Integrity Monitoring of IGS Products

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Abstract

The IGS has successfully produced precise GPS and GLONASS transmitter parameters, coordinates of IGS tracking stations, Earth rotation parameters, and atmospheric parameters. In this paper we discuss the concepts of integrity monitoring, system monitoring, and performance assessment, all in the context of IGS products. We report on a recent survey of IGS product users, and propose an integrity strategy for the IGS.

1 Introduction

Since its official beginning in 1994, the IGS has supplied precise GPS products based on analysis of data from the IGS global tracking network. Publications available at igscb.jpl.nasa.gov/igscb/resource/pubs/ contain the evolution of these products. Throughout its history, the IGS has paid close attention to the accuracy and precision of it its products.

While related, accuracy and precision do not by themselves necessarily indicate the extent to which users can "rely" on IGS products to achieve user objectives. To address this issue, we must begin to consider the broader concept of *integrity*, which considers the "correctness" of information provided by a system in relation to an intended use of this information. Providing integrity information for IGS products would allow users to understand the extent to which they can trust the products at any point in time.

The IGS exists ultimately because of a desire by its sponsors to serve the needs of users. Thus it makes sense for the IGS to consider integrity from the user point of view. In this paper, we first discuss the general ideas behind integrity monitoring, and how they apply to IGS products. Next, we look at the current quality of those products. Third, we report on the results of a survey of users of IGS products. We go on to outline an integrity strategy for the IGS, and close with some recommendations.

2 Integrity, system monitoring and performance assessment

In this section, we give first give definitions for the terms *integrity*, *system monitoring* and *performance assessment* and explain how they are understood in the context of this paper. Moreover, the term

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performance metric will be defined. We will realize that for IGS, both system monitoring sufficient to derive integrity information as well as performance assessment of the IGS are of relevance. An invited oral paper in thie Session will discuss the concept of integrity in the context of Europe's Galileo GNSS.

A working definition of "integrity" is as follows[1]: *Integrity is that quality which relates to the trust which can be placed in the correctness of the information supplied by the total system. Integrity risk is the probability of an undetected failure of the specified accuracy. Integrity includes the ability of a system to provide timely warnings to the user when the system should not be used for the intended operation.*

In this definition, the term *correctness of information* needs further explanation. In our discussion, we consider information in form of a quantitative value given for a parameter as correct, if the information itself plus the uncertainty attached to it does not violate the accuracy specifications for this particular parameter. Consequently, integrity requires clear specification of the accuracy of the quantitative information, and this specification depends on the intended operation for which the information is to be used. We can conclude that integrity most often will be provided for specified applications.

Assessing the integrity of information provided by a system requires knowledge of the system performance. Based on appropriate *system monitoring*, integrity information can be derived, e.g. in form of an integrity flag. Estimation of the integrity risk is far more difficult.

In this report, we consider monitoring of system performance largely as an integral part of the operational activities with the goal to describe the system performance with respect to the system specifications. Thus, the main result of this system analysis and measurement will be to detect any violations of the system specifications.

The infrastructure required for system monitoring normally will be defined as part of the system itself. For example, for a GNSS, a ground network of tracking stations can be used as satellite tracking network, while an additional network may be established as integral part of system and used to measure continuously the system performance at these sites against the system specifications. Based on such measurements, information concerning the integrity of the system can be derived and combined with additional information be used to determine the value of an integrity flag.

For GNSS systems including integrity information, the integrity parameter itself is an important contribution to system monitoring. Taking Galileo as an example, the ground network of stations used for integrity measurements will most likely be different from the network used for tracking purposes.

Here we define *performance assessment* as an act that gives a detailed characterisation of the system in terms of a relevant metric without necessarily comparing this to a given system specifications. The infrastructure providing information for the performance assessment normally will be independent of the system itself.

The primary goal of *system monitoring* thus is to assess compliance of the system with its specifications. Thus, system monitoring is relative to system specifications. System monitoring is important to ensure operational performance within the system specification and the integrity of the products.

The primary goal of the *performance assessment* is to measure system performance in an absolute metric thus giving information of the overall quality, performance and capabilities of the system.

[1]Concept Paper 1 (WP/43), AWOP (All Weather Operations Panel) Working Group Meeting, Kobe, Japan, February/March 1994, "Required navigation performance (RNP) - Considerations for the Approach, Landing and Departure Phases of the Flight"

Performance assessment is important whenever changes are made to the system and their impact are to be measured and when new application of the system requiring a performance better then the system specifications are discussed.

A key issue in performance assessment is the definition of an appropriate *system metric*, which can be used to measure the system in an absolute sense. In most cases, the metric is defined on the basis of parameters connected to the final system products. However, a full performance assessment would also include parameters related to internal components and intermediate products.

Thus, for a GNSS, performance assessment normally utilizes a metric based on parameters like coverage, availability, accuracy, and so on. Intermediate products such as satellite orbit and clock accuracy, ionospheric and troposphere contributions to User Equivalent Range Error (UERE), tracking network performance, orbit computation centre performance, and so on are normally not considered. However, knowledge of these parameters would help to elucidate system areas that would need improvements in cases of increased requirements and also identify system parts critical for the overall performance.

3 Current integrity of IGS products

Having defined these terms, we turn next to IGS products. An excellent summary of what is curently available is the *IGS Product Table* (attached) from igscb.jpl.nasa.gov/components/prods.html.

The Table is valuable for its intended use, indicating approximate[2] accuracies and nominal latencies. Weekly summaries of IGS combination products, such as *Ultra Rapid IGS Orbit Comparison*, *Trop Combination*, *IGS SINEX Combination*, and *IGS Final Orbits* are posted at igscb.jpl.nasa.gov/mail/igsreport/, and contain information that corroborates the nominal accuracies. The IGS AC Coordinator will present an invited oral paper in this Session, *Products produced under direction of AC Coordinator: Processes, accuracies and quality control*, to bring us up to date on what quality control measures are in place for many of the IGS products.

From the previous section, however, it is clear that we need more information than is in the Table before we can address integrity. Consider the IGS Ultra-Rapid real-time orbit as an example. In the attached IGS Product Table, this is denoted by *Ultra-Rapid (predicted half)*, meaning that the positions of GPS transmitters at the present (i.e., real-time) are based on extrapolations into the future of orbits determined from data in the past. The attached Figure (courtesy of the IGS Central Bureau) compares the RMS difference between the Ultra-Rapid orbits and the Rapid orbits as a function of GPS week. The assumption is that "truth" is represented by the Rapid orbit. (Since the Rapid orbits are based on data, one expects that mismodeling of satellites is detected as larger-than-usual differences among estimates by different ACs.)

The good news from the Figure is that the heavy horizontal band of points is in fact at the level of a few tens of cm. (As an aside, this suggests that the "$\sim$10 cm" from the *IGS Product Table* for the accuracy of this orbit is either optimistic, or perhaps based on an outlier-insensitive metric, unlike "RMS".)

But, the user of course needs to be concerned with the not insignificant number of times that the Ultra-Rapid orbit is in error by $\sim$meters. Upon review of our definition of *Integrity*, we might ask, for an intended operation of, say, real-time kinematic positioning to better than 1 m, is the system able to provide timely warnings to the user when the system should not be used? In this case, a warning could

[2]Numbers in the Table's *Accuracy* field are often qualified by a "$\sim$".

take the form of an appropriate value of the accuracy code filed in the sp3c files. If so, and provided also that there are sufficiently many satellites with good-enough accuracies, we would conclude that the integrity of the Ultra-Rapid system is good. (We have not explicitly mentioned that, in addition to real-time orbits, one needs real-time clocks to do absolute kinematic positioning.)

On the other hand, if the large deviations are not accompanied by large values of the sp3c accuracy codes, then we would conclude that the integrity of the Ultra-Rapid system is poor.

We can now see a tie-in to the *performance assessment* and *system monitoring* ideas of Section 2. For an intended operation of real-time kinematic positioning, we could, for example, use the IGS Ultra-Rapid real-time product to perform real-time kinematic positioning using data from one or more stationary receivers. Results acquired over a period of time would tell us what the integrity of the product was as a function of specification.

One can imagine going through a similar exercise for other IGS products: identify an intended operation, define a system to monitor the performance of the product for that operation, and exercise the system for a long enough period to assess the performance. As in the above example, the result will indicate what the integrity is as a function of specification.

It may not be the case for all IGS products/applications that the value of integrity monitoring is worth the cost of realizing it. Even if the system is unable to provide timely warnings to the user when the system should not be used for the intended operation, it may be that the *integrity risk*, as defined in Section 2, is low. That is, even without integrity monitoring the system works well enough often enough. Or, the consequences of an undetected failure at a certain rate are acceptable. Thus assessing the value of integrity monitoring for a given product and application is important.

4 User Survey

The authors surveyed users of IGS products in IGS mail 4756:

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Author: Jim Zumberge, Hans-Peter Plag

As co-chairs of the session called "Integrity Monitoring of IGS Products",
to be held at the March 2004 IGS Workshop in Berne, we would like to survey
users of IGS products.

If you are such a user, an email to plag@statkart.no and
James.F.Zumberge@jpl.nasa.gov would be appreciated. Please include as many
of the following as you can:

* particular IGS product(s) used (refer to
http://igscb.jpl.nasa.gov/components/prods.html if you like);

* quality control measures you have implemented (or indicate none if that
is the case);

* how you use the IGS product(s) (optional);

* any comments you have based on your experience as a user.

Additionally, should you be interested in presenting a paper in Berne,
please refer to the IGS mail at
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http://igscb.jpl.nasa.gov/mail/igsmail/2003/msg00433.html for instructions
on how to submit an abstract.

As a user of IGS products, your participation in this survey will help the
IGS better serve its community. A response by January 16 would be appreciated.

Thank you.
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We received 26 responses representing 12 countries (roughly half were from the US). Numerous applications were represented, including surveying, geodesy, geodynamics, time transfer, meteorology, ionosphere, sea level determination, and positioning of low-Earth orbiting spacecraft carrying GPS receivers. A mix of organizations was represented, including government organizations, academic institutions, and a few private individuals. In decreasing order of popularity are orbits (may or may not include clocks); Earth rotation parameters; coordinates (may include velocities) of IGS sites; atmosphere and ionosphere products; station clocks.

The most common feature of all responses was an appreciation and gratitude for IGS products[3]. Especially valuable are a number of constructive criticisms. Some that were mentioned by more than one respondent include:

- need a better real-time product (more satellites in the Ultra-Rapid product, and better quality flags in the sp3c files);
- difficulties associated with concatenation of sp3 files;
- year-to-year discontinuities in the realization of the terrestrial reference frame;

As for what quality control features users have implemented, "none" was the most common response, although many respondents did indicate their use of the sp3 flag for orbit QC. Other QC responses ranged in sophistication from *eyeball* to *Comparison of EOPs with those determined by independent space-geodetic techniques and with atmospheric and oceanic angular momentum series.*

Whle this survey cannot necessarily be considered representative of IGS users as a whole, it did solicit enough informative responses that the IGS ought to consider how to go about a more formal survey. An invited oral presentation – *The Use and Integrity Monitoring of IGS Products at Geoscience Australia* – will present a more detailed point of view from one particular user.

5 An integrity strategy for IGS

As stated in Section 2, the determination of the integrity of information requires both *a priori* specifications of the accuracy of the products and system monitoring. The specifications will depend on intended applications of the products.

[3]Some examples:

- "I am very pleased with the products and pray for their continued availability."
- "Our geodetic infrastructure depends on the availability of these products."
- "We are intensive and thankful users of your data."

Consequently, an integrity strategy for the IGS has to start at specifying the accuracy of products required for certain applications. Next, it should be demonstrated that the product/application in fact requries integrity monitoring.

If so, the necessary system monitoring can be designed and integrity computed.

Using orbits and clocks as a specific example (assuming that the value of integrity monitoring has already been established):

1. Define several standard applications of, for example, orbits and clocks (ultra-rapid, rapid, precise) and the "promised" maximum contribution of orbit and clock errors to UERE (of course, IGS cannot provide integrity in terms of the total UERE, which may come from user equipment problems, environmental conditions, ionosphere, troposphere).

2. Derive specifications for the required accuracy of orbits and clocks.

3. Measure the orbit and clock accuracy on the basis of an independent "integrity network" (stations not used in the orbit determination).

Note that "performance assessment" has been in progress for essentially all IGS products since their introduction.

6 Conclusions, Recommendations

We conclude that, to better serve its users, the IGS should move forward in monitoring the integrity of at least some subset of its products.

We recommend that the IGS initiate dialog with users to understand better the variety of intended applications as a function of IGS product. For each such major application, a specification for the required accuracy should be determined. Next, the value of integrity monitoring should be determined. If found to be sufficiently valuable, a system to monitor performance (which may already be in existence for some IGS products) should be defined.

Given the multitude of IGS products and applications, these recommendations amount to a major undertaking. A reasonable first step would be to pick one mature and popular IGS product, and work through the recommendations for that product alone.

7 Acknowledgements

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IGS Product Table [GPS Broadcast values included for comparison]

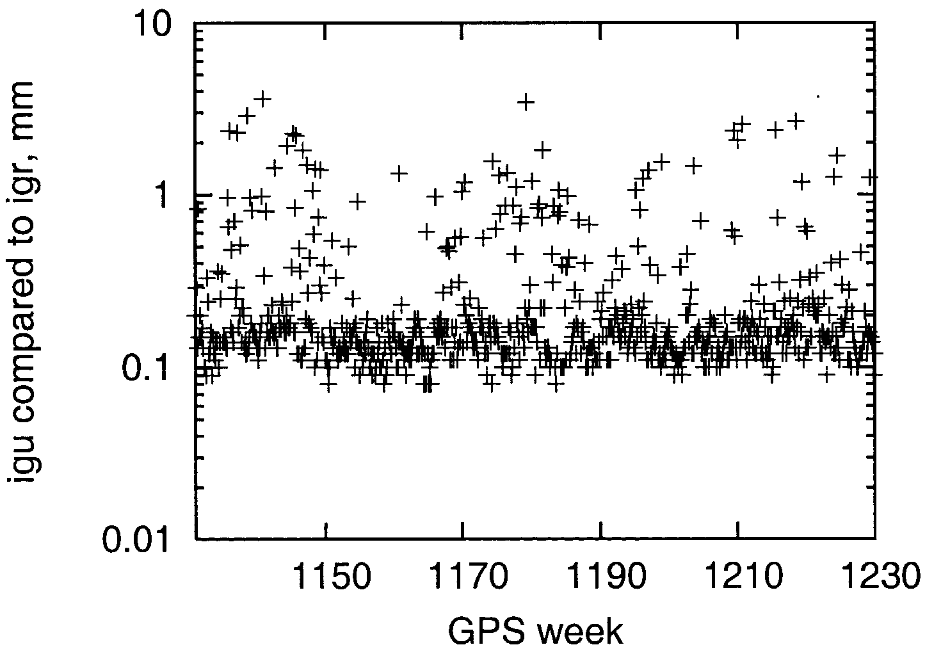
		Accuracy	Latency	Updates	Sample Interval	Archive locations
GPS Satellite Ephemerides/ Satellite & Station Clocks						
Broadcast	orbits	~200 cm	real time	--	daily	CDDIS(US-MD) SOPAC(US-CA) IGN(FR)
	Sat. clocks	~7 ns				
Ultra-Rapid (predicted half)	orbits	~10 cm	real time	twice daily	15 min	CDDIS(US-MD) SOPAC(US-CA) IGN(FR) IGS CB(US-CA)
	Sat. clocks	~5 ns				
Ultra-Rapid (observed half)	orbits	<5 cm	3 hours	twice daily	15 min	CDDIS(US-MD) SOPAC(US-CA) IGN(FR) IGS CB(US-CA)
	Sat. clocks	~0.2 ns				
Rapid	orbits	3 cm	17 hours	daily	15 min	CDDIS(US-MD) SOPAC(US-CA) IGN(FR) IGS CB(US-CA)
	Sat. & Stn. clocks	0.1 ns			5 min	
Final	orbits	2 cm	~13 days	weekly	15 min	CDDIS(US-MD) SOPAC(US-CA) IGN(FR) IGS CB(US-CA)
	Sat. & Stn. clocks	0.05 ns			5 min	

Note 1: IGS accuracy limits, except for predicted orbits, based on comparisons with independent laser ranging results. The precision is better.
Note 2: The accuracy of all clocks is expressed relative to the IGS timescale, which is linearly aligned to GPS time in one-day segments.

GLONASS Satellite Ephemerides						
Final		30 cm	~4 weeks	weekly	15 min	CDDIS(US-MD)
Geocentric Coordinates of IGS Tracking Stations (>130 sites)						
Final positions	horizontal	3 mm	12 days	weekly	weekly	CDDIS(US-MD) SOPAC(US-CA) IGN(FR)
	vertical	6 mm				
Final velocities	horizontal	2 mm/yr	12 days	weekly	weekly	CDDIS(US-MD) SOPAC(US-CA) IGN(FR)
	vertical	3 mm/yr				
Earth Rotation Parameters: Polar Motion (PM) Polar Motion Rates (PM rate) Length-of-day (LOD)						
Ultra-Rapid (predicted half)	PM	0.3 mas	real time	twice daily	twice daily (00 & 12 UTC)	CDDIS(US-MD) SOPAC(US-CA) IGN(FR) IGS CB(US-CA)
	PM rate	0.5 mas/day				
	LOD	0.06 ms				
Ultra-Rapid (observed half)	PM	0.1 mas	3 hours	twice daily	twice daily (00 & 12 [illegible]	CDDIS(US-MD) SOPAC(US-[illegible]
	PM rate	0.3 mas/day				

	LOD	0.03 ms			UTC)	CA) IGN(FR) IGS CB(US-CA)
Rapid	PM	<0.1 mas	17 hours	daily	daily (12 UTC)	CDDIS(US-MD) SOPAC(US-CA) IGN(FR) IGS CB(US-CA)
	PM rate	<0.2 mas/day				
	LOD	0.03 ms				
Final	PM	0.05 mas	~13 days	weekly	daily (12 UTC)	CDDIS(US-MD) SOPAC(US-CA) IGN(FR) IGS CB(US-CA)
	PM rate	<0.2 mas/day				
	LOD	0.02 ms				
Note: The IGS uses VLBI results from IERS Bulletin A to calibrate for long-term LOD biases.						
Atmospheric Parameters						
Final tropospheric zenith path delay		4 mm	< 4 weeks	weekly	2 hours	CDDIS(US-MD) SOPAC(US-CA) IGN(FR)
Ultra-Rapid tropospheric zenith path delay		6 mm	2-3 hours	every 3 hours	1 hour	CDDIS(US-MD)
Ionospheric TEC grid		2-8 TECU	~11 days	weekly	2 hours; 5 deg (lon) x 2.5 deg (lat)	CDDIS(US-MD) IGN(FR)
Rapid ionosphere products		(under development)				

Figure


10
1
0.1
0.01
1150
1170
1190
1210
1230
GPS week
igu compared to igr, mm