# What is the “Right” Answer?

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**Abstract:** This paper reviews approaches to discriminating among different outcomes of diverse equally credible analyses of the same data. Lacking precise benchmarks or ground truth, how does an investigator determine which of the different outcomes is the “right” answer. We give examples of outcome diversity and the manner in which different missions and disciplines deal with the differences. We review mathematically concrete decision criteria that should guide selecting the best approach and outcome for specific applications. There are rational, scientifically reproducible approaches to finding the “right” answer.

**Introduction:** Different orbit determination and propagation approaches give different answers with the same data. This diversity is amplified in conjunction assessment, which is dominated by numerous random processes and uncertainties in the states of both satellites. The objective of this paper is to expose approaches to dealing with diverse, potentially equally credible predicted outcomes for the same events. These circumstances are not unique to orbit determination. There are examples in precise time and time intervals, geodesy, and computational experimentation.

One should not expect outcomes predicted by different analysis techniques to be identical even for the same events founded on the same data. Different, even controlled, realizations of the same events will almost never all have identical outcomes either experimentally or analytically. Vallado and Finkleman have documented differences to be expected with different force models, model atmospheres, measurement uncertainties, numerical implementations, and other user specific decisions[2]. Geopotential, Earth Orientation, and atmospheric models evolve, and outcomes with current versions will differ from outcomes using earlier instances. Alfano and Finkleman have explored causes of conjunction false alarms and missed events and bounded analysis parameters based on decision makers’ risk tolerance. [3] Analysts and warning providers will always misidentify some events perceived otherwise by different providers. Who is right?

This is a very common circumstance, but how it should be approached depends on the analysis goals. If the goal is the convolution of many steps each of which can be diverse among analysts,

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[2] Vallado, D. and Finkleman, D., A Critical Assessment of Satellite Drag and Atmospheric Density Modeling, Paper **AIAA** 2008-6442, **AIAA**/AAS Astrodynamics Specialist Conference, August 2008.

[3]. Alfano, Salvatore and Finkleman, David, OPERATING CHARACTERISTIC APPROACH TO EFFECTIVE. SATELLITE CONJUNCTION FILTERING, AAS 13-435, 2013 AAS/AIAA Spaceflight Mechanics Meeting, Kauai, HI, USA. February 2013.

we can only strive to understand what others did to arrive at different results, try to transform all of the different predictions to as near a common set of parameters, reference frames, and other user preferences, and collaborate with others who might be involved to achieve a commonly understood course of action. No one is necessarily right or wrong.

We will explore different approaches to digesting diverse predictions in order to attain common understanding and action. Which one chooses depends on the goal: pointing sensors, downlinking data or uplinking commands, accessing areas of different sizes and locations on the Earth, launch collision avoidance, conjunction assessment, and space situational awareness, at least. In many cases the diversity among predictions does not affect the use of the information and any of the diverse predictions is sufficient for the purpose intended. Almost always no one is “right.”

**Back to Basics:**

The scientific method relies on three creative ideas[4].

1. *Order*: that there is a systematic pattern in physics, orderliness that can be described. Turing and Goedel[5] proved this. Whether one is capable always of revealing and studying these patterns is arguable.
2. *Causation:* that phenomena occur because of demonstrable events or states.
3. *Chance:* that relationships among causative factors can only be considered on a probabilistic basis. This is reflected in Heisenberg’s Uncertainty Principle. Even those who embrace predestination do not know in advance what will happen and when. Philosophically, prayer demonstrates real uncertainty.

Shuell[6] captures our situation well:

“Good scientists are extremely wary of dogmatic claims, especially those that are partially hidden. They insist that the data or logic used to support a knowledge claim be exposed so that a reasonable chance exists for the claim to be refuted. Although scientists often have strong preferences for a particular methodology or theory, the better ones realize that their ***interpretations, conclusions, and theories are more likely to be valid if they are aware of the strengths and weakness of both the methodology being used in their investigations and the strengths and weakness of alternative approaches.***”

Bayesian Decision Theory is an objective approach to discriminating among different, uncertain outcomes. Stated formally, one must evaluate the posterior probability of each resultant vector

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[4] Bronowski, J. (1978). The common sense of science. Cambridge, Mass.: Harvard University Press.

[5] Mitchell, M., Complexity, A Guided Tour, Oxford University Press, 2009

[6] Thomas J. Shuell, The Nature of Scientific Investigation, 1997, published and copyrighted by the author.

class, x, given prior observations, t, $P(t_i|x)$[7] and choose that with the largest conditional probability. This is stated mathematically as:

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$$P(\omega_1|x) \underset{\omega_2}{\overset{\omega_1}{\gtrless}} P(\omega_2|x)$$

In words, if the probability that the observation X exists when w1 exists is greater than the probability that X exists when w2 exists, then w1 is the most likely cause[8].

Applying Bayes theorem, this leads to the likelihood ratio test (LRT):

$$\Lambda(x) = \frac{p(x|\omega_1)}{p(x|\omega_2)} \underset{\omega_2}{\overset{\omega_1}{\gtrless}} \frac{P(\omega_2)}{P(\omega_1)}$$

Where P is the non-conditional probability of the state, w2. The advantage of the ratio is that priors based on data or belief divide out. When deciding which of two estimates of an orbit is "best," X is the set of orbit elements and w1 and w2 are the prior observations. Guterriez gives a cogent example:

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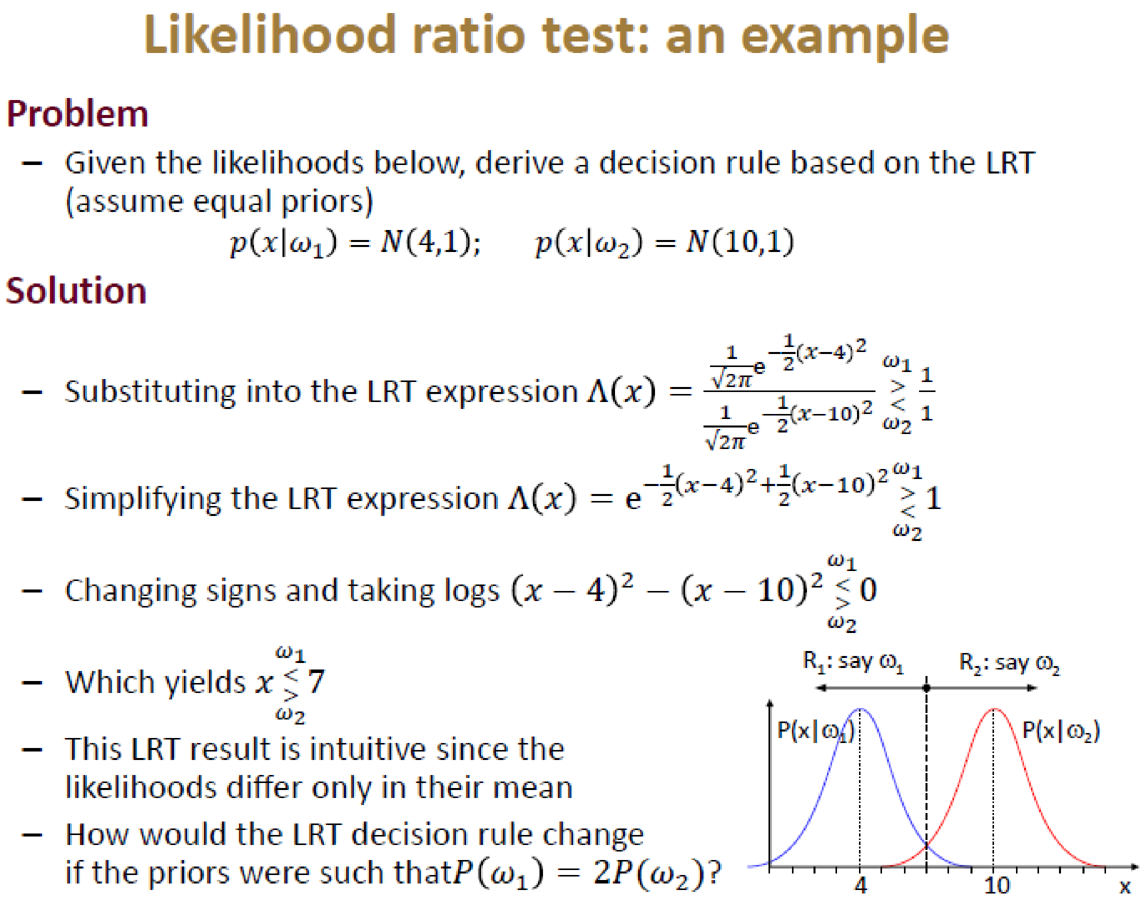
[7] $P(t_i|x)$= the probability that if an observation or result X exists, when vector of state variables $t_i$ exists. X can be a set of parameters describing an observation and the t elements can be orbit elements that lead to the observation.

[8] CSCE 666 Pattern Analysis, Ricardo Gutierrez-Osuna , Texas A&M University ( CSE@TAMU)



## Likelihood ratio test: an example

**Problem**

- Given the likelihoods below, derive a decision rule based on the LRT (assume equal priors)

$$p(x|\omega_1) = N(4,1); \qquad p(x|\omega_2) = N(10,1)$$

**Solution**

- Substituting into the LRT expression $\Lambda(x) = \frac{\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}(x-4)^2}}{\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}(x-10)^2}} \underset{\omega_2}{\overset{\omega_1}{\gtrless}} \frac{1}{1}$
- Simplifying the LRT expression $\Lambda(x) = e^{-\frac{1}{2}(x-4)^2+\frac{1}{2}(x-10)^2} \underset{\omega_2}{\overset{\omega_1}{\gtrless}} 1$
- Changing signs and taking logs $(x-4)^2 - (x-10)^2 \underset{\omega_2}{\overset{\omega_1}{\lessgtr}} 0$
- Which yields $x \underset{\omega_2}{\overset{\omega_1}{\lessgtr}} 7$
- This LRT result is intuitive since the likelihoods differ only in their mean
- How would the LRT decision rule change if the priors were such that $P(\omega_1) = 2P(\omega_2)$?

Figure 1: Likelihood Ratio Test Example (Guiterrez-Osuna, Ref 8)

In Figure 1, our observations are x=4 and x=1 each with Gaussian pdf of variance unity. The probability that one or the other will occur is unity, integrating the Gaussian between infinite extremes. The quantitative result is that if an observation, X, is less than 7, then the distribution N(4,1) is most likely and if it is greater than 7, N(10,1) is most likely. Although the example employs Normal (Gaussian) distributions, the principles are completely general.

Which outcome is most likely correct depends on the variances and covariances. It does not necessarily follow that the most precise pdf (smallest variance) is the "best" answer. That the outcomes are probabilistic means that either is a possible result, but one is more likely than the other.

One message is that each of the different outcomes is a possible result. Neither is "wrong." However, we have assumed implicitly that the dimensionality and specific states of each of the vectors are the same.

The astrodynamics and orbit determination problem often does not satisfy any of these assumptions. Different approaches may use different sets of state variables and even observations of different measure and number. As reflected in data exchange formats, the different outcomes are reduced to a common set of variances and covariances, usually 6x6 in position and velocity. However, reduction (or redaction) to a common form may mask the real uncertainties.

Comparisons are clouded in two ways. First, the variances and covariances may be unrealistic. Approximations and simplifications such as consider variables, may diminish the covariances unrealistically. There are realism tests, most straightforward propagate states forward and note whether excursions from the mean exceed variances determined at the same time as the states and propagated forward consistently. Second, additional solve for states such as ballistic coefficient expand the dimensionality of the covariance matrix so that even the common 6x6 submatrix depends explicitly on the states not held in common. In addition, different orbit determinations may be based on different sets of observations, either the same observations culled in different ways or even completely different sets.

We recommend Bayesian tests such as the Likelihood Ratio Test when an objective decision based on repeatable processes is required despite the limitations and caveats discussed. Liam Healy has invoked these principles and is evolving a similar Bayesian approach.[9]

### **Approaches when concrete mathematics are inapplicable**:

Several important phenomena either lack at present sound, demonstrated physical hypotheses that can be tested against observations. Some influences have not been observed well enough or long enough for meaningful statistical analysis. These include: accurate time, estimating solar cycles, and determining precise orbits for satellites measuring the Earth's surface or characterizing the atmosphere. We will review how the scientific community deals with diversity in analyses of these missions.

### Accurate Time:

For eons time was measured in fractions of a day, taken to be one complete rotation of the Earth. Egyptians had a twelve hour day and a twelve hour night even though day and night by some definition are different lengths. They changed the exit nozzles on their clepsydras regularly so that the rate of flow exhausted the reservoir during the day or during the night. Propagating Babylonian mathematics and understanding of the heavens, humankind allocated 86,400 seconds to a day. This led Simon Newcomb in the late 1800's to define a mean solar second based on a few hundred years of astronomical records of the Earth's position in inertial space. Astronomers knew for millennia that days did not fit evenly into years defined as complete orbits about the Sun. (Or orbits of the Sun about the Earth before Copernicus.) But it did not take long after Newcomb's mean solar second to recognize that the rate of rotation of the Earth decreases continuously but irregularly. The mean solar second would have to be redetermined at intervals. The burgeoning electronics industry did not appreciate having to recalibrate frequency standards every time the second changed. The atomic clock solved that problem with a constant second based on almost invariant properties of matter. Although smart people tried to define the constant second as close to the mean solar second at the time, the two would inevitably drift apart. Time would be disconnected from the astronomical phenomena it was based on for

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[9] Binz, C. and Healy, L., Association of satellite observations using Bayesian inference, AAS 13-245, AIAA/AAS Astrodynamics Specialist Conference, Hilton Head, SC, August 2013

thousands of years. Astronomers (and satellite operators) could not use a universally understood time scale to determine where to look for things from their current location on the Earth.

The answer was to connect time based on constant elapsed seconds with the rotation of the Earth in an interval of constant seconds and fractions thereof. The real time correction is called DUT=UTC-UT1, where UTC is coordinated universal time counted in standard atomic seconds with 86,400 seconds in a day, and UT1 is time in standard atomic seconds synchronized with Earth rotation. It was decreed that the difference between the two should never be greater than 0.9 standard atomic seconds and that a second would be added to or subtracted from UTC when the difference approached 0.9 standard atomic seconds. The International Earth Rotation Reference Service (IERS) was commissioned to keep track and to maintain the continuously changing formulae relating time to the Earth's position in inertial space. They accomplish this through collaborative long baseline interferometric analysis of the emissions of very distant and virtually stationary stars. The readings of over 200 atomic clocks are convolved to synthesize UTC. The clocks are distributed world-wide, and all "tick" at slightly different rates.

The question for this paper is, "How is UTC synthesized when there are about 200 different answers, and measurements of Earth rotation are imprecise?" Who is right?

Two components are used to determine Coordinated Universal Time (UTC): International Atomic Time (TAI) is a time scale that uses the combined running count output of some 200 highly precise atomic clocks measured in SI seconds from an epoch only 40 years ago. It is absolutely accurate in that interval and precise within the uncertainty in the SI second, which can be femtoseconds or less. It provides the exact speed at which our clocks tick. Universal Time (UT1), also known as astronomical time or solar time, refers to the Earth's rotation. It is used to compare the pace provided by TAI with the actual length of a day on Earth. To achieve the highest possible level of accuracy, the International Bureau of Weights and Measures (BIPM) combines the output of more than 200 atomic clocks in over 50 national laboratories worldwide to determine TAI. The time scale is weighted, prioritizing the time signal provided by institutions that maintain the highest quality of primary cesium.

The high level of precision achieved by using atomic clocks is both a blessing and a curse. On the one hand, accurate time-keeping is a necessity, for example for time-sensitive technology, such as modern air traffic control systems that rely on satellite navigation. On the other hand, TAI does not take into account the Earth's slowing rotation, which determines the length of a day. For this reason, TAI is constantly compared to UT1. No clock keeps the "official" version of UTC, because TAI and UTC are "paper" time scales that can only be calculated after all of the data from the international contributors are received. However, NIST and other laboratories maintain real-time versions of UTC that are often within just a few nanoseconds of the UTC calculations. The international contributors to TAI, and their offsets, are published in the BIPM Circular-T, which is a document updated monthly. The time-of-day expressed by UTC is the time at the prime meridian (0° longitude) located near Greenwich, England. The time in local time zones can be expressed as an offset from UTC.

Figure 2: An atomic clock. Actually an atomic chronometer since it produces a continuous stream of uniform seconds but does not actually keep time. A chronometer becomes a clock when it is synchronized with Earth rotation, or, alternatively the Sun’s passage through the sky, with noon at zenith.

The clocks at different institutions are regularly compared against each other. The International Bureau of Weights and Measures (BIPM, France), combines these measurements to retrospectively calculate the weighted average that forms the most stable time scale possible.[7] This combined time scale is published monthly in Circular T, and is the canonical TAI. This time scale is expressed in the form of tables of differences UTC-UTC(*k*) (equivalent to TAI-TAI(*k*)) for each participating institution *k*. (The same circular also gives tables of TAI-TA(*k*), for the various unsynchronised atomic time scales.)

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In this case study, the measurements of all contributors are combined in a weighted average with weights proportional to the relative stability of their atomic clocks. In real time, there are several local sources of TAI and UTC, each of which has available the deviation of its time hack from the weighted average. There is world-wide agreement on this without governmental regulatory pressure. As long as the participating institutions maintain good scientific practice, no one is right or wrong. There is a consolidated outcome and local realizations well registered against the consolidated result.

## Precision Orbit Determination for Jason II

Jason-2 is part of the joint NOAA, CNES, JPL, and EUMETSAT Ocean Surface Topography Mission (OSTM). It is in the heritage of TOPEX/Poseidon. In order to achieve required topographic precision with its radar altimeters, Jason-2 orbits must be maintained precise to a few cm. Orbit determination must be much better than that. Orbits for these satellites were chosen at altitudes and inclinations that minimize the influences of less well characterized variations in gravitation, orbit decay due to nonconservative atmospheric and solar perturbations, and that are consistent with instrument resolution and power requirements. These Geophysical Data Record (GDR) orbits are a standard for calibrating sensors and orbit determination schemes. They are studied continuously and meticulously.

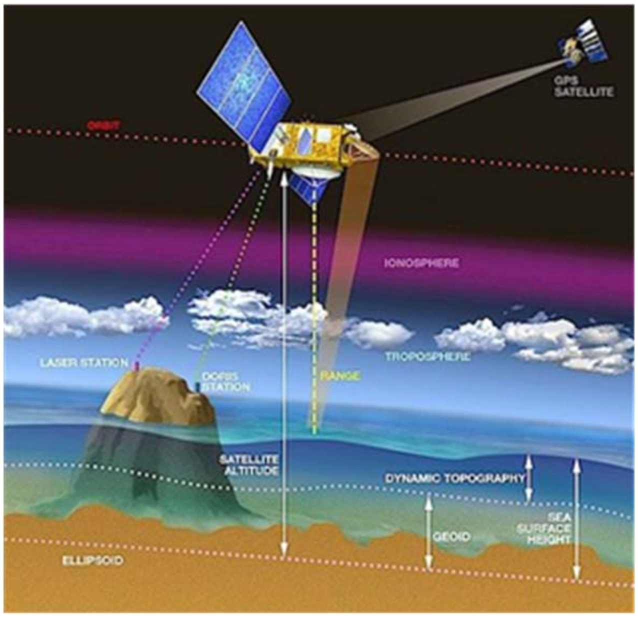

Figure 3: JASON II for ocean surface tomography, precision orbits from diverse contributors and analyses.

As Figure 3 indicates, there are several sources of observations and fundamental positional data: exquisite onboard GPS position and velocity determination with high quality instruments developed by JPL, ground based Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), laser ranging, and passive optical and radar observations. The Goddard Space Geodesy Laboratory observes that the *data diversity is essential to the continuous improvement of models of the Earth's geoid and precision orbit determination techniques*. Jason2 GDR orbit has been extensively compared with the solutions of other groups, including GSFC, JPL, and ESOC. All these solutions are obtained using similar though not identical models, different combinations of tracking techniques and different parameterizations.

As noted, satellites of this nature must be in very stable orbits. This enables deliberate consensus on reference orbits for primary mission science. It also facilitates intercomparison, sound collegial exchange, and adjustment of diverse hypotheses and techniques.

In this case study, collaboration on a common long term problem leads to establishing the range of outcomes of different models using the same or different data types so that each can employ its trusted tools confidently for primary scientific missions. There is no "right" answer, but the differences are well understood and resolved when the results of primary scientific missions are perceived to be inconsistent with each other.

## Climatology and Global Warming

There is perhaps no more visible contention over whose answer is right than in the Global Warming controversy. Many aspects are absolutely analogous to the issues of orbit determination and propagation. A seminal paper explores these issues.[10] The goal was to reconcile model projections of climate induced flow of the Colorado River. They note that models that predict historical events may seem correct but may not be so for the right reasons. One is interpolation within datasets with different resolutions. Equally down or up-scaled data sets do not often lead to the same, uniformly scaled data. Terrien, et al, [11] demonstrate that sampling frequency of time domain solvers or the number of points per period in numerical analysis is very important for numerical results.

Weather forecasting is one of the most important examples of adjudicating among diverse, equally credible analyses. There is a distinct difference between climatology, long term, aggregated estimates of the behavior of the atmosphere and its interaction with geography and bodies of water, and estimating short term, localized atmospheric phenomena, improperly termed "weather forecasting." Forecasting implies certainty and foreknowledge of what might occur. "Prediction" has the same connotation. It is more proper to estimate what might happen with quantified uncertainty derived from physical hypotheses and information about past occurrences. It is the mathematical discrimination among: estimation, filtering, and smoothing that most in the astrodynamics profession use and understand. There are many phenomena on short time scales, both ubiquitous and geographically or seasonally localized. In some cases, there is a robust sample of observations over a sufficient span of time. Nonetheless, solar and orbital evolutions change the underlying long period influences. Nate Silver's "The Signal and the Noise"[12] reveals the processes behind "weather reports."

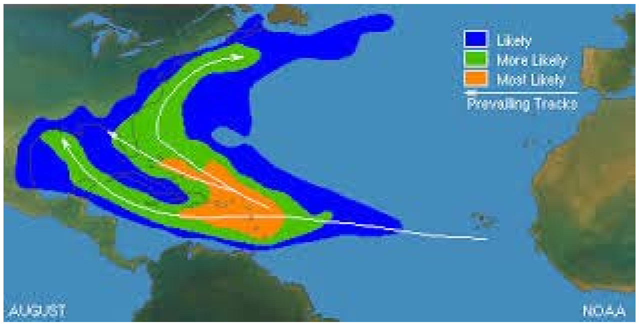

Figure 4: The hurricane track cone of uncertainty. Convolution of diverse observations and analysis.

The most important element of weather reporting is that *meteorologists now recognize, acknowledge, and accommodate uncertain observations, inevitably incomplete physical models, and numerical or computational artifacts.* It is effectively impossible to capture these automatically with algorithms, error trapping, and automated heuristics. Different equally credible estimates produce different outcomes. To account for inherent uncertainty in initial

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[10] Hoerling, M., Cayan, D., and Udall, B., "Reconciling Projections of Colorado River Streamflow," Southwest Hydrology, May/June 2009.

[11] Terrien, S., et al, Numerical resolution of a physical model of flute-like instruments: comparison between different approaches, Proceedings of the Acoustics 2012 Nantes Conference, April 2012.

[12] Silver, N., The Signal and the Noise; why so many predictions fail – but some don't, Penguin Press, New York, 2012

conditions or observations, small changes are introduced into the nonlinear, even deterministic, models to examine the influence of nonlinearities and reveal chaotic behaviors – the same data input and wildly different estimates of the future coming out. Forecasters know the flaws in the computer models. Even the most trivial bug can have profound effects. "These are the sorts of distinctions that forecasters glean over time as they learn to work around the flaws in the model, in the way a skilled pool player can adjust to the dead spots on the table" --- or a professional golfer can read the green.

Broadcast media now display a range of estimates, claiming no preference for any. What most do not realize is that the "weather reports" released by organizations such as the National Oceanic and Atmospheric Administration (NOAA) are seldom the raw products of analytical algorithms or numerical integration. There are carefully selected, tested, and very experienced teams of meteorologists who scrutinize inputs and outputs, judging based on their education, understanding, and experience which estimates are realistic and consistent. They reject even the most precise analyses that lead to outcomes inconsistent with their judgment. As Silver documents, such reports are significantly closer to what happens than are unfiltered outcomes of models and numerics. There is little doubt that no one's model or analysis is "right." There are institutional biases, as there are in astrodynamics. Reports on broadcast media are "wet." They predict rain even when the probabilities are extremely low because viewers and listeners are more forgiving when it is supposed to rain but doesn't than when it is supposed to be sunny but it rains. Real and often unconscious institutional biases are revealed by diverse outcomes among organizations.

## Operational Astrodynamics:

Our profession is not unique. We learned sampling, estimation, and navigation in the context of astrodynamics. Many among us assume that astrodynamicists conduct analyses that no one else does and that our techniques are at the analytical forefront. Others have been there before and are there now, usually ahead of us. This paper addresses two pivotal questions:

1. What is the standard for determining the accuracy and precision of orbit determination?
2. How should we consider and employ outcomes that are equally credible according to some standards?

## Standard Outcomes for Comparison

There are none! All observations are imprecise to a degree and in a manner that makes orbit determinations worse. Onboard GPS is not the most precise source of observations.[13] DORIS may be the most precise source of individual data gathering opportunities, but those opportunities may be infrequent or with error prone fusion geometries.

There is very nearly a standard for calibrating observing instruments, Precision Orbit Ephemerides. Our earlier discussion of precision orbit determination for JASON II is preamble to the more general capability. Well trusted, generally academic, organizations produce the

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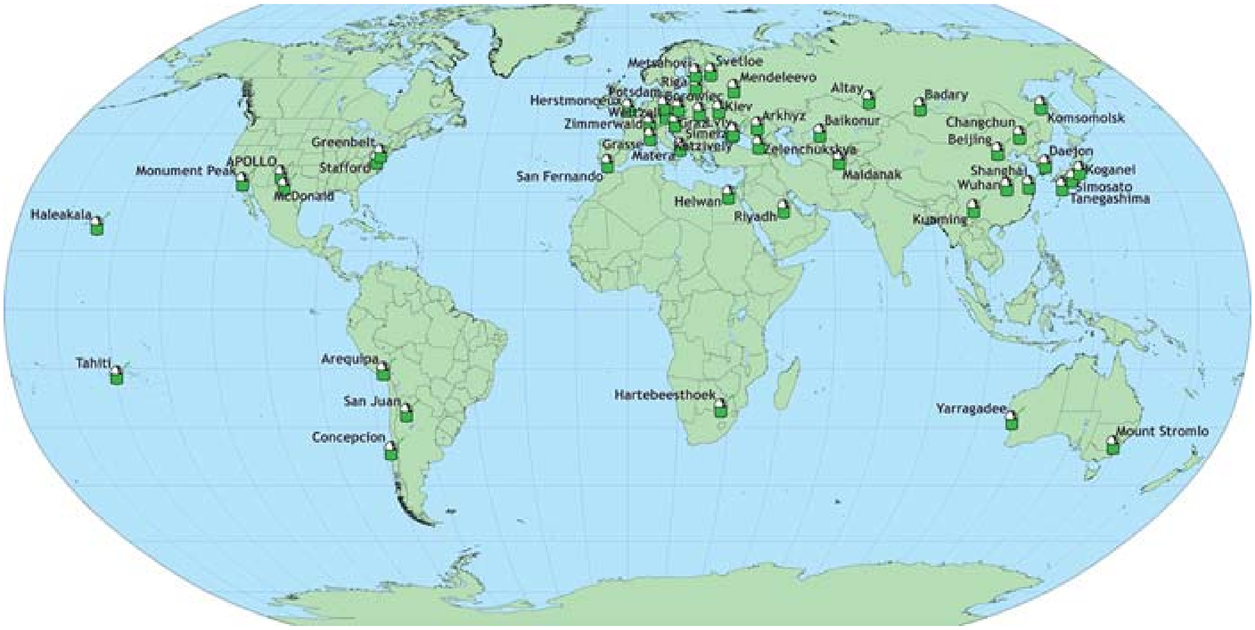
[13] Chiarada, A.P.M., Kuga, H.K., Bertachini de Almeida Prado, A.F., Onboard and Real-Time Artificial Satellite Orbit Determination Using GPS, Mathematical Problems in Engineering, Vol 2013.

most accurate and precise benchmarks currently available. They consume observations of well characterized satellites in very stable orbits gathered from dedicated and well characterized ground stations world-wide.

The Precision Orbit Ephemerides enterprise exemplifies orderly assessment and convolution of diverse outcomes. It flows almost completely from the International GNSS Service (IGS), formerly the International GPS Service, a voluntary federation of more than 200 worldwide agencies that pool resources and GPS & GLONASS fixed station data to generate precise GPS & GLONASS products as well as collaborative “standard” orbits for selected satellites. SLR data is presented in SINEX format, although the ILRS analysis enterprise is working toward a more effective mutually agreeable format.



“SLR Analysis Centers provide independent solutions, but have sometimes adopted reference frames and/or models for gravity, plate motion, tides, nonconservative forces, etc. which were either non-standard or poorly defined. These force model differences can produce apparent disparities and inconsistencies between solutions from centers employing different analysis techniques. Inadequate description of the reference frame can also create confusion among outside scientists attempting to use the archived results in their own analyses. It is therefore important that certain standards be uniformly applied to all formal solutions submitted by the Analysis Centers to the IERS and that those force or other models for which no standards have been adopted be clearly stated.”[14]

There are a dozen certified IGS analysis centers[15] and eight certified ISLRS analysis centers[16] world-wide. The Center for Orbit Determination in Europe (CODE) at the Astronomical Institute

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[14] http://ilrs.gsfc.nasa.gov/science/awg/awg_charter.html

[15] Center for Orbit Determination in Europe, AIUB, Switzerland; European Space Operations Center, ESA, Germany; Geodetic Observatory Pecny, Czech Republic; GeoForschungsZentrum, Germany; GRGS-CNES/CLS, Toulouse, France; Jet Propulsion Laboratory, USA; Massachusetts Institute of Technology, USA; National Oceanic and

of the University of Bern (AIUB) exemplifies the capabilities. AIUB develops precise orbits for a variety of Low Earth Orbiting (LEO) satellites GNSS and SLR data.

All data is provided with information related to its precision (SNR, SLR calibration RMS, etc.) as provided by the stations. Stations need to fulfill minimum standards and their data is evaluated by ILRS/IGS before they become official ILRS/IGS stations. In case of the SLR observations all stations perform calibration observations either on short-range targets (distance < few km) and/or internal (very short range) calibrations. Apart from providing internal delays, such observations also provide information on the precision of the systems. Obviously, the behavior of the systems may be different for the real (long range) observations to satellites (especially biases could be different).

ILRS/IGS define a set of standards to be used (system of constants, reference systems, reference frames, etc.), as well as additional requirements like the observation interval (arc length) to be used to determine the products. Products are orbits, Earth rotation parameters, clocks, station coordinates, etc. Orbits are given in the form of ephemerides (state vectors) including covariance information. The models and methods (and some of the software packages) used by the different Analysis Centers are made available with great details. In the same way as the stations, candidates have to pass demanding "tests" to become an official Analysis Center. The "tests" are transparent.

Products from the different Analysis Centers are then "combined" by the Analysis Center Coordinator (ACC) to generate the official ILRS/IGS products. As you may imagine, this is where debates about the methods to be used for this "data fusion" takes place! The good thing about it is that the discussion takes place, that the methods actually used are transparent, and that there is scientific competition among the Analysis Centers which grantees a continuous validation and improvement of the process. The current "combination algorithms" are based on careful weighting of the individual products based on information provided by the Analysis Centers, as well as a posteriori covariance analyses. For both the ILRS and the IGS products we are talking about a very high level of precision.[17]

The precision orbits so carefully prepared exist only for previously noted satellites in very stable orbits that are influenced mainly only by gravitation as opposed to aerodynamic resistance, radiation pressure, and the majority of other nonconservative forces. Although the current position and velocity of many satellites can be determined periodically by operators exploiting downlink ranging (subject to geometric dilution of precision), we are most concerned by what

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Atmospheric Administration / NGS, USA; Natural Resources Canada, Canada; Scripps Institution of Oceanography, USA; U.S. Naval Observatory, USA; Wuhan University, China

[16] Bundesamt für Kartographie und Geodäesie (BKG) Germany; Deutsches Geodätisches Forschungsinstitut (DGFI) Germany; ESA/ESOC, Germany; Groupe de Recherche en Géodésie Spatiale (GRGS) France; Helmholtz Centre Potsdam German Research Centre for Geosciences (GFZ), Germany; Italian Space Agency, Centro de Geodasia Spaziale "G. Colombo" (ASI/CGS), Italy; Joint Center for Earth System Technology/Goddard Space Flight Center, USA; and NERC Space Geodesy Facility (NSGF) formely RGO Satellite Laser Ranging Group, United Kingdom.

[17] The author thanks Dr. Thomas Schildknecht of AIUB for this cogent explanation.

the states of satellites will be in the future, when they are not visible to observers. This is the dilemma as near Earth space crowds.

There are no firm standards for representing atmospheric resistance (drag) or photon momentum transfer (light pressure). International collaboration is ongoing to develop guidance for representing atmospheric resistance. The phenomenology of photon momentum transfer is perhaps better characterized. Both nonconservative phenomena are severely affected by insufficient environmental databases, uncertain satellite dynamic states, and unknown satellite surface characteristics. The latter affect momentum and energy transfer through non-specular interactions of the local environment with satellite surfaces. When orbit estimates from different analysts differ, who is "right?"

## Dealing with Credible but Diverse Outcomes for Most Satellites

Meteorologists and astrodynamics have much in common. We can also borrow from them a scheme for judging among estimates[18].

- Quality or accuracy – how well did satellite orbits match a priori estimates? Over a reasonable interval, with trusted observations, did the satellite go where we thought it would.
- Consistency or honesty – were the estimates the best possible at the time? Were there enough observations? Were more observations available or accessible?
- Economic value – did the forecast help operators and policy makers make better decisions?

We should also recognize that different users and providers have different perspectives. User needs and requirements vary. Quality unacceptable for some applications might be acceptable for others. We see this in the accuracy and precision that TLE's were conceived to achieve: sufficient to capture cataloged satellites within the field of regard and field of view of space surveillance sensors. Current operations, such as closely spaced collections of communication satellites and avoiding collisions with minimum disruption and energy expenditure demand much greater precision.

Using these criteria, Precision Orbit Ephemerides are the most accurate, consistent, and valuable resource.

Owner/operator ephemerides should be the next most desirable.

Unfortunately, neither source spans the majority of the catalog, and the most comprehensive sources are not accessible for considerations of national security or competition.

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[18] Allan H. Murphy, "What is a good forecast? An essay on the nature of goodness in weather forecasting," American Meteorological Society 8 (June 1993) pp 281-293, http://www.swpc.noaa.gov/forecast_verification/Assets/Bibliography/i1520-0434-008-02-0281.pdf

## Conclusions:

There is no single best answer. There are only different answers. Credibility is the most important discriminant. Is there enough information, generally metadata, available that those who bear the ultimate risk can judge the quality of the data and the suitability of analysis techniques? If the outcomes are comparably credible, there are several alternatives.

- Combine the answers, as is done for accurate and precise time.
- Objective and experienced review by ecumenical experts as in weather forecasting.
- Issue products that bound the diverse possible outcomes, as in hurricane landfall predictions.
- Choose the product that claims greatest precision among equally credible estimates, as in some weapon fire control.
- Construct a single fused answer with trusted techniques applied to well characterized raw observations.

All of the alternatives leaven bare analysis estimates with expert skill and judgment.

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