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A SUMMARY OF ASTRODYNAMIC STANDARDS

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A Summary of Astrodynamic Standards

Abstract

This paper is an introduction to astrodynamic standards. I describe the progress on the AIAA Recommended Practices, including the work on Part II, Methods, Models, and Data formats. This effort is part of the AIAA Committee on Standards. I felt it was important to provide a concise summary listing that encompasses the findings and descriptions in the recommended practice, and the current tools and methods we consider as standards. The paper introduces the reader to the available techniques, sources, practices, and tools for astrodynamic propagation applications. To broaden the scope, I discuss the material along both functional and accuracy formats. This provides a two-fold look into the process, one being the broad categories within orbit determination, and the other as the models required for certain levels of accuracy. I specify low, medium, and high accuracy terms to permit the user an option when using the document. I envision future revisions to incorporate additional areas such as differential correction, attitude dynamics, interplanetary operations, and other methods.

Introduction

An important question sets the background for this paper: why should standards exist in the first place? Primarily, standards exist because they encourage uniformity, common practice, and interoperability. We have probably all seen instances where standards have not been kept, and the resulting incompatibilities that ensue. One recent example is the Mars probe that crashed due to incompatible units (English and Metric). Another example is found in some versions of SGP4 that state

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EPHEMERIS GENERATED BY SGP4 USING THE WGS-72 EARTH MODEL
COORDINATE FRAME=TRUE EQUATOR AND MEAN EQUINOX OF EPOCH
USING THE FK5 MEAN OF J2000 TIME AND REFERENCE FRAME
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This statement contains several inconsistencies. First, the WGS-72 model substantially predates the FK5 J2000 frame. Next, many embedded constants in the program have not been changed to reflect the new constants used in the FK5 system. Finally, the actual transformation of coordinates is only an approximation of the formal theory, so the resulting reference frame (TEME) is arbitrary at best. In practice, a unified equinox (Seago and Vallado, 2000) would be more appropriate if additional calculations had to be eliminated for computational speed.

Traditionally, standards have been simply a compilation of equations with little information on how to piece them together. Of course, the issue of teaching vs defining a standard is relevant. Standards should not teach, but rather consolidate information so the user can easily determine a minimum baseline that will yield acceptable results. It’s often difficult to assemble the myriad technical papers, books, documents, etc., that comprise a given standard.

What is a Standard?

So exactly what is a standard? From Webster’s Third New International Dictionary (unabridged, 1976), a standard is defined as a noun and an adjective:

3a: something that is established by authority, custom, or general consent as a model or example to be followed b. a definite level or degree of quality that is proper and adequate for a specific purpose 4. something that is set up and *established by authority as a rule for the measure of quantity, weight, extent, value, or quality … 7a. a carefully thought out method of performing a task*

1: constituting or affording a standard for comparison, measurement, or judgment 2a. having qualities or attributes required by law or established by custom 3a: regularly and widely available: readily supplied: not unusual or special b. well established and very familiar: not novel or experimental 4: having recognized and permanent value.

Recently, the Joint Astrodynamics Working Group (JAWG) at USSPACECOM agreed on another slightly different version (May 2001 JAWG minutes):

The astrodynamics theory, models, algorithms, and information exchange that have been proven to posses overwhelming merit, whose purpose is to promote improved accuracy and interoperability between the services under USSPACECOM.

There are several important concepts embedded in these definitions, and I will refer to them throughout the paper. For this paper, let me propose a definition:

The astrodynamics theory, models, algorithms, and information exchange that are well established, widely available, of overwhelming quality, whose purpose is to promote improved accuracy and interoperability between all organizations using space. xx

Using these definitions, let's focus on the authority, availability, quality, and well-established characteristics.

Clearly, authority is required to define a standard. Legacy plays a part in some practices, although governmental and international law can specify a particular organization to be responsible for designing and maintaining standards. Any organization proposing a standard must first have the authority to do so. For example, if I were to propose a new definition for the length of the meter, no one would recognize it due to my lack of authority. In addition to the authority, it's assumed the organization must have the technical means and knowledge, as well as any testing or measurements that will be required to establish a standard.

There are no formal organizations with the responsibility to develop and maintain astrodynamics standards. The IAU manages the international coordinates systems, but there is no specific body relegated to orbit determination, and precision issues. The AIAA Committee on Standards gives the following disclaimer.

The AIAA Standards Procedures provide that all approved standards, recommended practices, guides are advisory only. Their use by anyone engaged in industry or trade is entirely voluntary. There are no national or international industry or government agreements to adhere to any AIAA standards publication and no commitment to conform to or be guided by any standards report. In formulating, revising, and approving standards publications, the Astrodynamics Committee on Standards will not consider patents that may apply to the subject matter. Prospective users are responsible for protecting themselves against liability for infringement of patents, or copyrights, or both.

The availability of a standard is quite straightforward—a standard is non-existent if there is no information, data, etc. available. Consider the analytical propagation theory approach of Air Force Space Command. In 1980, the equations for a form of analytical propagation (SGP4) were presented in a classic paper by Hoots, and Roehrich. The paper contained both equations, and FORTRAN source code. The form of the two-line element sets describing the satellite orbital parameters remains the same today as in 1980. It wasn't until 1998 that a follow-on paper was finally published that summarized the current mathematical theory of SGP4. The paper (Hoots, 1998) was presented at the US Russian workshop, and it's significant for several reasons, not the least of which is the availability of the mathematical technique for the first time in almost 20 years. It will take time to modify any one of the multitudinous versions of SGP4 that exist on the Internet today because no intermediate formulations were available. So in a sense, this particular propagation technique has become a "standard' even though very little information is generally available. We'll see shortly the fact that software is not a standard, but this example highlights the aspect of availability, and the consequences of trying to impose a standard, and not releasing the specific details. In this example, the ability of the AF to "control" the process is less by law, and more by necessity as there exist few other resources for obtaining the "entire" satellite catalog.

The quality of a standard is subjective – one can define numerous levels of quality – and I'll discuss this at greater length in relation to the accuracy. Should a standard be comprised of the state-of-the-art on a topic, or should the common practice be specified? Compelling arguments can be made for both approaches, but I suggest that the state-of-the-art should be the standard, and common practice can be merely a deviation from that standard. In propagation, if I consider 70x70 gravity fields as the "state-of-the-art", but only require an 8x8 field for geosynchronous satellites, the 70x70 will meet requirements, as well as taking the most computational time! But an 8x8 field would not suffice for low-earth orbits, depending on the mission requirements.

A standard cannot be formed on a new technique or method. Some time must elapse before the community can accept a new technique. This length of time is debatable. Organizations should carefully introduce new techniques into a forum where other organizations will use the product. For example, Air Force Space Command could unilaterally make changes to its computer source code (SGP4), but because its general use is well established (although in varying forms), these changes should be well documented and made available to the general public. Thus, changes, documentation, and test cases should be released to promote interoperability among organizations considering operations requiring knowledge of other satellites.

Finally, an implementation of a standard must be exact. Modifications immediately defeat the underlying purpose for a standard. With orbit determination, propagation in particular, one could argue that the only standard is two-body motion because the solution is exact. Indeed, compelling arguments could arise from this position. However, the practical realization of a standard often results in modifications to the original formulation.

For several decades, the mantra for large scale orbit determination (1000's of satellites) has been to make the operations computationally efficient. Indeed, this is a driver in the original selection of analytical propagation techniques use of the TEME coordinate "frame". On the other hand, the new work that is proceeding with numerical orbit determination should take the opportunity to learn from the past, and to adhere to strict standards. Because accuracy is now a primary focus (with numerical techniques), features like the TEME coordinate system (Vallado, 2001, 114) should be phased out. While the need for computational efficiency is still somewhat true today, modern computer technology has made speed a less important issue, thereby enabling better adherence to the technical formulations that are originally presented. Variations should rarely, if ever, be implemented. When absolutely necessary, the mathematical technique, test cases, etc., should all accompany the distributions.

Atmospheric models demonstrate the need to adhere to original formulations. With the advent of routine operations of the International Space Station (ISS), conjunction analysis and prediction has become a common application for numerical solutions. However, the dominant error source still remains the atmospheric modeling. A great deal of interest centers on this topic, and numerous comparisons and studies have been performed, with few if any clear leaders. If we examine the Jacchia models (1965, 1970, 1977), we find three distinct sets of equations used to implement these force models. Jacchia (1971) even remarks about difficulties in matching the results of the experimental and observed data:

> While overhauling the basic models, we have also tried to reanalyze these variations. In so doing, we have found that for some of them—the geomagnetic effect, the semiannual variation, and the Helium variation—the analytical formulation we had used was inadequate and had to be altered, or even drastically changed. In particular, the dissociation of the semiannual variation from temperature variations has cleared up many puzzling results from the Helium-hydrogen region and eliminated the necessity of introducing ad hoc variations for these constituents.

If we examine existing computer code for these methods, we find many similarities because there are only so many ways to mechanize a given set of technical equations. However, we can also find numerous omissions from the original paper, additional, or updated constants, and shortcuts such as loading tables, and creating splines and polynomials to better fit the observed data.

Accuracy

Within orbit determination, to examine accuracy, we use two basic quantities: the accuracy of the state vector at some epoch (essentially the covariance, or uncertainty), and the accuracy of the state as it's propagated through time. Although my focus is not to discuss differential correction, it is necessary when defining the accuracy to use with a certain propagation technique. Let's look at both aspects.

The accuracy of the state vector at a given epoch is a function of the differential correction used to form the state vector. It's typically called a post-processed result. This aspect of accuracy is particularly difficult to quantify because it can (and does!) vary for each orbit, and it also relies heavily on the input data used to solve for the state, along with the quantity and type of data, force models used, processing, fit spans, etc. Thus, a "standard" set of force models to obtain a certain level of accuracy, say 100 m at epoch, for a LEO satellite, would be different than for 100 m of accuracy on a GPS (semi-synchronous) satellite.

The accuracy of the state as it's propagated through time presents even greater and different challenges. The method of propagation, the consistency of the force models to the differential correction, the use of solve-for parameters, and even the numerical integrator used for integration and to form the state transition matrix, represent important factors to determining the accuracy of the final result. The effect of atmospheric drag is particularly illustrative. In general, we know that atmospheric models tend to introduce about 10-15% error (Vallado, 2001, Gaposchkin, 1989?, Oza, Pardini 1999, etc). We also know the ballistic coefficient varies about 10-12 % (Hoots, 1999), given that our differential corrections have gravity fields of about 40x40 for LEO satellites.[1] A primary cause for this variation is the lack of available indices for the atmospheric models (F10.7, Ap) being known exactly for predictions into the future. A low-Earth satellite can experience 400-600m differences in one day simply between using the 3-hourly Ap values, and using a constant Ap value. Predictions into the future only compound the problem. Another cause of this variation is the lack of attitude information used in the differential correction to model the time varying cross sectional area of the satellite to the velocity direction. These factors are both a function of the dynamics of the problem. The value of the ballistic coefficient is affected because it acts as an arbitrary free parameter in the differential correction solution. A final difference comes in applications that share state vector information between programs that use different force models. If one program uses the MSIS 90 atmospheric model in the differential correction of a particular satellite, and the resulting state and covariance are propagated with a Jacchia 70 atmospheric model, additional errors will grow because the two models are not the same, and they react differently to the input atmospheric data (F10.7, Ap).

[1] Smaller gravity fields in the differential corrections tend to let the ballistic coefficient soak-up" the additional error, making it appear that the ballistic coefficient varies more.

For astrodynamics, we often state that the accuracy of the orbit is in terms of a 1, or 3 sigma uncertainty in the position and velocity vectors.[2] A single number sometimes represents the total 6-dimensional state. One could argue if this is even reasonable for position and velocity vectors that differ by orders of magnitude. To be useful, we must also include a confidence, or an uncertainty in the accuracy numbers. This can be a difficult process to perform accurately. Essentially, how does one assess the confidence of an orbit knowing that the orbit error is not independently and identically distributed (such that common statistical interpretations are not necessarily relevant)?

Coupled with the statistical features, how do we assess confidence in the results of an orbit determination process? The notion of covariance presents an opportunity to develop insight into the accuracy of the answer, however, it's generally recognized that the covariance (at least for satellite vectors) is often 5-10 times or more, optimistic.

If we say "high accuracy", almost any definition is a moving target because new theories, data, and approaches enter common use on a regular basis. After the launch of Sputnik, just determining the orbit was state-of-the-art. Years later, km-level accuracy became routine as the analytical theories entered operation for the military. By the late 1980's and early 1990's, m-level orbit determination became more routine. Today, GPS receivers and sophisticated ground tracking make sub-meter orbit determination almost routine.

Recalling the definition of standard reminds us that the approach should be well-established, however, with the advent of computers into astrodynamics, the timeline for new theories to enter the "public" domain is shrinking constantly. Recent examples include the MSIS 2000 atmospheric model, the GCRF coordinate frame, atmospheric indices E10.7, SSULI, etc.

To stimulate discussion, I suggest that accuracies could be divided into three categories.

Low - > 500m
Medium - 500m < 10m
High - < 10m

A breakout like this distinguishes the state-of-the-art (high), from the routine numerical operations (med), and the analytical (low).

If we examine some of the basic elements that would be present in a system producing these accuracies, we find (using information from the Appendix):

Low

These routines are designed for general propagation. The accuracy can be quite limited (as in the 2-body case), or have some approximations for drag, resonance, etc, as in the SGP4/PPT3 examples. The mean element theory in particular can be tailored to give more or less accuracy, depending on the mission needs.

Analytic technique
- *Two-body*
- *J2 secular effects*
- *SGP4/PPT3*
- *Other*

Expressions for average 3-body

Medium

Runge Kutta (4th order)

[2] Note that even the use of RSS and RMS are sometimes used interchangeably, causing additional confusion. RSS is simply the square root of the sum of the squares of the quantities, while RMS is the square root of the sum of the squares of the quantities divided by the number of terms. Using simple values one can easily see that RSS tends to be useful when one component dominates the error, while RMS gives an overall estimate for any combination of values.

Simplified force models
Coordinate systems FK5

High

Numerical – 8th, 12th order
Gauss Jackson,
Adams-Bashforth

ITRF/GCRF

EGM-96 or JGM-3
(70x70 for LEO, 40x40 for mid alt, 8x8 or 4x4 for GEO)
J77, JR71, MSIS-90 if perigee in atmosphere (<1500km)
Third Body DE 200 (FK5) or DE405 (ICRF/GCRF)
SRP (Macro models)
Tides
Solid Earth (~5m effect)
Ocean (15-25m effect)
Albedo

Of course, this doesn't mean that use of these force models will guarantee the accuracies shown, but for a general assemblage of orbits, the numbers should hold.

Related Issues

Many standards efforts in the past have tired to standardize computer code. The overall question is to standardize computer code, or just the mathematical theory and equations. This particular question has generated a lot of interest. I propose that in general, computer software does ***not*** represent a standard. It is so specific, that even when DLL's, object oriented code, executables etc. are created, they represent a tiny fraction of the necessary applications for orbit determination software. In many applications, timing requirements dominate a systems performance and the inefficiency of interfacing through a DDL package prevents system timelines from being met. It's impossible to design a single implementation of computer code that will meet all users requirements. In some rare cases, a form of computer code may be presented (as with the IERS and IAU theories), but the official committees and standards do not reference the code, rather the technical approach.

The difficulty with standardizing computer code goes far beyond the obvious technical challenges. For instance, users must often sign a waiver. If a bug, unacceptable error, or incompatibility exists, who is liable? Correcting the problem on site will be extremely difficult with only a DLL. Will 24-hr a day, 7 days a week service be made available? What will be the cost for this service? There are simply too many difficulties with making computer code a standard- at least in the area of orbit determination.

Are there examples we can follow?

Excellent examples of standards are the IAU and IERS celestial and terrestrial coordinate frame definitions (McCarthy 1992, 1996). These conventions define the necessary equations and mathematical constants required to realize the standard. They have the authority to make the standards in the first place, and the international community acknowledges their accuracy. Although they provide source code for some of their applications, they do not endorse, nor require its use.

What do the AIAA Standards have to offer?

The AIAA committee on standards offers the following rationale and background information for the standards they endorse.

"One of the most significant scientific and technological accomplishments since the beginning of the space era is the successful deployment of space systems and the necessarily ingenious application of astrodynamics to support these systems. Astrodynamics has been developed by extending the knowledge accumulated since the first recorded investigations into the motions of heavenly bodies.

The outgrowth of civilian and military rocket system developments has led to the establishment and implementation of numerous space systems, related physical models, and astrodynamics theories, algorithms, and procedures. With the proliferation of different and independent space systems and advancements in technology and astrodynamic sciences, the interfacing needed to ensure interoperability within space operations has become more complex.

The Standards Program is AIAA's latest major initiative in response to such needs. It has progressed rapidly in recent years, with the focus on national space standards, guides and recommended technical practices. To deal with the increasing necessity to establish American astrodynamics models, standards, and practices, the AIAA established the Astrodynamics Committee on Standards (ASD/CoS) in October 1990. The ASD COS initiated development of a series of formal technical documents designed to assist the astrodynamics community in improving standardization and interoperability. System designers, system operators, acquisition agencies, and general users who implement these practices should benefit from improved efficiency, productivity, flexibility, and reduced implementation and maintenance costs."

Thus, the AIAA COS seeks to blend the theoretical techniques for orbit determination with the actual practice. This provides a unique look into the design and development process for astrodynamic systems., and makes them particularly useful to a user

What is the AIAA Committee on Standards Charter?

The ASD/CoS charter is to " Identify, establish, and publish astrodynamics standards, guides, and recommended practices to ensure the continued enhancement of aerospace-wide efficiency and productivity to meet the scientific, technological and operational demands." To accomplish the chartered goals, the strategy is to:

1. *Research and establish the up-to-date status of the astrodynamics standards currently available.*
2. *Identify scientific, technological, and operational programs and system elements that have a need for astrodynamics standards.*
3. *Perform in-depth analyses of the existing standards and develop recommendations for possible adoption and/or modifications as AIAA standards.*
4. *Develop definition of standards and adopt formal guidelines and requirements of standardization.*
5. *Recommend and propose the areas where new standards, guides, and recommended practices are required. Additionally, identify areas where standards are currently not appropriate.*
6. *Identify, develop, and document initial candidate new astrodynamics standards, guides, and recommended practices for consideration.*
7. *Perform independent verification and validation, including solicitation of in-depth reviews within industry, academia, and government laboratories for all proposed and documented standards, guides, and recommended practices.*

8. *Submit proposed standards, guides, and recommended practices to Standards Technical Council for approval and publication.*
9. *Maintain all relevant technical materials and standards.*
10. *Maintain technical coordination with scientific and astrodynamics communities nationally and internationally.*

AIAA Standards Procedures provide that all approved standards, recommended practices, and guides are advisory only, and use is voluntary. Hence the committee's efforts have been directed toward developing recommended practices or guides.

To help provide coherent direction for its activities in identifying and selecting topics, the committee approved a set of criteria. Fundamentally, the committee has taken the view that the objective of a guide or recommended practice is to facilitate information exchange among relevant members of the using community. The following criteria have been useful in selecting topics that achieve this objective:

- ***Scope***: *Does the topic relate to processes associated with describing the motion of orbiting bodies?* Although rather evident, the committee has occasionally found itself considering topics that really fall within the purview of a different area or responsibility.
- ***Utility***: *Is the topic of wide concern to the majority of the astrodynamics community, and does it deal with the process of information exchange among members of that community?* If a topic is of only minor relevance to the community, developing guidelines or practices may not be particularly useful. Thus, such guidelines should aim at facilitating the broadest information exchange across the community.
- ***Alternatives (Ambiguity)***: *Does the topic involve alternative ways of performing a process or accomplishing an objective?* If there is only one commonly accepted alternative, it probably need not be guidelined.
- ***Urgency***: *Does guidelining the topic have a strong resource impact (time and money)?* If the effect of guidelining has minor impact (ultimately economic), it probably should be delayed or eliminated, and available resources devoted to more significant topics.
- ***Practicality***: *Can agreement be achieved on guidelining, and can it be done within the available resources?* Despite meeting all the above criteria, insufficient consensus (or lack of adequate time, or money to accomplish a viable effort) may demand not treating the topic.

The committee uses several guidelines for developing the recommended practices.

Background (provide motivation for the topic, including a brief discussion and historical setting.

Definitions Provide a crisp, clear description of the topic – what is the basic topic or problem being addressed?

Context

Organizing Principles and Concepts. To the extent possible, identify the concepts underlying and surrounding the topic. Here should be a succinct, generally qualitative description og the basic principles upon which the topic is based. In many cases, it may be appropriate to state basic physical principles in equation form. For example. The equation of motion consists of the central body term, plus terms for various perturbing sources:

Principal Applications / Implementations

Methods Describe each separate, "stand-alone" method to the extent necessary t achieve understanding. Large amounts of required data, constants, or other information are best incorporated by referencing the appropriate source in References or Bibliography.

Accuracy / Precision. To the extent practical, discuss the precision / accuracy, limitations, estimate of error bounds, benchmarks, etc. for each method. If such accuracy or precision statements are impractical/inappropriate, try to at least give qualitative guidance as to how the method should best be applied, and under what circumstances.

Organizations Identify key organizations making use of each method, and that a prospective user might contact for more information.

References / Bibliography

References Include material that has been referenced earlier.

Bibliography Additional Sources of information- texts, other standards, etc.

Contents of the AIAA Committee on Standards

The ASD/CoS' initial effort, *Recommended Practice, Astrodynamics - Part I*, was chaired by Dr. Joseph J. F. Liu. It includes the following five sections:

- Units (chaired by Dr. Richard Holdaway)
- Fundamental Physical Constants, Coordinate Systems, and Time (chaired by Dr. Kenneth Seidelmann)
- Earth Gravity Models (chaired by Mr. Jerome R. Vetter)
- Glossary (chaired by Dr. Victor Szebehely)
- Space-Related Acronyms (chaired by Ms. Darla German)

The current document, *Part II*, is the second in the series of *Recommended Practices, Astrodynamics*, undertaken by the ASD/CoS. This effort has been chaired by Dr. Hamilton Hagar, and includes the following five sections:

- Earth Mission Design and Analysis (chaired by Dr. George Chao)
- Propagation Methods (chaired by Mr. David Vallado)
- Neutral Density Models for Atmospheric Drag (chaired by Mr. Mark Storz)
- Orbit Determination Methods (chaired by Mr. Jerome Vetter)
- Formats for Astrodynamics Data Interchange (chaired by Dr. Paul Schumacher)

Proposal

To facilitate a unique consolidation of material, I propose that a single document be generated that contains the following items for aspects of orbit determination.

1. Original references from which the theory or technique was originally derived and presented.

2. Detailed equations necessary to implement (but not derive) the technique.

3. Data files, etc, as needed to implement the technique. For instance, the tabular data from a standard atmosphere, (1976), or the tabular data of the Jacchia, MSIS, models, etc.

4. Test cases, either published in the document, on the Internet, etc.

5. Computer source code, though only as an example implementation!

This proposal would combine all the aspects of the AIAA COS parts I and II, and could easily become the standard reference document that would detail the standards (state-of-the-art), and the recommended practice. The detailed references would guide the reader to the original formulations without teaching the material. The appendix illustrates these ideas in a draft form with regard to the topic of propagation.

Conclusions

- Standards are required to ensure efficient, interoperable operations are possible. The key thoughts discussed examined the authority, quality, availability, and well established nature of standards.
- Standards promote a baseline through which ideas are exchanged.
- The AIAA committee on Standards seeks to define and expand standards by detailing the recommended practices. This combination for standards and accepted practice bridges the gap between theory and practice so the new engineer can enter astrodynamics "with ease", and be able to compare results with other agencies and programs.
- Standards provide a forum upon which new theories can be designed, tested, and introduced.
- A proposal is set forth to provide an outline for the next round of astrodynamic standards.
- The Appendix illustrates an example outline for a standard on propagation. Its use is intended for discussion only as it is not complete!

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Appendix
Example Outline for Propagation

In this section, we examine an example outline for orbit propagation. In perspective, propagation is must one piece in the overall orbit determination activity. Propagation is generally divided into 3 basic types. We will focus on just numerical integration for this paper.

1. Analytical

Brouwer, Dirk. 1959. Solutions of the Problem of Artificial Satellite Theory Without Drag. *Astronomical Journal*. 64(1274): 378–397.

Kozai, Yoshihide. 1959. The Motion of a Close Earth Satellite. *Astronomical Journal*. 64(1274): 367–377.

SGP4 An approximate analytical theory based on the work of Kozai and Brower (both 1959). Developed by the US Air Force in the 1970's.

Hoots, Felix R. 1998. A history of Analytical Orbit Modeling in the United States Space Surveillance System. Third US/Russian Space Surveillance Workshop. Washington, D.C.

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2. Numerical

Cowell,

3. SemiAnalytical

DSST

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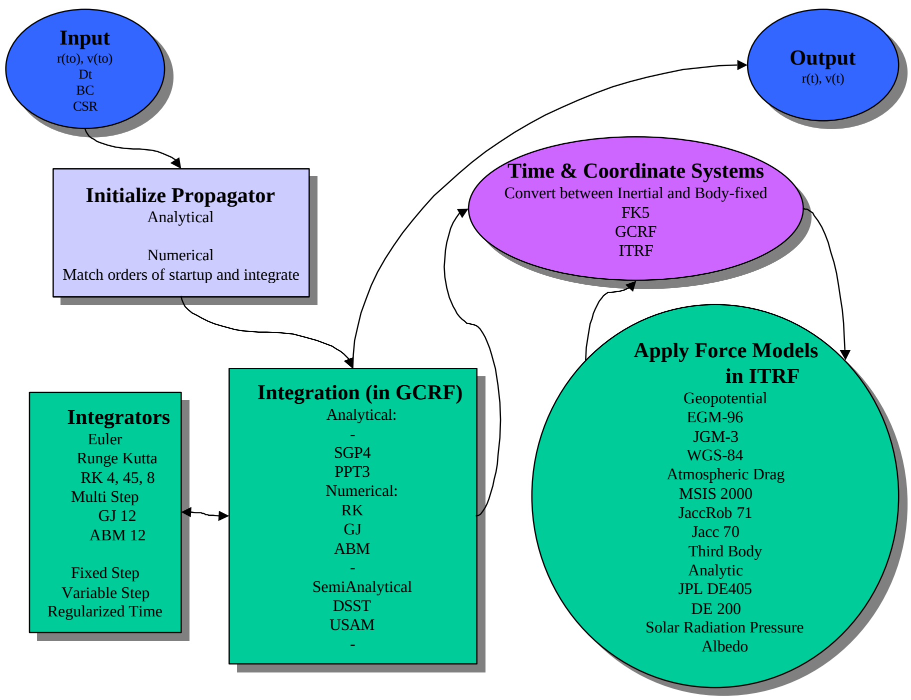
Yurasov, V. 1996. Universal Semianalytical Satellite Motion Propagation Method. Paper presented at U.S.-Russian Space Surveillance Workshop, Poland.

HANDE:

SALT:

In general, numerical propagation requires several areas in which we can define standards: coordinate systems, time, force models, and integration techniques. The following figure depicts the interrelations of each of these areas.



We can now describe each of the areas within propagation.

Constants, Coordinates, and Time

1. Constants

A related issue with the geopotential models is the constants used for distance and velocity calculations. It is extremely important to be consistent when using a particular geopotential model that all conversions reference the initial set of constants. This process becomes especially difficult when embedded constants are used.

For EGM-96, JGM-3

1. Grav Parameter ì =398600.4415 km^3/s^2
2. Radius of the Earth r= 6378.1363 km
3. Flattening f=1/298.257
4. Rotation rate of the Earth ùe=7.292158553e-5 rad/s

For WGS-84 and WGS-84/EGM-96

5. Grav Parameter ì =398600.4418 km^3/s^2
6. Radius of the Earth r = 6378.137 km
7. Flattening f = 1/298.257…
8. Rotation rate of the Earth ùe=7.292158553e-5 rad/s

2. Coordinate Systems

These are geocentric systems that define basic orientations…..

FK5

Seidelmann, Kenneth 1992. *Explanatory Supplement to the Astronomical Almanac.* California: University Science Books.

NIMA. 2000. *Department of Defense World Geodetic System 1984.* NIMA-TR 8350.2, 3rd ed, Amendment 1. Washington, DC: Headquarters, National Imagery and Mapping Agency.

ICRF/GCRF

McCarthy, Dennis. 1996. *IERS Technical Note #21.* U.S. Naval Observatory.

Pending

Reference Frames

These are practical realizations within the reference systems above.

Geocentric:

ITRF Earth Fixed

J2000 Inertial within the framework of FK5

IAU2000 (a and b) Inertial with respect to the non-rotating origin

Guinot, B. 1979. Basic Problems in the Kinematics of the Rotation of the Earth. A79-53001 24-89. Time and the Earth's rotation-Proceedings of the Eighty-Second Symposium. San Fernando, Spain. 7-18.

Topocentric

Horizon (SEZ)

Equatorial (IJKt)

Orbital

Perficoal (PQW)

Radial (RSW) also commonly called radial, in-track (actually along track), cross-track

Normal (NTW)

Equainoctial (EQW)

3. Time

Dynamical time replaced Ephemeris time in 1984 (xx).

UT1 = UTC + DUT1
UTC = UT1 – DUT1
TAI = UTC + DAT
TT = TAI + 32.184s (TDT in the past)
M = 357.5277233 + 35999.05034 TTT
TDB = TT + 0.001658s SIN(Me) + 0.00001385 SIN(2Me)

UTC
Dynamical (TT, TDB)
(TCG, TCB)

Data Sources

EOP
http:

Timing
Bulletin A: xp,yp, DUT1, XLOD, Dpsi, Deps
4 day lag
1 year look ahead for daily values
Bulletin B: xp,yp, DUT1, XLOD, Dpsi, Deps
~ 2 month lag
EOP xp,yp, DUT1, XLOD, Dpsi, Deps
4 day lag
http:

$$\vec{a} = \frac{\mu}{r^3}\vec{r} + \vec{a}_{nonspherical} + \vec{a}_{drag} + \vec{a}_{3\text{-}body} + \vec{a}_{SR}$$

Integrators

In general, numerical techniques use fixed, variable, or regularized (s-integration) methods to move forward through time.

Runga Kutta

Fehlberg, Erwin. 1968. Classical Fifth-, Sixth-, Seventh-, and Eighth-Order Runge-Kutta Formulas with Stepsize Control. NASA Technical Report, TR-R-287.

Gauss Jackson

Maury, Jesse L. Jr., and Gail P. Segal. 1969. Cowell Type Numerical Integration as Applied to Satellite Orbit Computation. Goddard Space Flight Center. NASA Technical Report TM-X-63542, X-553-69-46.

Adams-Bashforth

Other

Force Models

1. Geopotential

The general equation for the gravitational attraction uses a spherical harmonic potential equation of the form

$$U = \frac{\mu}{r}\left[1 + \sum_{\ell=2}^{\infty} \sum_{m=0}^{\ell} \left(\frac{R_{\oplus}}{r}\right)^{\ell} P_{\ell m}\left[\mathrm{SIN}\left(\phi_{gc_{sat}}\right)\right]\left\{C_{\ell m}\mathrm{COS}\ (m\lambda_{sat}) + S_{\ell m}\mathrm{SIN}\ (m\lambda_{sat})\right\}\right]$$

$$U_{2\text{-}body} = \frac{\mu}{r}$$

$$\hat{\vec{a}}_{nonspherical} = \nabla\,(U - U_{2\text{-}body}) = \nabla R$$

$$\hat{\vec{a}}_{drag} = -\frac{1}{2}\rho\frac{c_D A}{m}v_{rel}^2\frac{\vec{v}_{rel}}{\left|\hat{\vec{v}}_{rel}\right|}$$

The standard model for gravitational perturbations is a spherical harmonic expansion of the aspherical gravitational potential in an Earth-centered, Earth-fixed reference frame:

$$U_{aspherical} = \frac{m}{r}\sum_{n=1}^{n_{\max}}\sum_{m=0}^{n}\left(\frac{R_{\oplus}}{r}\right)^{n} P_{nm}(\sin f)\left[C_{nm}\cos(m\,l\,) + S_{nm}\sin(m\,l\,)\right]$$

where

See Vallado 2001, 514

Coefficients for Cnm and Snm are from the geopotential models. To ensure interoperability with legacy systems, use the same gravity model to propagate an orbit as was used to compute the orbit. As an exception, it is possible to estimate a new orbit with a different gravity model, using the ephemeris as observations.

The gravitational coefficients are often normalized:

$\Pi_{nm} = \sqrt{\dfrac{(n+m)!}{(n-m)!k(2n+1)}}$, k=1 if m=0 and k=2 if m>0

$C_{nm} = \Pi_{nm}\overline{C}_{nm}$ and $S_{nm} = \Pi_{nm}\overline{S}_{nm}$

Where the bar represents normalized coefficients. When normalized coefficients are used, they must be used with the corresponding normalized associated Legendre function:

$$P_{nm} = \frac{\overline{P}_{nm}}{\Pi_{nm}}$$

such that $\overline{C}_{nm}\overline{P}_{nm} = C_{nm}P_{nm}$ and $\overline{S}_{nm}\overline{P}_{nm} = S_{nm}P_{nm}$ and the standard model is preserved. Computer software programs generally all use double precision values when converting these coefficients.

The field is often truncated. While the original solution requires the complete field, many applications use reduced gravity field orders to speed computational processing. An example is as follows:

Number of coefficients (degree and order) for "high accuracy" (DEFINE) solutions

i) 70x70 for LEO

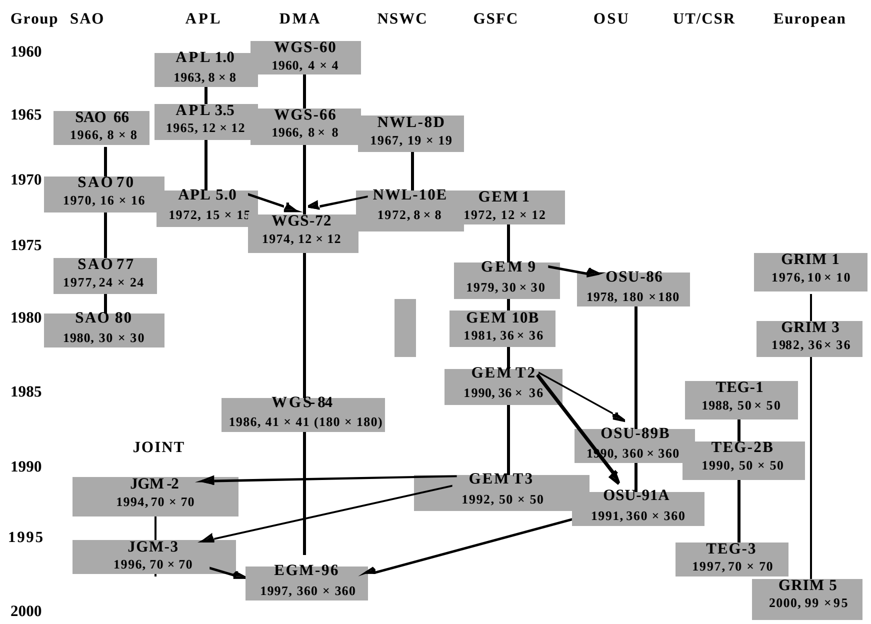
ii) 40x40 for MEO

iii) 8x8 for High Altitude

iv) 70x70 for Highly Eccentric

Standard Models:
Models for gravitational perturbations are spherical harmonic expansions of the aspherical gravitational potential are in an Earth-centered, Earth-fixed reference frame.

From Vallado (2001, 559)



1. EGM-96 : Earth Gravity Model, 1996. Collaborative effort with UT Austin/CSR, NIMA, OSU, etc. Next update due in about 2005

   Ref:

   Give sample data – say first 12x12 field.

   Data: http://

2. JGM 1, 2, 3

   Ref: Tapley, B.D., M.M. Watkins, J.C. Ries, G.W. Davis, R.J. Eanes, S.R. Poole, H.J. Rim, B.E. Schutz, C.K. Shum, R.S. Nerem, F.J. Lerch, J.A. Marshall, S.M. Klosko, N.K. Pavlis, and R.G. Williamson, "The Joint Gravity Model 3." The Journal of Geophysical Research, Vol 101, No B12, pp:28029-28049, 1996.

   Ref: Nerem, R.S. et al. 1994. Gravity Model Developments for TOPEX/POSEIDON: Joint Gravity Models 1 and 2. Journal of Geophysical Research. 99 (C12):24,421-24,447.

   Give sample data – say first 12x12 field.

   Data: http://

3. WGS84 : World Geodetic Survey, 1984. US Military model. Now used extensively with GPS observations, and tied closely with the ITRF.

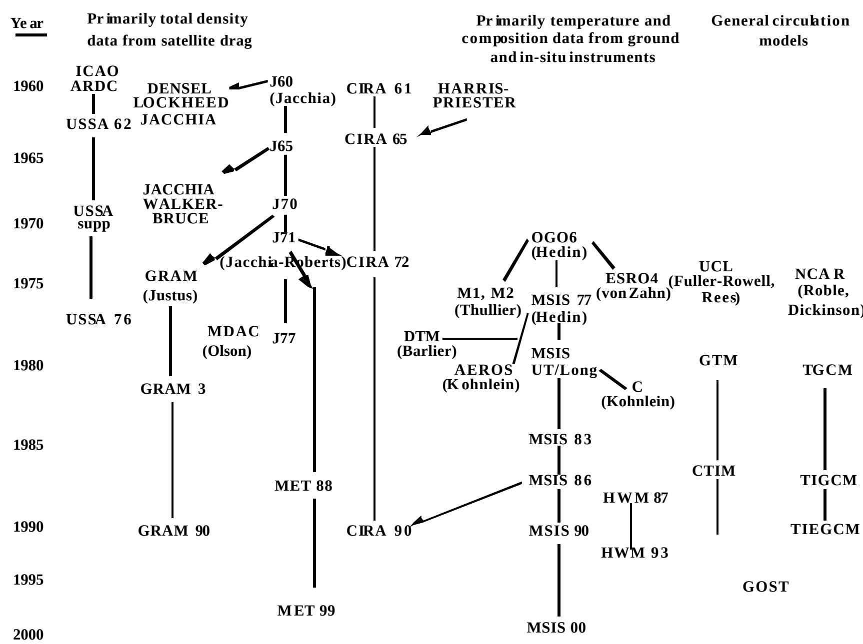
Ref: NIMA. 2000. *Department of Defense World Geodetic System 1984.* NIMA-TR 8350.2, 3rd ed, Amendment 1. Washington, DC: Headquarters, National Imagery and Mapping Agency.

Give sample data – say first 12x12 field.

Data: http://

2. Atmospheric Drag

From Vallado (2001, 533)



The general equation for atmospheric drag is

The primary inputs are the atmospheric density (handled via a specified model), and the ballistic coefficient (m/Cd A). The mass and cross-sectional area are usually known, and an estimate of the drag coefficient permits reasonable approximations. However, experience shows that the BC varies by as much as 10% or more over time, depending on the gravity field. Likewise, the atmospheric models also vary depending on several factors, including the satellite orbit, intensity of the solar activity, and the geomagnetic activity.

Basic data required to handle atmospheric drag is Kp, Ap, F10.7, E10.7, other?

i) Flux (F10.7, E10.7 (Needs to be proven before being included in standards)

ii) Geomagnetic Indices (kp, ap, Ap)

Data: http://www.ngdc.noaa.gov

/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/
daily 3 hourly Ap and Kp values, F10.7 values
Data from 1932
Actual values lag about 1 month

Data: http://www.sec.noaa.gov

/ftpdir/forecasts

daypre.txt	3 hourly predicts of Ap (mid, high lat, estimated)
predict.txt	7 year monthly F10.7 predict (low, pred, high)
dsd.txt	last 30 daily F10.7values
dgd.txt	last 30 daily Ap, Kp values (mid, high lat, est)
45df.txt	predicts the next 45 daily Ap and F10.7 values

Because atmospheric drag has perhaps the largest number of different models, defining an absolute standard is difficult to do. There have been numerous studies to evaluate how well the atmospheric models perform, yet, no clear "winner' has ever emerged. Thus, we list models and present references that discuss the various merits of many of the models.

Oza, D. H., and R. J. Friertag. 1995. Assessment of Semi-empirical Atmospheric Density Models for Orbit Determination. Paper AAS 95-101 presented at the AAS/AIAA Spaceflight Mechanics Conference. Austin TX.

Gaposchkin

Other…talk to Alan Segermann

An additional comment is necessary. Most models, as implemented in computer code, do not follow the exact technical derivation as defined in the literature. Numerous short cuts, and many additional features are included that may be the result of internal studies and information. This makes standardization of atmospheric models especially difficult.

Standard Models:

Static:

US Standard 1976 0-1000 km

U.S. Standard Atmosphere. 1976. Washington, DC: U.S. Government Printing Office.

Time-varying:

COSPAR (CIRA) 25-2500 km

COSPAR Working Group. 1965. *COSPAR International Reference Atmosphere*. Amsterdam: North Holland Pub. Co.

Code: http://

DTM 200-1200 km

Barlier, F., et al. 1978. A Thermospheric Model based on Satellite Drag Data. *Annales de Geophysics*. 34(1): 9-24.

Thuillier, G., J. L. Falin, and F. Barlier. 1977. Global Experimental Model of the Exospheric Temperature using Optical and Incoherent Scatter Measurements. *Journal of Atmospheric and Terrestrial Physics*. Vol. 39: 1195. Computer code in the paper.

Jacchia 1965, 1970, 1971, 1977 70-2500 km

Popular dynamic atmospheric model. Several different versions. 1971 and 1977 are quite popular. The US military uses the 1970 version extensively.

1965 too

Jacchia, L. G. 1970. *New Static Models for the Thermosphere and Exosphere with Empirical Temperature Profiles*. SAO Special Report No. 313. Cambridge, MA: Smithsonian Institution Astrophysical Observatory.

Jacchia, L. G. 1971. *Revised Static Models for the Thermosphere and Exosphere with Empirical Temperature Profiles*. SAO Special Report No. 332. Cambridge, MA: Smithsonian Institution Astrophysical Observatory.

1977 too

Jacchia Roberts 1971

Roberts, Charles E., Jr. 1971. An Analytic Model for Upper Atmosphere Densities Based upon Jacchia's 1970 Models. *Celestial Mechanics*. 4(314): 368–377.

MSIS-90

Hedin, A. E. 1987. MSIS-86 Thermospheric Model. *Journal of Geophysical Research*. Vol. 92: 4649-4662.

Code: http://

MSIS – 2000 pending…

MET88 / MET 99 Marshall Engineering Thermosphere

GRAM 95 0-2500 km

Code : jerry.owens@msfc.nasa.gpv, and jerry.Justus@msfc.nasa.gov

GOST Russian, 120-1500 km

3. Third Body

The general form of the acceleration due to third body forces is

$$\vec{a}_{3\text{-}body} = -\frac{G(m_{\oplus} + m_{sat})\vec{r}_{\oplus sat}}{r_{\oplus sat}^3} + Gm_3\left(\frac{\vec{r}_{sat3}}{r_{sat3}^3} - \frac{\vec{r}_{\oplus 3}}{r_{\oplus 3}^3}\right)$$

There are two primary methods to find the third-body acceleration. The analytic form has several variations. We present a compact form here from Vallado (2001, xx).

Analytic

Equations:

Standard Models:

DE-200, DE-405. These accurate numerical models are valid over long periods of time (1000's of years), and are regarded as the standard for any precise orbit determination work. DE-200 is designed for use with FK5 and DE405 is designed for the ICRF (GCRF)

Data Http://willbell-com??

Standish, Myles. 1990. The Observational Basis for JPL's DELOD, the Planetary Ephemerides of the Astronomical Almanac. *Astronomy and Astrophysics.* Vol. 233: 252–271.

4. Solar Radiation Pressure

The equation

$$\hat{a}_{SR} = -\frac{p_{SR} c_R A_{\odot}}{m} \frac{\hat{r}_{\odot sat}}{|\hat{r}_{\odot sat}|}$$

Ries, Shum, Tapley. "Surface Force Modeling for Precise Orbit Determination," Geophysical Monograph 73, Vol 13, 1993, 111-124.

a. spherical vs. realistic model
b. absorption
c. diffuse reflectivity
d. specular reflectivity
e. shadow model

Data: http://

5. Ocean Tides

Tidal models do not enjoy the popularity (yeT0 of the gravitational and atmospheric models. At this point in time, several models exist, and no clear "leader" has been recognized as the standard approach.

9. Ocean Tides
10. Solid Earth Tides

Data: http://

6. Albedo

11. Albedo Ries, Shum Tapley and Knocke, P.C., J. C. Ries, and B.D. Tapley, "Earth Radiation Pressure Effects on Satellites," AIAA/AAS Astrodynamics Conference, Technical Papers, pp577-587, August 15-17, 1988.

7. Attitude

As future accuracies continue to improve, attitude knowledge will become important in helping to solve the atmospheric and solar radiation effect problems.

8. Emissivity:

Ries, Shum, Tapley and Knocke, Ries, Tapley

9. Thrust

There is a need to distinguish between simple maneuvering for station keeping and attitude control, versus the larger maneuvers designed to move a satellite to a different location.

a. In-track through B*
b. Out of plane
c. Impulse vs. finite burn

10. Relativity

d. General Relativity Huang, C., J.C. Ries, B.D. Tapley, and M.M. Watkins, "Relativistic Effects for Near-Earth Satellite Orbit Determination," Celestial Mechanics, Vol. 48, No. 2, pp167-185, 1990.

b. Special Relativity

11. Other