The International GNSS Service
Any Questions?

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COLLABORATION IS CONSIDERED by many to be an inherent aspect of human society. It is through collaboration that society advances in different ways. In particular, progress in science depends on individuals and organizations collaborating with each other to develop theories, to test those theories using experimental data, to revise and enhance the theories on the basis of data analyses, and to test again.

Looking on Wikipedia, we find the following traits necessary for successful collaboration: "shared objectives; sense of urgency and commitment; dynamic process; sense of belonging; open communication; mutual trust and respect; complementary, diverse skills and knowledge; intellectual agility." These words fittingly describe the International GNSS Service (IGS) and how it operates.

INNOVATION INSIGHTS
with Richard Langley

The IGS is a model of scientific collaboration.

The IGS was established in 1994 in order to provide the highest quality GNSS data and products in support of Earth science research, multidisciplinary applications, and education. It was and is still the aim of the IGS to advance scientific understanding of the Earth system components and their interactions, as well as to facilitate other applications benefiting society.

The IGS consists of over 200 actively contributing organizations in more than 80 countries and a global network of over 370 stations. In addition to providing GPS and GLONASS raw measurements, the IGS contributes to the maintenance and improvement of the International Terrestrial Reference Frame, produces high accuracy GPS and GLONASS satellite orbit and clock data, and monitors the Earth's rotation and the state of its ionized and neutral atmospheres. Among other applications, IGS measurements and products help monitor the movement and flexure of the Earth's tectonic plates, assess sea-level variations, carry out precise time transfer, and determine accurate trajectories for low-Earth orbiting satellites.

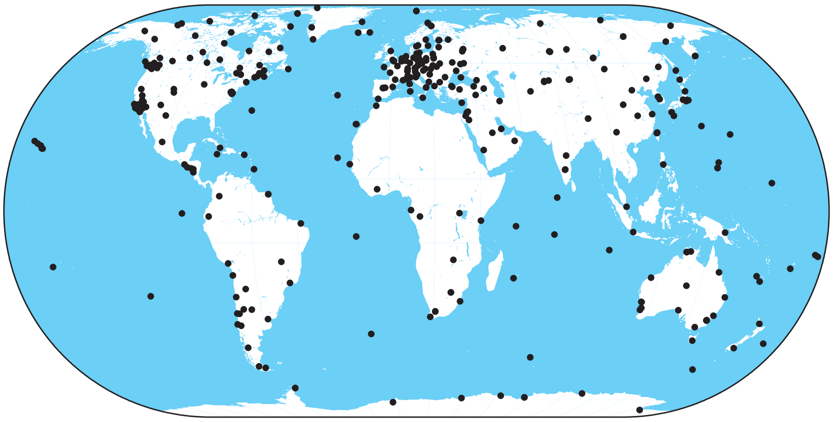
In this month's column, Angelyn Moore, the IGS Central Bureau's deputy director, overviews the organization's service, history, and future, demonstrating that the IGS is a model of scientific collaboration of which not just the GNSS community but the whole world should be proud.

"Innovation" is a regular column that features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 10.

Readers of *GPS World* likely are familiar with the International Global Navigation Satellite Systems (GNSS) Service (IGS), if only from the frequent mention within these pages, but we find that people often harbor questions that they've "always wondered about." This article briefly reviews the history and organization of the IGS before turning its attention to questions that readers might have and highlighting a few active topics in the IGS today.

The IGS currently is based on a global network of 379 permanent, continuously operating, geodetic-quality GPS and GLONASS tracking stations operated by more than 100 agencies worldwide (**FIGURE 1**). The station data are archived at four global data centers and six regional data centers. Ten analysis centers regularly and independently process the data and contribute the results to product coordinators, who combine individual analysis-center submissions into the official IGS products. The product suite today includes GNSS satellite ephemerides, satellite and station clock solutions, the IGS time scale, station positions, Earth rotation parameters, and ionospheric and tropospheric parameters. The Central Bureau, hosted by the Jet Propulsion Laboratory, is responsible for day-to-day management following policies set by the IGS International Governing Board. The current suites of data and product offerings are summarized in **TABLES 1 AND 2**.

The IGS grew out of the experiences of agencies that performed early evaluations of geodetic use of GPS in the 1980s. A typical station featuring a Texas Instruments TI 4100 (one of the first dual-frequency geodetic-quality GPS receivers) cost approximately $100,000, motivating resource pooling among geodetic agencies, research organizations, and universities; and logis-



▲ **FIGURE 1** The IGS network of tracking stations

TABLE 1 IGS Data Types

	Latency	Updates	Sample Interval
Ground observations			
GPS & GLONASS	~1 day	Daily	30 seconds
	~ 1 hour	Hourly	30 seconds
	~15 min	15 min	1 second
GPS Broadcast Ephemerides	~1 day	Daily	N/A
	~1 hour	Hourly	
	~15 min	15 min	
GLONASS Broadcast Ephemerides	~1 day	Daily	N/A
Meteorological	~1 day	Daily	5 minutes
	~1 hour	Hourly	5 minutes
Low-Earth Orbiter observations			
GPS	~4 days	Daily	10 seconds

tical aspects of organizing a GPS observation campaign on a continental scale also benefited from communication and cooperation among the countries involved.

By 1991, 70 agencies were collaborating to put together a defined-duration dataset that would yield the first GPS solutions to be used in a realization of the International Terrestrial Reference Frame (ITRF91). The International Association of Geodesy (IAG), realizing that an enduring global civilian reference network would be required for the increasing use of GPS in geodesy and geodynamics, formed a planning committee to study the formation of such a system by cooperatively leveraging many individual agencies' resources. A demonstration including stations, data distribution, archiving, analysis, and management was carried out in 1992 with a 42-station network that was reasonably well distributed around the globe, but quite sparse by today's standards. The activity continued following the demonstration period, and the IAG officially established the International GPS Service for Geodynamics in 1994.

The first decade of official IGS operation saw the price of equipment drop dramatically, enabling the network to grow to today's 379 stations, but the efficiency in collaboration remains. A culture of friendly competition among participating agencies encourages continuing improvement in all areas (**FIGURE 2**). The latency or delay in availability of the IGS GPS Final Orbits product progressed from 2 months to 15 days, then 11 days, and the Rapid Orbits (slightly less accurate but available more quickly) improved from 38 hours latency to 24 hours. Predicted orbits were initiated in 1997 and are now included in the Ultra-rapid Orbit, which is half "observed" and half predicted, and released four times per day.

Pilot projects and working groups are formed as appropriate to develop current and future products. New analysis centers and data centers have joined in the past few years, indicating continuing interest in the IGS' activities. Geodynamics was dropped from the organization's name in the late 1990s, reflecting the wider use of its products, and in 2005, the IGS Governing Board changed the organization's name to the International GNSS Service, in view of the successful integration of GLONASS and interest in future GNSS. The IGS holds regular governing board meetings, workshops, and strategic planning sessions to verify and improve the IGS' performance. Investigators all over the world benefit from the IGS infrastructure when they use IGS data and precise products.

The IGS is active in the global geodetic and GNSS communities, and participates in the International Committee on Global Navigation Satellite Systems (ICG), established by the United Nations in December 2005, adopting terms of reference and a work plan that had been developed at international meetings since 2002. The ICG's work plan includes compatibility and interoperability, enhancement of the performance of GNSS services, information dissemination, interaction with national and regional authorities and international organizations, and coordination.

Just Wondering

This section anticipates questions that *GPS World* readers might have. For more information, the IGS maintains a complete Frequently Asked Questions (FAQ) document on its website (see Further Reading).

What is the IGS? The IGS is a voluntary federation of many worldwide agencies that pool resources and permanent GNSS station data to generate precise (and accurate) GNSS products. In general, you can think of the IGS as the highest precision international civilian GPS community.

How is the IGS funded? Each participating organization voluntarily brings its own funding according to its own mission. These organizations tend to be public or government institutions or other research organizations (including universities). Con-

TABLE 2 The Suite of IGS Products. The orbits (ephemerides) and clocks broadcast by the GPS satellites are included for comparison. Note: mas = milli-arcseconds; TECU = total electron content units.

		Accuracy	Latency	Updates	Sample Interval
GPS Satellite Ephemerides/ Satellite & Station Clocks					
Broadcast	Orbits	~160 cm	Real time	--	Daily
	Satellite clocks	~7 ns			
Ultra-Rapid (predicted half)	Orbits	~10 cm	Real time	4 times daily	15 min
	Satellite clocks	~5 ns			
Ultra-Rapid (observed half)	Orbits	<5 cm	3 hours	4 times daily	15 min
	Satellite clocks	~0.2 ns			
Rapid	Orbits	<5 cm	17 hours	Daily	15 min
	Satellite & station clocks	0.1 ns			5 min
Final	Orbits	<5 cm	~13 days	Weekly	15 min
	Satellite & station clocks	0.1 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 time scale, which is linearly aligned to GPS Time in one-day segments.					
GLONASS Satellite Ephemerides					
Final		15 cm	2 weeks	Weekly	15 min
Geocentric coordinates of IGS tracking stations (>130 sites)					
Final positions	Horizontal	3 mm	12 days	Weekly	Weekly
	Vertical	6 mm			
Final velocities	Horizontal	2 mm/yr	12 days	Weekly	Weekly
	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	4 times daily	4 times daily
	PM rate	0.5 mas/day			
	LOD	0.06 ms			
Ultra-Rapid (observed half)	PM	0.1 mas	3 hours	4 times daily	4 times daily
	PM rate	0.3 mas/day			
	LOD	0.03 ms			
Rapid	PM	<0.1 mas	17 hours	Daily	Daily
	PM rate	<0.2 mas/day			
	LOD	0.03 ms			
Final	PM	0.05 mas	~13 days	Weekly	Daily
	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
Ultra-rapid tropospheric zenith path delay		6 mm	2-3 hours	Every 3 hours	1 hour
Final ionospheric TEC grid		2-8 TECU	~11 days	Weekly	2 hours; 5 deg (lon) x 2.5 deg (lat)
Rapid ionospheric TEC grid		2-9 TECU	<24 hours	Weekly	2 hours; 5 deg (lon) x 2.5 deg (lat)

sequently, the IGS requires redundancy or multi-year commitments from important components to ensure reliability.

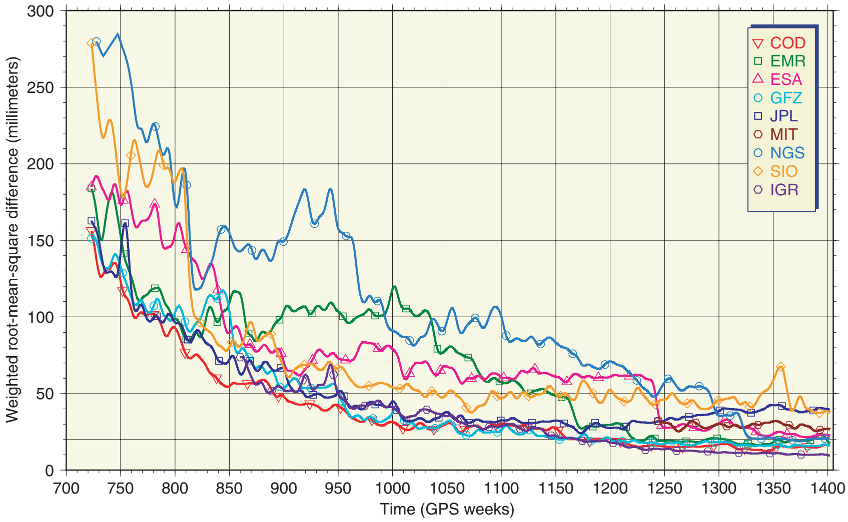
Are there costs or restrictions in using IGS data or products? The IGS has an open data policy. All of the present suites of products are available without charge from the IGS data centers. Although the IGS strives for the highest quality of data and data products, it cannot make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information or product. Use of the IGS data and products is the sole responsibility of the user.

By the way, when your use of IGS data or products results in a publication, please include a citation. We suggest:

J.M. Dow, R.E. Neilan, G. Gendt, "The International GPS Service (IGS): Celebrating the 10th Anniversary and Looking to the Next Decade," *Adv. Space Res.*, vol. 36, no. 3, pp. 320-326, 2005. doi:10.1016/j.asr.2005.05.125

What is an IGS station? An IGS station conforms to the IGS Site Guidelines, which are found on the IGS website, and it is noted on IGS network maps and lists.

What is the relation of the IGS network to regional networks? Networks such as EUREF, SCIGN, and NGS CORS are dense regional networks composed of



▲ **FIGURE 2** The consistency of the individual analysis centers' satellite orbit solutions has improved over the years to approximately 2 centimeters today. Each trace shows one analysis center as compared to the weighted mean. Graph courtesy G. Gendt, GFZ.

stations that in most cases meet the IGS Site Guidelines. They are considered to be related networks and the IGS works closely with the agencies that operate them. Typically, a subset of a regional network's stations is designated also as IGS stations. The choice of which stations should also be IGS stations is motivated by their benefit to the generation of IGS products, according to geographic location and type of instrumentation. Think of the IGS as the global grid that links the denser regional networks.

May I propose a new IGS station? If it is expected to be beneficial to an IGS product or project, please do. See the IGS new station checklist on the IGS Central Bureau website. Please bear in mind that the IGS has a global focus and limits new additions to those that have a definite benefit to the IGS' global activities. Stations in areas that are well represented and similar to others in the area should instead seek to join the appropriate regional network.

What equipment is acceptable for use in the IGS? Both the receiver and its antenna must have certain characteristics. The receiver must

- track both code and phase on the L1 and L2 frequencies under non-AS [anti-spoofing, meaning encrypted P-code, or P(Y)] as well as AS conditions. Required observables are L1 and L2 (the symbols used by the IGS to denote the carrier-phase observable on L1 and L2 respectively), P2 (P(Y) pseudorange measurement on L2), and at least one of C1 (C/A-code measurement on L1) or P1 (P(Y) pseudorange measurement on L1). Equipment capable of reporting both C1 and L1 should do so
- be capable of, and set to, record data from at least eight satellites in view, simultaneously
- track with a sampling interval of 30 seconds or smaller
- be set to record data down to an elevation angle cutoff of 10 degrees or less
- synchronize the actual instant of observation with true GPS (System) Time to within +/- 1 millisecond of the full second epoch.

The antenna must

- be represented accurately in the IGS phase-center variation file. If it is not, contact the IGS Central Bureau. A calibration from an independent, recognized laboratory will be required
- be leveled and oriented to true (astronomical) north using the north reference mark and/or antenna RF connector
- be rigidly attached, such that there is not more than 0.1 millimeter motion with respect to the antenna mounting point.

These are only the minimal requirements on receivers and antennas. Please refer to the IGS Site Guidelines document for further characteristics and ancillary equipment that add significant value to a station's dataset.

Avoid using radomes over antennas unless required operationally, for instance, due to weather conditions, antenna security, or wildlife concerns. Current best practice in geodetic monumentation is considered to be the drilled-braced monument type. A variety of other monuments are currently present in the IGS. Whether any particular station is suitable for the IGS is based on many factors, including location, monumentation, and instrumentation. Agencies planning station installation can contact the IGS Central Bureau to be connected with more information on monument types and considerations (for an example, see the photo on page 62).

Does the IGS endorse equipment? No, the IGS maintains vendor neutrality and instead publishes functional requirements.

Does the IGS certify equipment as meeting the guidelines? We do not issue certifications, but we can ask an IGS analyst to examine sample data sets from new equipment types and comment.

What standards apply to reference frame stations? The position time series of the specially designated reference frame stations must be kept particularly free of discontinuities. This leads to special practices for reference frame sites, discussed in detail in the IGS Site Guidelines. In summary, reference frame sites are strongly discouraged from disturbing or changing equipment unless absolutely necessary. Antenna relocations are especially disruptive and, if unavoidable, require prior announcement and overlapping datasets at the old and new monuments. Surveys between the marker and the GPS antenna, and other co-located space geodetic instruments, are critical and must be periodically verified.

What kind of support from equipment manufacturers do IGS users expect? IGS data is archived permanently and used in long-term studies. Therefore, questions arise about receiver and antenna models that are no longer current, so it is helpful to have familiarity with historical products. We need to know how various models differ from each other.

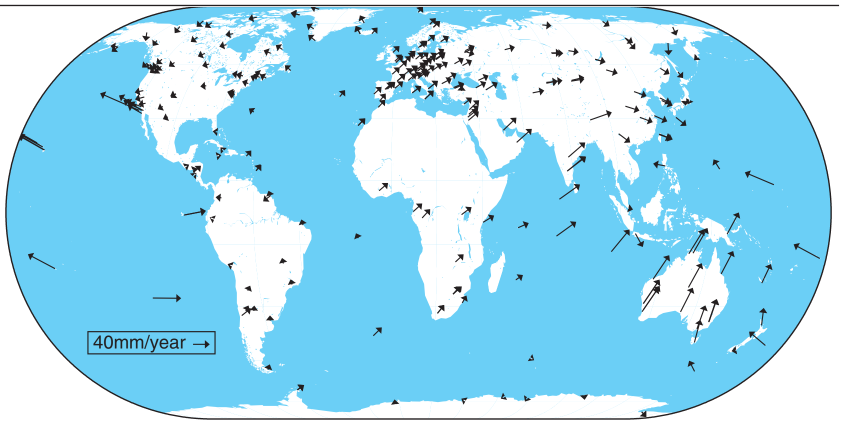

Photo courtesy of F. B. Madsen, Danish National Space Center.

▲ **THE TAPER OF** this pillar monument in Thule, Greenland, results in a top surface of smaller diameter than the antenna, which is recommended for pillar monuments.

It is also necessary for the IGS to establish which observables are directly tracked by each receiver type. We can determine this from data, but appreciate information from the manufacturer as well.

What should equipment manufacturers keep in mind in product-planning stages? Please read over the IGS Site Guidelines and take note of things such as the necessary antenna calibration, and requested settings such as recording data from satellites marked unhealthy.

In view of new constellations and signals, the IGS is forming a group to study and recommend which signals IGS stations should track. The typical IGS position to date has been for stations to track all available signals, but we recognize that continuing this policy with the growing number of GNSS could result in equipment that has higher expense and power requirements than would be reasonable for all stations. The IGS might designate minimum, desirable, and optimum sets of signals. If you are uncertain whether the IGS has the proper contact information for your company, contact the IGS Central Bureau.



▲ **FIGURE 3** Calculated velocities of IGS stations from a recent weekly update of the IGS cumulative reference frame product. The velocities reflect the movement and deformation of the Earth's tectonic plates.

IGS Activity Areas

The IGS supports several projects to enhance the benefits of GNSS data and products.

Contribution of the IGS to Reference Frame Determination. A terrestrial reference frame is an accurate, stable set of positions and velocities providing a coordinate system that allows measurements to be linked over space, time, and varying measurement techniques (**FIGURE 3**). The International Terrestrial Reference System Product Centre of the International Earth Rotation and Reference Systems Service (IERS) realizes the ITRF using coordinate solutions from a number of geodetic networks. The IGS station time series are now an integral part of each ITRF realization, and the IGS' network density provides access to the ITRF through the many stations whose coordinates are published in the IGS component of the ITRF. As mentioned above, a subset of IGS stations designated as reference frame stations has special requirements to ensure the stability of the reference frame. Station co-locations with other geodetic techniques that contribute to the ITRF (such as very long baseline interferometry, satellite laser ranging, and Doppler Orbitography and Radiopositioning Integrated by Satellite or DORIS) are increasingly important in determining measurement biases and developing observation-level multitechnique analysis.

GNSS. The IGS' first use of GNSS other than GPS was demonstrated in the International GLONASS Experiment of 1998-1999. A pilot project achieved full integration of GLONASS dataflow with GPS operations in 2004, and four analysis centers currently generate GLONASS satellite ephemerides resulting in a combined orbit product precise to about 15 centimeters. This demonstrates the IGS' interest and ability to incorporate other GNSS. The IGS GNSS working group is tasked with establishing information exchange between the system operators of various GNSS, and preparing for upcoming new signals and activities.

Low-Latency/Real Time. IGS station data was offered only in daily files of 30-second sampled data until a few station operating agencies started to offer hourly files in 1998, which enabled the first subdaily orbit products. The hourly subnetwork now contains more than 200 stations and offers reasonable global distribution. Another low-latency subnetwork was initiated in 2001 to collect files of 1-second sampled data every 15 minutes for the Low-Earth Orbiter Pilot Project, but the data has been used more generally, including recently to study seismic surface waves and co-seismic displacements. The IGS also has a real-time working group to study the cooperative exchange of streamed 1-second data, which has resulted in a demonstration of a real-time quality monitor for the IGS Ultra-rapid Orbits.

Summary

The IGS is an international, voluntary collaboration that self-organized to cooperatively manage a global reference network of dual-frequency GPS and GLONASS stations. IGS data and IGS products generated from the datasets are openly available with a variety of latencies. The IGS is active in improving its function and organization, and interfaces with higher level geodetic and GNSS bodies. Much more information about the IGS organization and activities is available at the IGS website, *http://igscb.jpl.nasa.gov.*

Acknowledgments

This article describes the result of the diligent efforts of the many agencies and individuals worldwide that participate in the IGS. The author's part of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration. Maps were created using Generic Mapping Tools (GMT) software. ⊕

ANGELYN MOORE is the network coordinator and deputy director of the International GNSS Service's Central Bureau at the Jet Propulsion Laboratory, California Institute of Technology. Prior positions at JPL include the GPS Networks and Ionospheric Systems Development group (1995-1998) and the Time and Frequency Standards Research and Development group (1988-1995). She holds a B.S. in physics from Harvey Mudd College, an M.S in physics from California State University, Los Angeles, and a Ph.D. in physics from the University of California, Riverside.

FURTHER READING

■ International GNSS Service

IGS Central Bureau website. IGS FAQ, Site Guidelines, data and product access information, and network details are available: http://igscb.jpl.nasa.gov

"The International GPS Service (IGS): Celebrating the 10th Anniversary and Looking to the Next Decade" by J.M. Dow, R.E. Neilan, and G. Gendt in *Advances in Space Research*, Vol. 36, No. 3, pp. 320-326, doi:10.1016/j.asr.2005.05.125, 2005.

Celebrating a Decade of the International GPS Service. Proceedings of IGS Workshop and Symposium 2004, held in Berne, Switzerland, March 1-5, 2004. Edited by M. Meindl. This publication and other workshop proceedings and annual reports are available in electronic format on the IGS Central Bureau website.

■ United Nations International Committee on Global Navigation Satellite Systems

http://www.unoosa.org/oosa/SAP/gnss/icg.html

■ Reference Frames

"IGS Reference Frames: Status and Future Developments" by J. Ray, D. Dong, and Z. Altamimi in *GPS Solutions*, Vol. 8, No. 4, December 2004, pp. 251-266, doi:10.1007/s10291-004-0110-x.

"International Terrestrial Reference Frame" by C. Boucher and Z. Altamimi in *GPS World*, Vol. 7, No. 9, September 1996, pp. 71-74.

International Earth Rotation and Reference Systems Service (IERS) website: *http://www.iers.org*

■ IGS Time Scale

"New IGS Clock Products: A Global Time Transfer Assessment" by J. Ray and K. Senior in *GPS World*, Vol. 13, No. 11, November 2002, pp. 45-51.

■ Sample Scientific Studies Using IGS Data

"Rapid Determination of Earthquake Magnitude Using GPS for Tsunami Warning Systems" by G. Blewitt, C. Kreemer, W.C. Hammond, H.-P. Plag, S. Stein, and E, Okal in *Geophysical Research Letters*, Vol. 33, L11309, doi:10.1029/2006GL026145, 2006.

"Modified Sidereal Filtering: Implications for High-rate GPS Positioning" by K. Choi, A. Bilich, K.M. Larson, and P. Axelrad in *Geophysical Research Letters*, Vol. 31, L22608, doi:10.1029/2004GL021621, 2004.

"Detection of Arbitrarily Large Dynamic Ground Motions with a Dense High-rate GPS Network" by Y. Bock, L. Prawirodirdjo, and T.I. Melbourne in *Geophysical Research Letters*, Vol. 31, L06604, doi:10.1029/2003GL019150, 2004.