GPS, GLONASS, and More

Multiple Constellation Processing in the International GNSS Service

Tim Springer and Rolf Dach

In 2005, the International GPS Service (IGS) was renamed the International *GNSS* Service. With this change, the IGS governing board and the IGS community expressed their expectation to extend activities from the well-established GPS to other active and planned global navigation satellite systems such as GLONASS, Galileo, and Compass. Meanwhile, the GLONASS satellite constellation, as well as the IGS GNSS tracking network, have evolved significantly. Since 2003, the GLONASS satellite constellation has been improving steadily, leading to the current, May 2010, constellation with 21 operational satellites and two in-orbit spares. And starting in 2008, the GNSS capabilities of the IGS tracking network have been greatly enhanced giving rise to a truly global GNSS tracking system with more than 100 GNSS (GPS plus GLONASS) receivers. The almost-complete GLONASS satellite constellation, coupled with a readily available global tracking network with high-quality receivers, have greatly increased the interest in and need for GNSS products such as precise satellite orbit ephemerides. However, the IGS analysis center products are still mainly GPS-only. Only two analysis centers provide true multi-GNSS solutions. Two analysis centers provide GLONASS-only solutions (a GLONASS combined IGS product is available but without accurate clocks). No combined IGS GNSS product exists. In view of the large interest from the user community, this is a really disappointing situation. In particular, because experiences gathered with handling GPS plus GLONASS will make the incorporation of other GNSS such as Galileo, Compass, and the Quasi-Zenith Satellite System (QZSS) that much easier.

However, during a meeting of the IGS analysis centers in December 2009, it became clear that many of the centers had started to implement and enhance the GLONASS processing capabilities in their software. This was happening as a direct consequence of the improvements in the GLONASS constellation, the IGS GNSS tracking network, and increased user interest (if not demand). Throughout 2010 and 2011, we will therefore see a significant increase in the number of true GNSS solutions within the IGS. A very positive development for the GNSS world.

In this article, we give an overview of the recent developments in the area of multi-

ARE WE THERE YET — at a multiple-constellation GNSS world? The European Galileo system only has two test satellites in orbit, with constellation completion not scheduled until 2014. The Chinese Beidou/Compass system has launched some test satellites, but global coverage is not promised until 2020. And the first Japanese Quasi-Zenith Satellite System space vehicle is scheduled for launch this year with the system not fully operational until 2013. So, does this mean GPS is still the only game in town? No, not by a long shot. We have overlooked Russia's GLONASS.

Standing for *Global'naya Navigatsionnaya Sputnikova Sistema*, GLONASS was conceived by the former Soviet Ministry of Defence in the 1970s, perhaps as a response to the announced development of GPS. The first satellite was launched on October 12, 1982. But because of launch failures and the characteristically brief lives of the satellites, a further 70 satellites were launched before a fully populated constellation of 24 functioning satellites was achieved in early 1996. Unfortunately, the full constellation was short-lived. Russia's economic difficulties following the dismantling of the Soviet Union hurt GLONASS. Funds were not available, and by 2002 the constellation had dropped to as few as seven satellites, with only six available during maintenance operations! But Russia's fortunes turned around, and with support from the Russian hierarchy, GLONASS was reborn. Longer-lived satellites were launched, as many as six per year, and slowly but surely the constellation has grown to 21, with two in-orbit spares.

INNOVATION INSIGHTS
with Richard Langley

GLONASS was reborn.

But are there any users outside Russia? Although dual-system GPS/GLONASS receivers have been around for at least a decade, manufacturers have taken notice of GLONASS's recent phoenix-like rebirth. All of the high-end manufacturers now offer receivers with GLONASS capability. Does combining GPS and GLONASS observations make a difference? You bet — just ask any surveyor who uses both systems in the real-time kinematic (RTK) approach. Scientific applications requiring high-accuracy satellite orbit and clock data also benefit. The International GNSS Service (IGS) has been providing such data for several years, and in this month's article representatives from two IGS analysis centers discuss the past, present, and future of IGS GNSS monitoring and product development.

So, getting back to our question, are we there yet? Many early adopters of GPS plus GLONASS data and products would reply with a resounding "yes."

GNSS processing within the IGS in general, but with a focus on the activities of the two analysis centers in the IGS that are leading the GNSS efforts: the Center for Orbit Determination in Europe (CODE) and the European Space Operations Center (ESOC) of the European Space Agency.

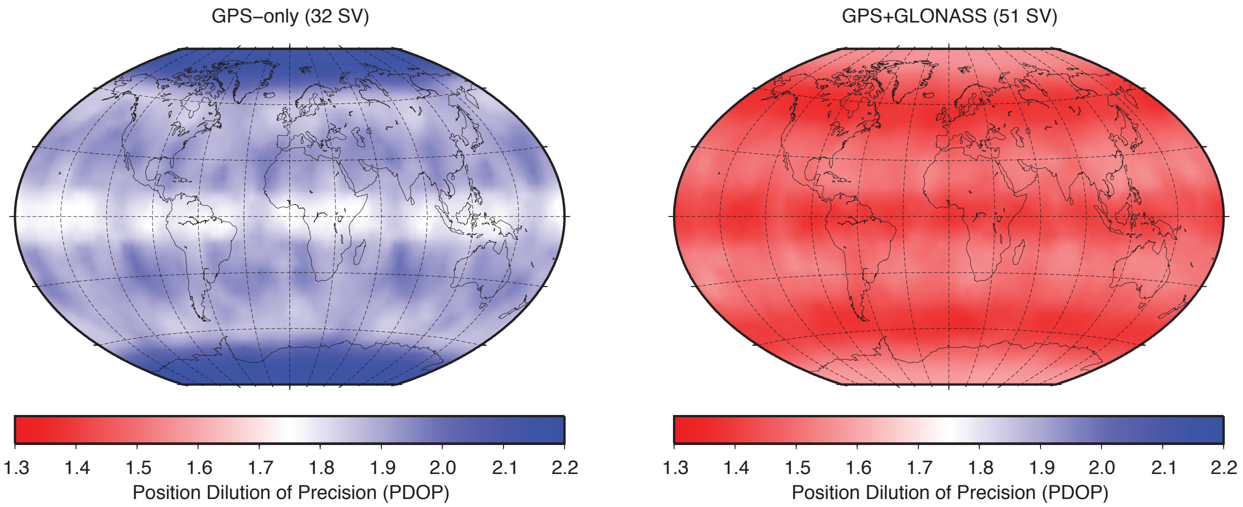
Why GNSS?

Within the IGS, we are often confronted with the question: Why GNSS? Why should I go through the burden of adding GNSS capabilities to my software, having larger processing loads, and so on, for little or no benefit? Well, from an IGS analysis center point of view, this question is valid. The accuracies achieved with GPS alone are so good that there will be little visible benefit of including another system. Nevertheless, there are indeed benefits.

There is a large number of users worldwide who would see benefits of using GNSS products compared to GPS-only products. Clearly, all real-time users will benefit enormously from the increased number of satellites. **FIGURE 1**, showing the so-called position dilution of precision (PDOP), demonstrates this very clearly. The two panels in Figure 1 show the GPS-only PDOP and the GPS-plus-GLONASS PDOP using the satellite constellation of May 3, 2009. **FIGURE 2** shows the PDOP improvement in percentage when comparing the GPS-only to the GPS-plus-GLONASS PDOP values. At high latitudes, that is, above 55 degrees, the improvement is at the 30 percent level. At mid-latitudes, the improvements are still well above 15 percent, demonstrating the significant improvements real-time GNSS users may expect compared to real-time GPS-only users.

With the current GPS constellation, daily solutions are not limited by the number of available satellites, but rather by the analysis models (such as that for the troposphere), calibration uncertainties (such as models for antenna phase-center variation), and environmental effects (such as multipath). For these reasons, IGS-like processing strategies, in which data from reference stations are processed in 24-hour batches, will not show clear benefits from adding data from more satellites and other systems.

However, besides real-time users, users at high latitudes (including the whole of Canada and most of Europe) will see improvements. Recently, several researchers have noticed that for latitudes higher than 50 degrees, the addition of GLONASS brings benefit. This is, of course, thanks to the higher orbital inclination of the GLONASS satellites (about 64 degrees) compared to the inclination of the GPS satellites (about 55 degrees), which is also very nicely demonstrated in the PDOP (see Figure 1). So, from a service point of view — the "S" in IGS — there is a clear need to provide GNSS solutions to the user community. Besides offering significant benefits in terms of accuracy, the increased number of satellites will also make solutions more reliable and robust. The completely different repeat cycle of the GLONASS satellite orbits is especially important as it changes the sensitivity to multipath completely. Multipath effects in GPS-only data repeat almost perfectly from day to day with a 4-minute time shift giving rise to spurious, near yearly signals in GPS time series. Satellites from



▲ **FIGURE 1** Effect of GLONASS on position dilution of precision.

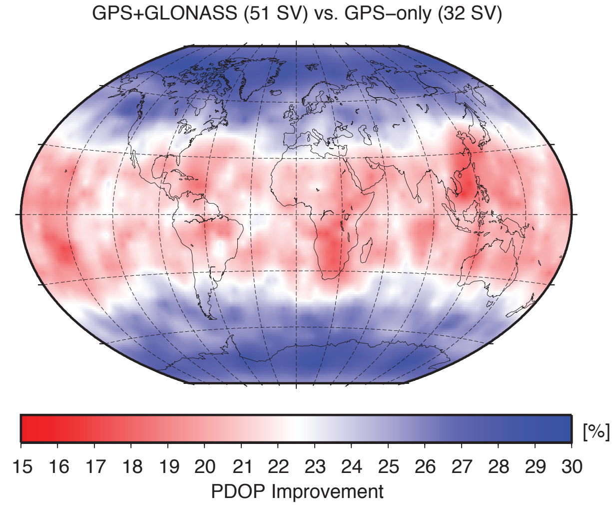
other constellations, such as GLONASS, introduce other system-related frequencies, which results in a general reduction of such GNSS-induced frequencies in a multi-GNSS solution.

Because of the constellation design, each GPS satellite follows its own ground track in each orbit cycle. That means that at a ground station, each GPS satellite is observed on one and the same track each day so that a systematic influence of a satellite (such as a mismodeling of the satellite antenna position with respect to the satellite's center of mass) has a systematic effect on the obtained (daily) station positions. This systematic translation of satellite-related errors into station-related parameters doesn't happen for any other GNSS constellation.

IGS GNSS Analysis Centers

A detailed description of the IGS is beyond the scope of this article; an excellent overview was provided in an earlier *Innovation* column (see Further Reading). We simply point out here that it is important to know that the IGS serves as *the* reference in many GNSS applications by providing data and products of the highest possible quality. Very well known and widely used are the tracking data from the IGS station network — the raw pseudorange and carrier-phase measurements — and the orbit and clock products of the GPS satellites. The IGS generates these products by combining the orbit and clock solutions of the individual analysis centers that contribute to the IGS. For the GPS-only products, 10 different analysis centers contribute to three different product series called the ultra-rapid, rapid, and final products. The final products deliver the highest possible quality but have the longest delay, as they become available 12 days after the end of the observation week. The rapid products are roughly comparable in quality to the IGS final products, but they are delivered daily with a delay of only 17 hours after the end of the observation day. The ultra-rapid products are delivered four times per day 3 hours after the end of the last used observation. For example, at 03:00 UTC, an ultra-rapid product is delivered that used data up to 00:00 UTC. It consists of two parts: an estimated part and a predicted part that may be used for real-time purposes. The quality of the estimated part is very similar to that of the rapid products. The predicted part is, of course, significantly less accurate, although the orbits have an astonishing precision of well below 30 millimeters — much better than that of the orbits in the satellites' broadcast navigation messages.

In addition to these GPS-only products, there is also a GLONASS product. However, contrary to the GPS side of things, for GLONASS, only a final product is generated. Four analysis centers provide products for the IGS GLONASS combination: the Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt am Main, Germany; CODE, based at the Astronomical Institute of the University of Bern, Switzerland; ESOC, Darmstadt, Germany; and the Information-Analytical Center (IAC) of Roscosmos, Moscow, Russia.



▲ **FIGURE 2** Position dilution of precision improvement using GLONASS.

The analysis centers BKG and IAC determine the GLONASS satellite orbits, introducing the information for the GPS satellites from the IGS solution without further estimation. The analysis center CODE provides, since May 2003, orbits for GPS and GLONASS based on a rigorously combined analysis of the data of both GNSS, that is, a true multi-GNSS solution. Since January 2008, ESOC follows this strategy as well. From these four analysis centers, only two, ESOC and IAC, provide satellite clock estimates for the GLONASS satellites. This situation prevents the IGS from making a robust and reliable combined GLONASS clock product. With four analysis centers contributing to the orbits, the IGS can and does make an excellent GLONASS combined orbit product.

In our definition of true multi-GNSS solutions, the measurements from each system contribute to all relevant parameters to the same extent. This can only be achieved by the rigorous combined processing of the data from all available GNSS. The two-step approach, introducing the GPS solution when solving for the GLONASS orbits and satellite clocks, is regarded as an extension of a GPS-only solution to GLONASS. As the contributions from BKG and IAC in the IGS GLONASS product demonstrate, this two-step procedure provides excellent results.

From a user point of view, a big disadvantage is the fact that the IGS does not provide a real GNSS product. The IGS provides a high-quality GPS product and a high-quality GLONASS orbit product, but there is no combined GNSS product. Also, the IGS is only capable of generating final GLONASS products because only two analysis centers, CODE and ESOC, submit GNSS products for the rapid and ultra–rapid products. IGS policy requires contributions from at least three analysis centers for a meaningful and robust combined product.

Users of GNSS orbits and/or clocks therefore have to use the products of one of the individual analysis centers or combine the GPS-only and GLONASS-only products from the IGS. Here, the GNSS products of the CODE and ESOC analysis centers are clearly preferable over those of the IGS and other analysis centers since these are the only two true GNSS products that guarantee the full consistency between the two GNSS.

GLONASS Tracking Network

Until 2003, the IGS had established a GLONASS tracking network of merely 20 stations. In 2003, this number grew rapidly from 20 to 30, but after 2003 the number of stations remained stable for quite a long time with a very inhomogeneous distribution. For example, there were only a few stations in the whole western hemisphere. In 2006/2007, a new generation of combined GPS/GLONASS receivers became available, produced by several well–known GPS receiver manufacturers. With this new equipment available, the number of GLONASS tracking stations in the IGS network started to increase steadily. In 2008, the increase rate went up significantly (see **FIGURE 3**) and, more importantly, the global distribution of the receivers improved as, finally, significant numbers of stations started to emerge in both North and South America. Orbits and clocks of the GLONASS satellites are, since early 2009, determined from the data of more than 100 globally well-distributed tracking stations in the IGS network (see **FIGURE 4**). A good global distribution of observing sites is extremely important for orbit determination and even more so for the clock determination. Until early in 2008, the GLONASS clock determination suffered from gaps in the global tracking network, which had severe impact on the clock estimates. If tracking gaps cause an interruption of the carrier-phase tracking of a GNSS satellite, the clock estimates are basically reset and a jump will occur. The size of the jump is delimited by the accuracy of the code (pseudorange) observations, that is, at the 1-meter level, or 3 nanoseconds in clock terms.

We may state that today orbit and clock determination for the GLONASS satellites may be based on a truly global tracking network of high-quality geodetic–type receivers. This significant improvement is due to the efforts of many IGS station managers and their institutions.

GLONASS Constellation

After reaching a full orbit constellation of 24 satellites in early 1996, the GLONASS constellation degraded rapidly due to Russia's economic difficulties following the break-up of the Soviet Union coupled with the short lifetime of the GLONASS satellites. Since 2002, the GLONASS constellation has slowly but surely been rebuilt (see **FIGURE 5**). Currently, there are 21 active modernized GLONASS (GLONASS-M) satellites, which have a significantly longer lifespan compared to the original satellites. Additionally, there are two reserve satellites on orbit.

Russia intends to have a full 24-satellite constellation in place by the end of 2010. To achieve this goal, two more triple-satellite launches are planned, one in August and one in November. The November launch could include a new type of GLONASS satellite, GLONASS-K. The GLONASS-K version is a lighter, unpressurized spacecraft, with a design lifetime of 10 years. In addition to the legacy frequency-division-multiple-access signals, it will transmit code-division-multiple-access signals and use an additional frequency band overlapping with the GPS L5 band.

Orbit and Clock Accuracy

The developments of both the GLONASS tracking capabilities of the IGS station network as well as the steady increase in the number of GLONASS satellites has had a positive influence on the accuracy of the GLONASS orbits and clocks. It also has significantly increased the interest in the GLONASS system. The enhancement of the IGS GNSS tracking network from an almost purely European network to a truly global network between 2008 and now has had a significant impact on the quality of the GLONASS orbits and clocks. To show the effect on the quality of the GLONASS orbit estimates, we look at the difference between two independent consecutive solutions spanning 24 hours from 0 to 24 hours GPS Time. We compare the "midnight point" of both solutions, that is, the solution at the end of one day (or arc) and the beginning of the next day (or arc). This will give us a worst-case estimate for the orbit quality because typically the orbit is less accurate at the boundary of the orbital arc compared to the middle of the orbital arc. We have analyzed these orbit differences for all GPS and GLONASS satellites separately for four half-year time spans using the routine IGS GNSS solutions from ESOC. The differences are computed in three different satellite-orbit-related directions: radial, along-track, and cross-track. The times spans are:

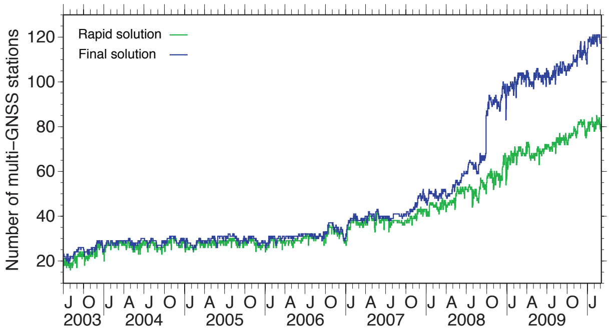
- January to June 2008 (6 months)
- July to December 2008 (6 months)
- January to June 2009 (6 months)
- July to December 2009 (6 months)

The results are shown in **FIGURE 6**. For the GPS satellites, we cannot see any improvement over time. The quality of the GPS orbits is excellent at the 25- to 35-millimeter level for all three components.

Remember, we are looking at the worst-case differences here. For GLONASS, we can see a significant improvement over the four time spans. Early in 2008, the orbit quality was at the 120-millimeter level (cross-track), which has improved significantly to the 85-millimeter level. It is important to note that no processing changes were made during this time interval, and that the improvements are thanks to the improvements in the station tracking network and the GLONASS satellite constellation.

The clock quality is more difficult to assess, but over the timeframe of 2008 to 2009 we have noticed that the clock estimates of the GLONASS satellites have become complete. In 2008, with the still-far-from-global tracking network, there were many gaps in the tracking of the GLONASS satellites. This means that at some epochs no stations were tracking a GLONASS satellite. Such gaps cause jumps in the satellite clock estimates, because the carrier-phase observations become discontinuous, and these jumps are at the 1-meter (3-nanosecond) level. With the improvements of the IGS GNSS tracking network, the GLONASS tracking is now complete and clocks for all epochs are estimated. A comparison of the clocks of the two analysis centers that provide estimated clocks for the GLONASS satellites shows an agreement at the 80-picosecond level, which is only slightly worse than the agreement between the GPS clocks. Significant biases at the few-hundred-nanosecond level exist only in the GLONASS clocks because of receiver internal frequency-dependent delays. The ESOC GNSS orbit and clock products are, however, perfectly suited for precise point positioning using either GPS, GLONASS or, even better, both GNSS simultaneously. It should be noted that since February 2010, the ESOC IGS clock products are now sampled at 30 rather than 300 seconds, which further enhances their suitability.

Conclusions and Outlook

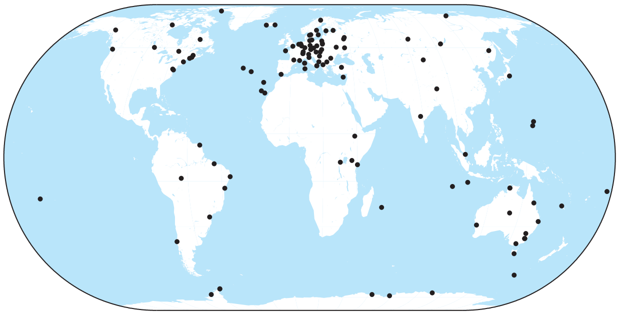


▲ **FIGURE 3** Number of sites in the IGS network providing GLONASS data, used for orbit determination at CODE.

The IGS has promised to become a GNSS service by changing its name in 2005, more than four years ago. Meanwhile, the GLONASS satellite constellation as well as the IGS GNSS tracking network have matured and are practically complete. For the IGS to become a true GNSS service, a substantial number of the analysis centers should provide GNSS contributions to all IGS products: final, rapid, ultra-rapid, and real-time. These products should come from performing a rigorous combined analysis of the observations of all active GNSS satellites. It is expected that over the next two years, we will see a significant increase in the number of true GNSS solutions within the IGS, a very positive development for the GNSS world.

Within the IGS, the analysis centers CODE and ESOC are leading the GNSS efforts. CODE has provided fully consistent GPS/GLONASS products from a rigorously combined processing approach for all IGS products (final, rapid, and ultra-rapid) since May 2003, or for seven years. Since the beginning of 2008, ESOC has followed this good practice for its final products, and in February 2010 ESOC started to produce rapid and ultra-rapid GNSS products. A unique feature of the ESOC products is that they include the clocks for the GLONASS satellites, even with a sampling rate of 30 seconds for the final products. CODE will add GLONASS clocks to its IGS products very soon, during the first half of 2010. The GLONASS orbit and clock product quality has become comparable to that of the GPS products within the IGS. However, because GLONASS carrier-phase integer ambiguity resolution is difficult, the GLONASS products are and will remain somewhat less accurate than the GPS products.

The experiences gathered at CODE and ESOC by fully combining the observations from the GPS and GLONASS systems will pave the way for the integration of additional systems and signals within the IGS. Hence, IGS will retain its leading position in providing *the* reference, in the broadest sense of the word, for all GNSS. In the near future, this means the integration of QZSS and Galileo observations as well as the integration of the new triple-frequency signals from the latest generation of GPS satellites, Block IIF, the first of which was scheduled for launch last month.

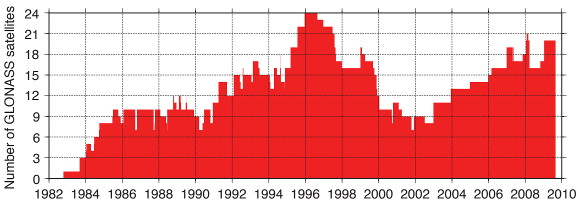


▲ **FIGURE 4** Current distribution of IGS combined GPS and GLONASS tracking stations.

The positive GNSS developments within the IGS will require an update of the IGS combination software to enable a true GNSS combination. The CODE and ESOC analysis centers have indicated that they are interested in taking on this important task of rewriting and enhancing the IGS orbit and clock combination software to make the IGS a true GNSS service.

Acknowledgments

CODE is a collaboration among the Astronomical Institute,

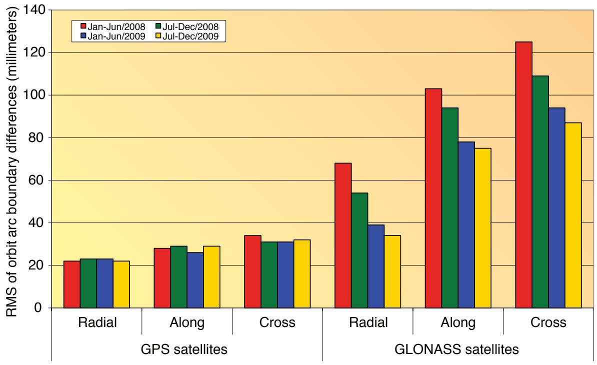


▲ **FIGURE 5** Development of the GLONASS satellite constellation since 1982.

University of Bern (Bern, Switzerland), the Swiss Federal Office for Topography (Wabern, Switzerland), the Bundesamt für Kartographie und Geodäsie (Frankfurt am Main, Germany), and the Institut für Astronomische und Physikalische Geodäsie of the Technische Universität München (Munich, Germany).

The authors are very grateful to the IGS and its numerous contributors for providing the global GNSS tracking data network.

TIM SPRINGER received his Ph.D. in physics from the Astronomical Institute of the University of Bern (AIUB) in 1999. He has been a key person in the development of the Center for Orbit Determination in Europe (CODE), one of the IGS analysis centers, located at AIUB. Since 2004, he has been working for the Navigation Support Office (OPS-GN) at the European Space Operations Centre (ESOC) of the European Space Agency (ESA) in Darmstadt, Germany. In this group, he has led the development of the new ESOC GNSS software, which is used for most GNSS activities at OPS-GN, including GIOVE-A and -B analyses.



▲ **FIGURE 6** Evolution of GPS and GLONASS orbit quality from January 2008 to December 2009.

ROLF DACH received his Ph.D. in geodesy at the Institut für Planetare Geodäsie of the University of Technology in Dresden, Germany. Since 1999, he has been working as a scientist at AIUB, where he is head of the GNSS research group. He oversees the development of the Bernese GPS Software, used at CODE for activities in the frame of the AIUB IGS analysis center and elsewhere.

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GPS WORLD (ISSN 1048-5104) is published monthly (12 issues/yr) by Questex Media Group LLC, 306 W Michigan St, Ste 200, Duluth, MN 55802. **SUBSCRIPTION RATES:** U.S. and possessions — 1 year (12 issues), $73.70; 2 years (24 issues), $128.70. Canada and Mexico — $95.70, 1 year; $150.70, 2 years. All other countries — $139.70, 1 year; $255.20, 2 years. International pricing includes air-expedited service. Single copies (prepaid only): $7 in the United States, $9 all other countries. Back issues, if available, are $19 in the U.S. and possessions, $23 all other countries. Include $6.50 per order plus $2 per additional copy for U.S. postage and handling. Periodicals postage paid at Duluth, MN 55806, and additional mailing offices. **POSTMASTER:** Please send address changes to ***GPS WORLD***, P.O. Box 1270, Skokie, IL 60076-8270, USA. Canadian G.S.T. number: 840 033 278 RT0001, Publications Mail Agreement Number 40017597. Printed in the U.S.A.