inc.

A dominant issue in missed conjunctions was the configuration or implementation of analysis pre-filters. Significant care must be taken in the configuration and use of these filters to avoid conjunction identification errors. These filters have a strong impact on computational performance of the tools which used them.

In closing, several issues were identified in the performance of common conjunction analysis tools. Many have already been corrected or otherwise addressed. It is hoped that this analysis leads to further improvements in the state of the art for conjunction analysis screening.

Acknowledgements

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[1] Abernathy, B, Harvey, S., Surka, D., O'Connor, M., "The CAOS-D Architecture for Conjunction Analysis", *Infotech@Aerospace 2011 Conference*, 29-31 Mar. 2011, St. Louis, MO

[2] Healy, L. M., Close Conjunction Detection on Parallel Computer", *Journal of Guidance, Control, and Dynamics*, Vol. 18, No. 4, 1995, pp. 824-829

[3] Stodden, D. Y., Galasso, G. D., "Space System Visualization and Analysis Using the Satellite Orbit Analysis Program (SOAP)," *Proceedings of the 1995 IEEE Aerospace Applications Conference*, 4 – 11 February 1995, Aspen, Colorado, http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=00468892.

[4] Runge, Carl, "Über empirische Funktionen und die Interpolation zwischen äquidistanten Ordinaten", Zeitschrift für Mathematik und Physik, 1901, 46: 224–243

[5] Vallado, D., "Companion Code" for "*Fundamental of Astrodynamics and Applications, 3rd Ed.*", 2007, http://celestrak.com/software/vallado-sw.asp