GLOrbit: A 3D Satellite Orbit Propagator for Network Topology Analysis

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Abstract—**Traditional networking protocols were developed for earth-based networks characterized by highly static topologies. In this scenario, erratic link failures were the most demanding change a network configuration could face. In the other hand, mobile networking protocols copes with dynamic topologies but assumes unknown trajectories and high connectivity. Neither of these applies to satellite constellations network paradigm where their orbiting nature describes a time-varying but highly predictive topology.**

To study satellite constellations networks we propose GLOrbit; a tool capable of propagate space nodes in time, create a 3D visual environment, and record the topology in different formats for further analytical studies. For this we implemented SGP4 propagation algorithm, OpenGL graphic library, and DOT language among other libraries interacting in a C++ program. This allows to obtain precise outputs for network graph and physical analysis while gaining visual intuition on satellite networks topologies for different orbital configurations.

We demonstrate the tool capabilities with a first work on three representative low earth orbit topologies analysis generated by GLOrbit. Lineal, transversal, and different altitude scenarios are studied concluding that the first evidence an important strength in inter-satellite links while the second on ground to space contacts.

I. Introduction

Inter-networking is an old practice and knowledge area with many development throughout the years deriving in complex networks such as Internet. Recently, Inter Planetary Network [1] droved the attention to expanding these concepts to space, where satellite communications could benefit from evolving from simple data relays to intelligent constellation of routers capable of directing information to its destination. Despite this is a widely evolved area of science in earth applications, expanding packet networking to space environment implies several challenges. Dealing with highly dynamic -but predictive- topologies is one of them.

In a first approach to time varying topologies, we faced the initial problem of physically understand how the real nodes (orbiting satellites) behave in time for a given orbit path. For this we developed a OpenGL [2] based 3D environment to visualize the network. The environment allows to rotate the camera, move around space, and controlling time speed.

Secondly, we implemented SGP4 (Simplified General Perturbations) [4] propagation model in order to calculate the position of network nodes on a given time. This models takes NORAD TLE (Two Line Element) [4] files as inputs and

generates satellite orbit state vectors relative to Earth-Centered inertial coordinate system (ECI). It also predicts the effect of perturbations caused by Earth's shape, drag, radiation, and gravitation effects from other bodies such as the sun and moon. SGP4 model is solved via algorithms described in [5], whose implementation is provided by Celestrak [6] in C++ and Matlab. This were incorporated to the tool library.

In third place, during GLOrbit simulation execution, nodes position are updated on a configurable regular basis. The position can be processed on demand by a 'topology record' function that stores physical network information in DOT [7] and CSV format output files for further processing. The former allows to study possible ISL (Inter Satellite Links), and ground station links, while the latter grants physical measurements.
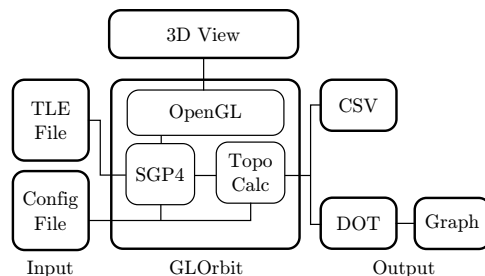

Fig. 1. GLOrbit Architecture

This three work-phases form the architecture of GLOrbit illustrated in Figure 1. The present paper is organized as follows: we describe the visual environment in section II; the Orbital Propagator implementation details are discussed in Section III; in Section IV we review the topology output graphs and processing; and finally, in Section V, we provide the first topologies results for linear, transversal and different altitude orbits configuration and their corresponding processing and analysis.

II. Visual Environment

The visual environment of GLOrbit is based on OpenGL graphics library version 1.4 [2]. OpenGL is a widely known open API standard for 3D visualization. Older version was chosen for implementation for sake of compatibility with non-GPU (Graphic Processing Unit) capable computers and Windows OS whose OpenGL support is way behind Khronos

[3] (currently maintaining the library) releases. Figure 2 show a screenshot of a simulation of Iridium constellation [13].

Free-glut (free GLUT) [9] was chosen for windows management, context creation and configuration, and providing basic user I/O operations using mouse and keyboard functions. The main reason driven the use of Free-glut is the fact that is cross-platform allowing GLOrbit to be available for Linux, Windows, Mac OS, and others systems simultaneously. The same reason derived in using GLEW [10] (OpenGL Extension Wrangler Library) as well, which provides easy OpenGL Core and Extensions access. GLU [11] Utility library is used for generic OpenGL functions, and SOIL [12] (Simple OpenGL Image Library) for loading images as textures.

GLOrbit main loop is based on two functions: *postRedisplay* -for drawing the scene- and *idle* -for processing when not drawing-. The former takes ECI coordinates of all satellites, earth stations, sun, moon, camera position, and strings containing simulation data and plot them on the screen. The latter performs time advance control, orbital mechanics calculation, including satellite propagation, earth rotation, sun and moon position, user I/O, and topology calculations. Time is kept along the simulation Julian Date (easily converted to Gregorian time) while Sun and Moon angles are derived from Vallado algorithms [5]. Integration of this libraries and APIs allowed GLOrbit to provide a user friendly interface to intuitively understand the analytical topologies outputs provided.
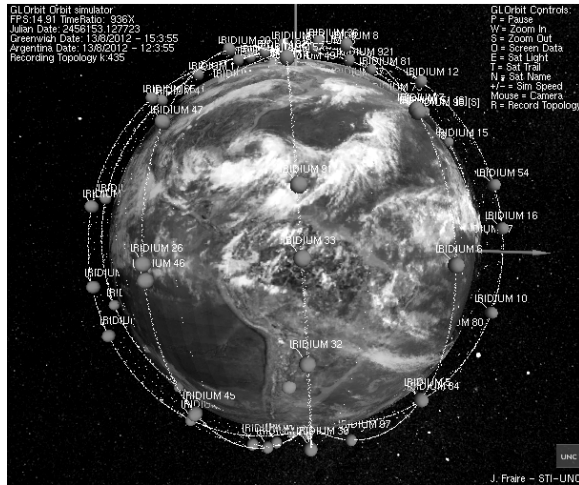

Fig. 2. Iridium Simulation

III. ORBITAL PROPAGATOR

GLOrbit requires orbital information (position over time) for the nodes in the simulation in order to derive distances -and attitude- to conclude with a corresponding network topology. Initially we took STK (Satellite Toolkit) [14] ephemeris files with ECI coordinates for every second in a text file whose sizes quickly becomes prohibitive for large period and large nodes quantity simulations. Implementing a orbital propagator such as SGP4 would not only solve this issue but allowed us to easily create or use real updated NORAD orbital files provided as TLEs.
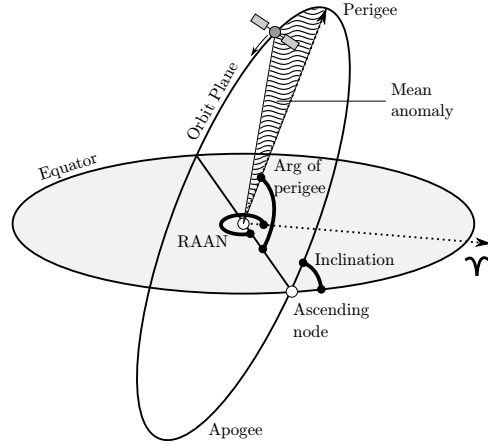

Fig. 3. NORAD TLE format

Fig. 4. Orbital Parameters

NORAD creates TLEs files with 'mean' values by removing periodic variations. Proper values reconstruction must be performed for good position and velocity predictions. This is performed by specific prediction models such as SGP4. SGP4 was developed by Ken Cranford in 1970 [15] and includes gravitational and atmospheric models for near-earth (period less than 225 minutes) orbiting elements. [16] states that SGP4 model has an error of 1 km at epoch (TLE accuracy) and grows at 1–3 km per day, providing enough accuracy for topology analisys, the primary objective of GLOrbit.

GLOrbit reads a list of concatenated TLE from a text file. TLE format is specified in [16] as well and illustrated in Figure 3. In the first line, column *Satellite Number* indicates a unique NORAD catalog number, and repeats in both lines; *Class* field indicates classification (U is unclassified); *International Designator* is and additional unique number assigned by WDC-A-R&S; *Epoch* is the base time for the element onto which the rest of time-varying fields are referenced; *Mean motion derivates* are in revolutions per day units, and give information on the mean motion variation, however this is not used by SGP4; *BStar* is a drag coefficient representing how susceptible an object is to drag; *Eph* represents the ephemeris type used to generate the data, in general is zero representing SGP4/SDP4 orbital model; *Element Num* increments with each TLE generation for a given element; *Chk Sum* is a modulo-10 checksum equal to the last number of the sum of all numbers of the line (minus signs get a 1 value). The second line contains element calculated using SGP4/SDP4 orbital model. All units are in degree and range from 0 to 360, *inclination* is the angle between the orbital plane and the equatorial plane, it only goes up to 180 degrees. *Right*

```
# name: SAC-D
1 37673U 11024A   12223.10521307 -.00000049  00000-0  00000+0 0  3822
2 37673 098.0108 228.9936 0001039 074.9222 285.2135 14.72289895 62753
```

Fig. 5.   TLE File Example

Ascension of the Ascending Node (RAAN) is the angle from Aries as a reference longitude to the direction of the ascending node (point where the body crosses the equator from south to north) measured in a reference plane (equatorial); *Eccentricity* is a unitless value with an assumed leading decimal point that determines the amount by which the orbit derivates from a perfect circle (0 is perfectly circular and 1 is parabolic); *Argument of Perigee* is the angle between the orbit perigee (closest point to the center) and the ascending node; *Mean Anomaly* relates position and time of a body in a Kepler orbit, goes from 0 to 2π, and it is not an angle, but proportional to the area swept from the focus to body line from perigee which is equal in equal time intervals; *Mean motion* is measured in revolutions per day, if eccentricity is different than 0 it is rather an average value than a instantaneous angular velocity; and *Revolutions at Epochs* specifies the number of orbits the body has made since its launch (not real usage for SGP4).

These parameters are taken as input in GLOrbit on a per satellite basis. All existing satellites TLEs are publicly available and non existent body can be manually created by using parameters illustrated in Figure 4. TLEs to be simulated in GLOrbit should be concatenated in TLE File. # is considered comment in the file ($\#name : SAC-D$ specifies *SAC-D* as name for the following satellite). An example can be seen in Figure 5. There is no limit on the number of bodies to propagate in GLOrbit.

IV. TOPOLOGY OUTPUT

In order to demonstrate the results and output files GLOrbit provides for analysis we propose a comparison between different orbital configurations. These scenarios must be described with a series of TLE files to feed GLOrbit propagator engine. For sake of simplicity we evaluate all 4 nodes sized networks in what we define as *linear*, *transversal*, and *different altitude* -all relative to equatorial plane- configurations. Figure 6 illustrates graphically each of these.
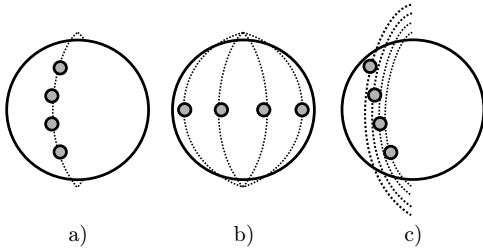

Fig. 6.   a) Linear, b) Transversal, and c) Altitude Topologies

Linear topology is essentially a "train" of nodes in the same circular orbit plane, with a $5°$ *perigee argument* difference resulting in a inter-satellite distance of $603Km$ at $570Km$

average height. This flight configuration implies no complication from a launcher point of view since it can be achieved by a multi payload adapter with successive satellite releases. Inter-satellites communications can be easily accomplished by fixed antenna alignment thanks to the constant relative distance and angle. NASA A-train protect [17] propose a similar configuration for earth observation mission (it does not use inter-satellite links though) with separations of a few seconds between each node.

Transversal topology aims at nodes in different orbital planes separated by $10°$ in the equatorial plane (right ascension of the ascending node) bringing about a inter-satellite distance of $1207Km$ at $570Km$ average height. This is the further the ISL distance can get and it happens at the moment when the nodes travels through the equator. However, in the pole, all satellites get very close to each other, generating a likely scenario of medium access competition. One of the main drawbacks of this configuration is that in both, poles and equator, mechanical or electrical inter-satellite antenna alignment is required for proper communication. Also, from a launcher point of view, the maneuver for RAAN shifting is considerably more complicated than perigee shift for Linear topology [18].

Both linear and transversal topologies supposes all nodes at the same height. As consequence, a third scenario of different altitudes is proposed. Here, all satellites remain on the same plane but at $10Km$ of incremental height distance (550, 560, 570, and $580Km$) . Mean motion (η) decreases with altitude by (1), where h_p is perigee height, provoking different revolution time, deriving in an out of sync topology. Inter-satellite antenna alignment requires mechanical or electrical pointing as well. Also, the launcher will require to perform orbital transfer maneuvers such as using Hohmann transfer elliptical orbits [19].

$$\eta = \frac{86400}{h_p} \qquad (1)$$

The three topologies proposed TLE parameters are summarized in Table I. Basically, the linear scenario can be generated by shifting the perigee argument, the transversal topology by shifting RAAN, and different altitudes involves different mean motion values.

TABLE I
TOPOLOGIES PARAMETERS

	Linear	Transversal	Altitude
Inclination	90°	90°	90°
RAAN	0°	0°, 10°, 20°, 30°	0°
Eccentricity	0°	0°	0°
Arg Perigee	0°, 5°, 10°, 15°	0°	0°
Mean Anomaly	0°	0°	0°
Mean Motion	15.07561	15.07561	15.7090, 15.4285, 15.1578, 15.8965

Once the TLE parameters are defined for each scenario, we can administer them as inputs for GLOrbit, who can
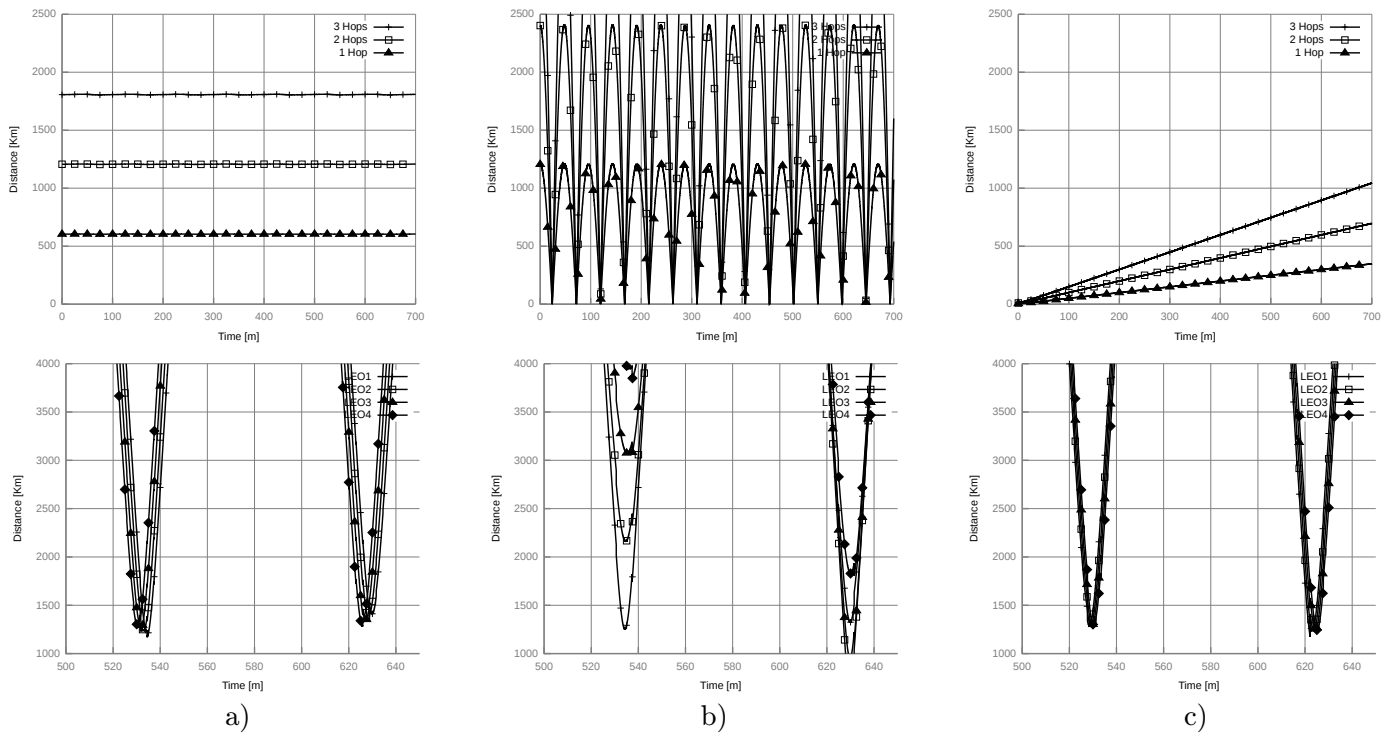
Fig. 7. ISL (up) and GS (down) distances for a) lineal, b) transversal, and c) different altitude topologies

provide two types of results files for topology analysis: comma separated values file (CSV) with relative nodes distances and DOT [7] based language file for topology graph generation. Time resolution can be configured for short and precise, or long and relaxed analysis. GLOrbit manages two parameterizable time realms: a topology time and visualization time. The former, is a high resolution (small time steps) used to record topology both in CSV and DOT format. Topology recording can be enabled and disabled on real time since it demands processing and storage resources proportional to the complexity of the network. The latter is a rather relaxed time with highly dynamic time steps that adapts to the visualization speed the user requires during the simulation. Very high time ratio speeds can be reached even while recording topologies. For example, we executed a 60 day long simulation period with topology time step of 1 second for the three scenarios proposed in less than 20 seconds in a mobile Intel Core i3 processor ($TimeRatio = 360000\%$ aprox.). Such a vast data can be complex to work with, but having standard outputs such as CSV or DOT allows to easily focus the analysis and process the information.

A first result to analyze is Inter-satellite distances. They are resumed in Figure 7 for the scenarios proposed in the first 12 hours of simulation. Regarding inter satellite distances, as expected, lineal topology shows constant ranges between satellites with minimum variations probably provoked by earth oblateness in SGP4 model. ISL distances increases in steps with each hop increment. Transversal topology results clearly evidences the zero distance in pole zone while reaching around 1200km in equator for adjacent nodes, 2400km for second

adjacent nodes, and further apart for the third adjacency links. Different Altitude topology might look very promising with the lowest relative inter satellite distance at the very beginning of the simulation. However this remains true for a limited period of time when all nodes are aligned together in the same earth centered radial line, since as the time advances, the difference in relative velocity separates them apart considerably. This effect is hardly seen in a 12 hour plot, so with the same CSV output from GLOrbit we can further study longer period of times such as the graph of Figure 8 describing ISL distances along the 60 simulation days. This plot allows us to conclude that different altitude topology provides very large windows (contact oportunities) but between very long period of time. In this scenario we
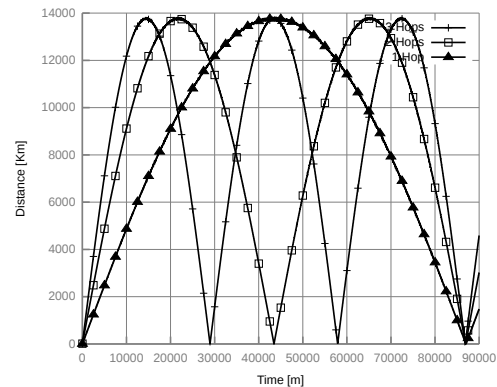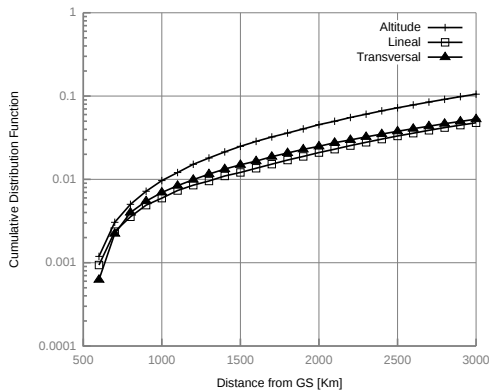

Fig. 8. ISL distances for Altitude Topology

Fig. 9. CDF for GS distance

determined that every 10km in height increment, the inter contact oportunity time among adjacent nodes is around 60 days, 30 days for 20km, 15 days for 30km and so forth. The bigger the altitude distance, the shorter the contact period, but shorter the window time frame as well.

Another interesting result to analyze is the distance to the Earth or Ground Station (GS) shown in the bottom of Figure 7. Figure 9 shows the cumulative distribution function (CDF) of the distance of the closest node to the GS on each topology (i.e. earth to network distance). CDFs expresses the probability that the distance is below the value given in x ($CDF(x) = P(X < x)$). This plot is based on the 60 day simulation period, with a resolution of 1 minute, and GS placed in Córdoba, Argentina, where this work is taking place. Linear topology evidence equally spaced time slots of contact with earth with a slight offset (1 minute 23 seconds) product of the small geographical movement of the earth on satellites paths. Linear topology has the less GS to network contact probability. Moreover, in transversal topology, contact possibilities are very different between each flying node and earth due to the different RAAN described by their "tracks". This implies that in a given window there is a node considerably closer (with a longer contact period as well) to the ground station. The latter suggest that the transversal topology is beneficial from a space to earth contact point of view. This twist becomes more important when considering the topology nature of covering larger equatorial distances, provoking higher distribution of network to GS contact than the linear scenario. In the other hand, different altitude topology initially provides highly overlapped contact to ground at initial phase, but separates beneficially over time becoming the topology with higher network to GS distributed

TABLE II
TOPOLOGIES SUMMARY

	Linear	Transversal	Altitude
ISL contact	Permanent	Frequent with short duration	Infrequent with long duration
GS contact	Highly overlapped	Distributed	Highly distributed

and probable contacts. However, as demonstrated previously, this configuration lacks of sustained ISL capabilities. Table II summarizes the qualitative characteristics concluded from the simulations on the three topologies proposed.

V. CONCLUSION

In this work we introduced GLOrbit, a 3D satellite orbit propagator for network topology analysis. We combined different available libraries to provide a powerful tool able to generate precise output files for dynamic satellite networks with a 3D visual interface for intuitive understanding of the values generated.

We demonstrated the tool capability by evaluating three different constellations configurations: lineal, transversal and different altitude. Considering the physical outputs generated by GLOrbit we derived interesting qualitative and quantitative properties from a inter-satellite and ground station contact perspective. Lineal approach evidenced important advantages in the former while transversal in the latter.

Further work involves analysis on the DOT graph outputs based on the already studied or similar scenarios in order to qualify logical topologies design and routing algorithms performance in such a dynamic environment.

REFERENCES

[1] Interplanetary Internet Special Interest Group (IPNSIG): http://www.ipnsig.org
[2] M. Segal; K. Akeley. "The OpenGL Graphics System: (Version 1.4)" http://www.opengl.org/registry/doc/glspec14.pdf 1992-2002 Silicon Graphics, Inc.
[3] The Khronos Group - Connecting Software to Silicon - http://www.khronos.org/
[4] Hoots, Felix R.; Ronald L. Roehrich (31 December 1988). "Models for Propagation of NORAD Element Sets". United States Department of Defense Spacetrack Report. Retrieved 16 June 2010.
[5] D. Vallado. "Fundamentals of Astrodynamics and Applications", Third Edition, Space Technology library. October 2011.
[6] Celestrak http://www.celestrak.com/
[7] Emden R. Gansner, et al, "A Technique for Drawing Directed Graphs", 1993, AT&T Bell Laboratories, Murray Hill, New Jersey 07974
[8] GLPK "GNU Linear Programming Kit" http://www.gnu.org/software/glpk/, Version 4.45
[9] Free-Glut: The Free OpenGL Utility Toolkit by Mark Kilgard http://freeglut.sourceforge.net/
[10] M. Ikits, M. Magallon. "GLEW: The OpenGL Extension Wrangler Library" http://glew.sourceforge.net/
[11] Norman Chin et al. "The OpenGL Graphics System Utility Library" (Version 1.3), 1998, http://www.opengl.org/registry/doc/glu1.3.pdf
[12] Simple OpenGL Image Library, 2008, http://www.lonesock.net/soil.html
[13] R. J. Leopold, A. Miller, and J. L. Grubb, "The Iridium System: A New Paradigm in Personal Communications" in Appl. Microwaves & Wireless, pp. 68-78, Fall 1993
[14] AGI - Stellite Toolkit www.agi.com/stk
[15] Lane, M.H. and Hoots, F.R., "General Perturbations Theories Derived from the 1965 Lane Drag Theory", Project Space Track Report No. 2, December 1979, Aerospace Defense Command, Peterson AFB, CO.
[16] David A. Vallado, et al. "Revisiting Spacetrack Report #3", AIAA 2006-6753 , Center for Space Standards and Innovation, Colorado Springs, Colorado, 80920.
[17] The afternoon constellation (A-Train) http://atrain.nasa.gov/, NASA, 2012
[18] Edward J. Taylor. "Orbit Theory and Applications", June 1991 http://www.cdeagle.com/pdf/taylor.pdf
[19] Walter Hohmann, The Attainability of Heavenly Bodies (Washington: NASA Technical Translation F-44, 1960)