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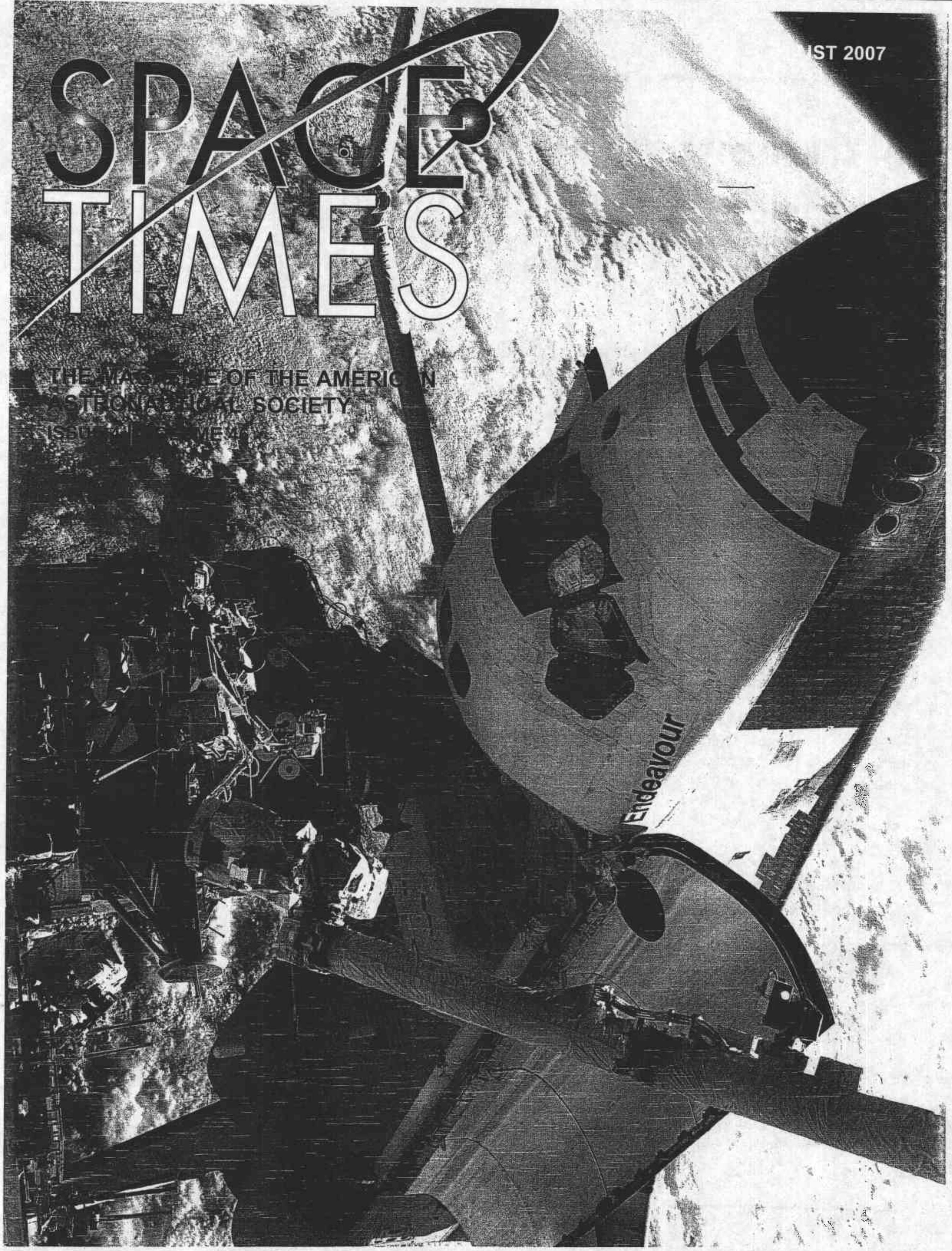


Do You Know Where Your Satellite is Tonight? Insufficient Capability for an Essential but Misunderstood Task

by Dave Finkelman

One of the most important space endeavors - tracking satellites and determining their orbits - is also among the least understood and appreciated. If we take knowledge of current and future satellite location for granted, our continued ability to determine that information is jeopardized. The objective of this article is to refresh understanding and explain problems that must be overcome.

Do you know where your satellite is tonight? Perhaps you do. A few national space tracking networks might also know, but the rest of us do not. Why don't we? Satellites travel in circular or elliptical orbits, don't they? Their behavior is predictable and repeatable, isn't it? Satellites in geostationary orbits even stay in one place relative to the Earth. So why do we need sophisticated radars and telescopes to keep track of them?

Most tasks assigned to satellites demand extremely accurate orbits. Distances, angles, and times must be known precisely so that we can at least quantify inevitable uncertainties. How can we determine orbits that well? How do we know where the satellites may have migrated when they were out of sight?

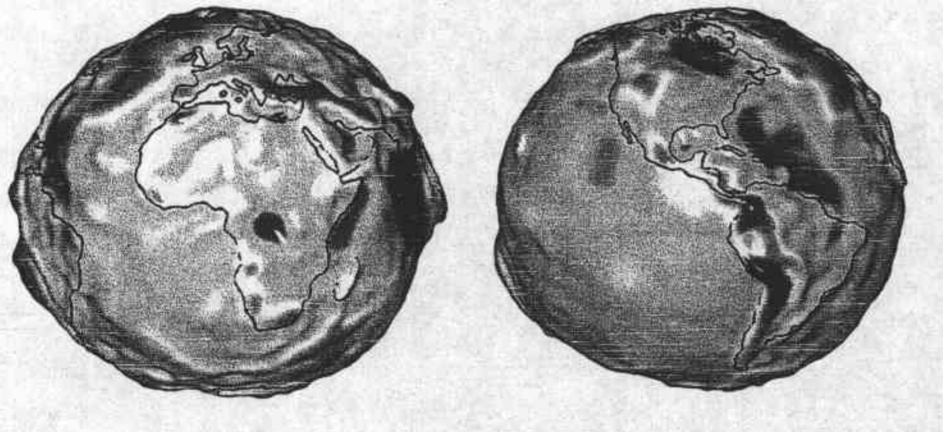
Newton, Flamstead, Kepler, Leibnitz, Huygens, and Galileo made diligent observations and contributed immensely toward understanding of the motion of orbiting objects. As instruments and observations advanced, differences were noted in orbits from those predicted by two-body or linearized three-body motion. The degree to which these great men were incorrect is the essence of an astrodynamicist's profession.

Satellites do not describe precisely elliptical or circular orbits. They are, in fact, unpredictable, and to a significant degree not repeatable. Astrodynamicists may know this, but many of those who depend on satellites do not.

Satellite orbits are not perfect ellipses or circles because the Earth's gravitational field is not uniform. Satellites in different places experience varying gravitation even if they are at the same altitude. The Earth's mass is not uniformly distributed, nor is the Earth perfectly spherical. The oceans and the Earth's molten core are continuously in motion. This dynamic soup is influenced by the Moon and other bodies. There are even tides in the Earth's crust.

As Earth is viewed from increasing distance, it gradually appears that its mass is concentrated at a point. Non-uniform mass distribution, however, is an essential factor for low Earth orbits. The predominant effects are static, but there are noticeable dynamic components with periods of hours or days. The Gravity Recovery and Climate Extraction (GRACE) mission documents these non-uniformities by monitoring the separation between two satellites which are several hundred kilometers apart and located in common, very stable polar orbits.

The relatively static portions of gravitational perturbations cause orbits to precess about the Earth's axis. These forces make the semi-major axis of the orbit ellipse rotate about the Earth's center within the satellite's orbital plane. This lowest order (J2) effect makes Sun synchronous satellite orbits possible. Exploitation of this gravitational non-uniformity allows a satellite to always view the earth with the same lighting conditions. To this order of approximation, there is a unique relationship between altitude and inclination for which the orbit precesses around Earth's axis at the same rate that



Using non-uniform gravity data collected by the GRACE satellite, gravity maps of Earth can be used to create accurate satellite orbit predictions. (Source: NASA/University of Texas Center for Space Research) the Earth revolves around the Sun. Sun-synchronous orbits do not exist in Newton's simple two-body problem with concentrated masses.

If non-uniform gravity were neglected, satellite positions propagated merely hours into the future would differ from their actual locations by hundreds of kilometers.1 This is enough of a disparity that we would not be able to observe the satellites if sensors were directed to their predicted locations.

Atmospheric drag also influences low-Earth orbiting satellites greatly. Atmospheric effects are important up to altitudes of many hundreds of kilometers. Though atmosphere is sparse at that altitude and drag is small, it is still noticeable relative to the diminishing gravitational forces at high altitude. Atmospheric drag is the principal reason that orbits decay and satellites descend, yet it is very difficult to predict drag forces due to the volatility of our space environment.

Drag is uncertain for a number of reasons. The orientation of satellites in orbit varies, often in unintended ways. The area that the satellite presents to the relative wind is uncertain. Uncertainties in the atmosphere's composition are a significant source of disparity. Atmospheric density can vary appreciably in the course of a single satellite orbit. We fly satellites with well-known spherical drag coefficients in order to infer atmospheric variations, once we have confidence in the knowledge of non-uniform gravitation.2 Therefore, physical models of the atmosphere depend to some extent on the model of the Earth's gravitation. This model was developed when atmospheric density variations were inferred from orbit observations.

Nearby massive bodies influence the orbits of satellites. If the Moon's gravitation is strong enough to cause tides on Earth, it must also affect satellite orbits. We need to know something about the distribution of mass within the Moon in order to predict the perturbation. This causes more uncertainty.

Finally, radiation pressure can be appreciable relative to gravitation when spacecraft are far from the Earth. In addition to incident solar radiation, inputs include radiation reflected or emitted from the Earth. Momentum transfer from photons to spacecraft surfaces is significant for geostationary and geosynchronous orbits. Photon-induced drag varies as the satellite moves and the Earth rotates. There is at least diurnal variation.

Geostationary satellites are not actually geostationary. If the satellite orbit has any inclination or eccentricity, the orbit will rotate and precess. Radiation pressure, multi-body gravitation, and other effects will also change the orbit. Left unattended, a satellite in even the most circular and equatorially oriented orbit will drift in its orbit around the Earth.

Orbit Determination and Satellite Tracking

Determining orbits requires observations, physical hypotheses, and computational techniques. To say it more accurately, orbits are actually "estimated," not precisely determined. We test our physical hypotheses against observations and determine the degree to which our hypotheses match reality. Measures of a solution's quality, called "covariances," are essential; they reveal the degree of uncertainty in the satellite states we predict. Almost no widely available sources of orbit data reveal covariances. As a result, those who rely on widely distributed orbit data seldom know how long mean orbits3 remain sufficiently valid. Therefore, it is very important that these users are provided with new mean orbit elements frequently.

For centuries, scientists have determined orbits using observations from the Earth. Radars gather precise range measurements on satellites. They are less precise in azimuth and elevation, which depend on mechanical measurements rather than electronic measurements. Even the registration of elements of a phased array radar relies on "imprecise" physical measurements. Telescopes can determine azimuth and elevation precisely (often taking advantage of magnification to perceive very small angles), but they do not measure range at all. The Global Positioning System (GPS) makes it possible to determine orbits from onboard measurements, which are subject to changing and often unfavorable geometry and the errors introduced by a rapidly moving platform. GPS is not precise to millimeter resolution when it is riding on a satellite that moves at a rate of kilometers per second.

Each of these sources is imprecise to a degree that affects many modern satellite applications. Sophisticated data fusion schemes can combine all of these sources in a profound, mathematically consistent manner to achieve results more precise than any of the independent contributions. While this technology is a great advancement, the process still demands continuous measurement and estimation.

An artist's concept of the GRACE spacecraft performing high-resolution variable gravity mapping of Earth. (Source: NASA)

The perturbations to Newton's two-body problem described above are not an exhaustive set. Additional influences include relativistic effects and multiple body gravitation. There are many physical hypotheses about the characteristics of the atmosphere, and guidelines for which observable quantities are the best "proxies" to represent atmospheric density variations.4

Determining orbits is a highly nonlinear activity, mathematically speaking.

Changes in solutions are not proportional to changes in independent variables or changes in the specification of the problem (such as the Earth's gravitational field). The numerical solution of the governing equations is plagued by small differences in large quantities. While the difference between observation locations may be just a few kilometers, the satellite may be thousands of kilometers away.

The process of orbit determination is a journey of linear approximations, simplifying mathematics and moderating nonlinearity by focusing on small changes. Linearization restricts the time interval over which orbits can be predicted. The most widely used techniques ("General Perturbations") still linearize around a trusted nonlinear solution or precise initial orbit and develop "differential corrections" to that solution.

There are also a variety of "semi-analytical" techniques that substitute approximate closed-form formulas for some of the numerical integration. Numerics are simplified by developing analytical expressions - approximate equations which don't require complex numerical schemes. Such approximations were necessary to estimate orbits sufficiently in operationally meaningful time spans when computational capability was insufficient.

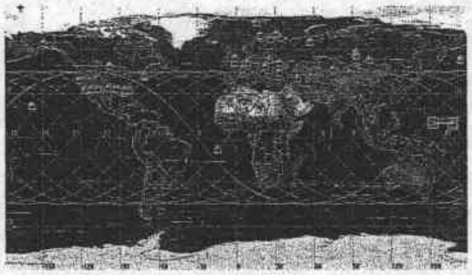
Full, nonlinear numerical solutions ("Special Perturbations") have been in existence for many years, but such techniques have only recently been applied to the entire space population as permitted by advances in computational capability.

Insufficient Observation

The world doesn't contain enough sensors to keep track of satellites with sufficient coverage and frequency. This problem overshadows imprecise measurements, approximate physics, and numerical and mathematical difficulties.

The European Space Agency (ESA) has published a survey of the world's space surveillance capability.5 Radars dominate low-Earth orbit observations, and telescopes are most productive for high and geostationary orbits. Most radars only "contribute" observations, and are not dedicated to observing satellites. The United States BMEWS and PAVE PAWS radars are a good example. Several scientific radio telescopes, such as the MIT Lincoln Laboratory Haystack facility, also contribute satellite observations when time allows.

Optimal distributions of sensors are not available— most are concentrated in the Northern Hemisphere. Two sensors on the equator 90 degrees apart in longitude with hemispherical coverage and unlimited range should "see" all but geostationary satellites at least once every six hours. In reality, that degree of coverage cannot be achieved. There are few feasible locations that meet the 90 degree equatorial criterion, and six hours may be much too long to observe and estimate the intense influence of non-gravitational forces on low-Earth orbiting satellites.



The World Wide Space Surveillance Radar distribution. (Source: Dave Finkelman)

Amid these difficulties, those who own and operate satellites have the best possible observations of their own satellites. Long period, pseudo-random codes imposed on satellite downlinks can be used to range very precisely, just as GPS receivers determine "pseudo-range" to GPS satellites. However, satellite owner/operators can communicate with their satellites only from sparse ground stations. Without external data, they cannot observe or estimate where their satellites are between contact opportunities. If they relied on totally predictive ("open loop") tracking based upon past observations, they could literally "lose" their satellite. These entities compensate for the growing uncertainty by using large search and capture volumes, and by interrogating the sky with much more energy than would otherwise be necessary. Satellite contacts are also much shorter.

Many independent analyses have explored optimal sensor distributions for specific criteria, such as the minimum value of the longest gap between observations of selected satellites sets. None is very practical or affordable.6

We must always live with uncertain satellite locations. The question becomes: "How much uncertainty is acceptable, and for which satellites?"

The Significance of Orbit Determination

Who cares if we know exactly where any particular satellite is? Why is this information so important?

There are several classes of satellite users: those who launch satellites, satellite operators, satellite service providers, satellite service users, and government agencies bound to protect and preserve space capabilities.

It's a big sky, but satellites are concentrated in just a small fraction of it. There are few launch sites, and debris from past launches can persist at those latitudes. Therefore, it is prudent for satellite launch service providers to check for obstructions before launch activity begins.

Satellite operators need to know where their satellites are in order to provide promised services. They must also avoid physical or radio frequency interference (RFI) impingement upon other satellites. The same comments about crowded portions of the sky apply, including the geostationary region and polar orbits.

Satellite service providers such as DirectTV or Sirius Satellite Radio need to keep their satellites on track in order to fulfill service commitments. Those who need to contact non-geostationary satellites must have their antennas track the satellites across the sky.

Users have to know where satellites are, and the user community extends far beyond casual recreation. National

Oceanic and Atmospheric Administration (NOAA) remote locations must be able to contact search and rescue satellites. Environmental monitoring tasks, such as tracking electronically tagged wildlife, require knowledge regarding which satellites can retrieve uplinked data.

Imaging and surveillance require precise and virtually continuous orbit information to determine access. They must also be able to register images in a prescribed reference frame - one that isn't moving as the satellites are.

The government also has a duty to monitor space for untoward acts toward spaceborne assets, and to preserve access and the orbital environment.

Almost everyone should care where satellites are. Almost everyone depends on satellite services and information.

Concerns and Remedies

Advancing commerce greatly burdens orbit determination. More satellites and more debris require more precise and timely assessment of satellite motion. This problem is so complex that the most modern computer architectures and precise observations are insufficient for some of the most important applications. There are many avenues to improve the situation without compromising national security or proprietary interests. We need to clear obstructions from these paths. Below, a few of these obstructions are named along with suggestions for their mitigation.

1. Orbit data are incomplete. Important tasks require quantified uncertainty, therefore covariances should be revealed. The International Standards Organization is addressing this concern with a standard and consensus-driven scheme for orbit data transfer. This could take several years, but the community is free to adopt this emerging standard as consensus grows.

2. Sensors are sparsely distributed. This problem should be attacked first through worldwide data sharing. The sensors currently in place do not incorporate collaboration among themselves, yet collaboration should be a high priority. Every trustworthy source should contribute its observations toward building a more robust orbit determination process. Sensors should be dedicated to satellite tracking rather than a best effort among other demands. A well-selected set of additional sensors should be funded and built. ESA is considering some.

3. Orbit data are not widely available and are often not in formats most efficient for the broad user community. Even the NASA Orbit Information Group (OIG) could not meet all community needs, leading to several no-cost, value-added secondary providers. The Air Force-sponsored Space-Track service, established under PL 108-36, made fundamental orbit data more widely available. However, it cannot meet the community's needs at the existing level of effort.

4. Quantitative observations of satellites in orbit are not well enough characterized or sufficiently shared within the community that needs orbit information. The worldwide laser ranging network consists of more than thirty sites among countries whose national interests are not always congruent. It is a paragon of international collaboration for mutual benefit. However, it examines a small set of satellites expressly outfitted with reflectors and traveling in benign orbits. This network establishes a benchmark for calibrating other sensors. Within the constraints of each nation's interests and security, greater collaboration and data exchange would enhance the quality and availability of satellite orbit knowledge.

Conclusion

The significance of timely and precise orbit information is masked from the broad user community which depends on satellites. The small community dedicated to determining and disseminating orbit data is underappreciated and often ignored. Fiscal pressures diminish the already insufficient capability. Upgrades to the former Naval Space Surveillance Fence have been delayed for many years. The PARCS radar in North Dakota and FPS-85 in Florida are annually in fiscal jeopardy; system-wide surveillance performance characterizations would highlight their importance. Essential orbit data dissemination capabilities, such as the NASA Orbit Information Group, have disappeared.

It is hoped that this article will illuminate the difficulty of the task at hand, and describe the significance of satellite orbit knowledge well enough to arrest this unfortunate trend.

Footnotes

1 David A.Vallado, Fundamentals of Astrodynamics and Applications, Space Technology Library, Kluwer Academic Press, 2001, ISBN 0-7923-6903-3.

2 Yu. P. Gorochov and A.I. Nazarenko, "Methodical Points in Building Models of Fluctuations of the Atmospheric Parameters," Astronomicheskii Sovet Akademii Nauk SSSR, Vol 80, 1982.

3 In the simple two-body representation, six quantities, called orbit elements, are sufficient to describe an orbit forever (eccentricity, semi-major axis, inclination, argument of perigee, right ascension of the ascending node, and true anomaly). These are called "classical" or "Keplerian" element sets. When other forces are considered, these represent a "mean" or "osculating" orbit upon which perturbation effects are imposed.

4 It is difficult to measure atmospheric density explicitly; however, density is related to pressure, temperature, the composition of the atmosphere, and other quantities that can be measured directly. These other quantities are called "proxies."

5 Monitoring Space – Efforts Made by European Countries, Heiner Kilnkrad, ESA/EOC, Darmstadt, Germany, Nov 2004.

6 "European Space Surveillance System Study – Final Report, Donath, et. al., ESOC Contract 16407/02/D/HK(SC), Document DPRS/N/158/04/CC, 10 Dec 2004. ■

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