Toward Broadband Exploration of Tectonic-Magmatic Interactions: **Demonstration of Self-Consistent, "All-in-One" Rapid Analysis of GPS Mega-Networks using the Ambizap Algorithm.**

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INTRODUCTION

In recent years, transients have been detected in GPS networks reflecting rheological responses to the history of stress changes in the so-called "solid Earth" over a broad spatio-temporal spectrum. Although rheological responses can be modeled as linear, independent processes, connections between different spatio-temporal scales are possible due to common forcing factors, such as earthquakes and magmatic events, and due to feedback between such processes and the resulting changes in stress. Transients in geodetic data over different scales have recently suggested a link between deep crustal magmatism [*Smith et al.*, 2004] (Figure 1) and the spatio-temporal pattern of strain spanning the extensional plate boundary of the Great Basin, USA [*Davis et al.*, 2006].

As a measurement technique to explore such interactions, geodesy is ideally suited to connect the spectral gulf between seismology and geology. Toward "broadband exploration" of tectonic-magmatic interactions, it is essential to develop a GPS analysis scheme that is self-consistent over all spatio-temporal scales of interest. For this purpose we have developed an "all-in-one" approach to the analysis of GPS mega-networks. This new capability "Ambizap" can in principle be used to reduce all the world's geodetic GPS data to a unique solution, with potential temporal resolutions of 0.01-10 years, and spatial resolutions of 1-10,000 km.

A major hurdle to GPS network analysis in the past has been the problem that computation time goes as the number of stations to the power 4 (Figure 2). This arises from the estimation and resolution of the integer ambiguities in the double-difference carrier phase measurements [*Blewitt*, 1989], more specifically, the "bootstrapping" algorithm. *Zumberge et al.* [1997] proposed the revolutionary precise point positioning (PPP) technique, which scales linearly with number of stations but only in the case that integer ambiguities are not resolved. Here we adopt an approach that augments PPP with ambiguity resolution, but gives up bootstrapping in favor of including data from as many GPS stations as possible to ensure successful ambiguity resolution. The Ambizap algorithm has a processing time that scales linearly with the number of stations, and gives statistically the same positioning results (<< 1 mm) than when using the full network approach (Figure 3).

THE AMBIZAP ALGORITHM

A well-known property of ambiguity resolution is that the sum of integer ambiguities associated with two sides of a triangular (3-station) network equals the integer ambiguity for the third side (for observations to the same pair of satellites). More generally, the ambiguity resolution of any linearly independent set of N-1 baselines is sufficient to completely solve the problem. This property leads to the conclusion that the estimated vector between a pair of stations is insensitive to data from the rest of the network. Thus the entire solution can be constructed from the analysis of N-1 station pairs, which implies an ambiguity-resolved solution that scales linearly with N.

"Linear independence" requires that no selected baseline vector can be constructed by the sum of any other selected vector. Each station is connected to the network by at least one baseline, and can be connected a maximum of N-1 times (the "hub and spoke" limit). Thus care must be taken not to count PPP data twice for stations that are used in more than one baseline.

The Ambizap algorithm was designed and implemented to satisfy the properties of (1) linear independence of data, (2) insensitivity of ambiguity-resolved baselines to data from the rest of the network, (3) reduction to the original PPP solution for stations that cannot be connected to the network by ambiguity resolution, and (4) not counting data twice. The N-1 baselines are chosen to minimize the baseline distance at each step in the selection, so as to maximize the probability of success at each step in resolving the integer ambiguities. No "bootstrapping" is performed (accounting for ambizap's exceptional speed) except within the set of ambiguities associated with each baseline. For this reason, tests show that ambizap works best if nearest neighbor distances are < 500 km. Since ambizap is intended to be applied to GPS networks with hundreds (or more) stations, this is not a serious practical limitation.

Tests show that a 98 station network is resolved on 1 cpu in 7 minutes versus the 22 hours it takes using the current GIPSY-OASIS II method – nearly a factor of 200 improvement in speed. The resulting station coordinates agree to 0.8 mm RMS, smaller than the daily repeatability (approx 3 mm for PPP), and so are "near-optimal." A block-diagonal covariance is also produced which closely approximates the rigorously formal variances of station and baseline coordinates, suitable for subsequent strain analysis.

In addition to reducing processing time, linear schemes readily lend themselves to parallel processor implementation. Thus real processing time can be reduced by several of orders of magnitude for extremely large networks. For example, on our 40 cpu cluster, the above 98 station network can be resolved in ~15 seconds, a factor ~5000 faster than the standard approach. Ambizap allows for very rapid, multiple reanalysis of extremely large networks, and makes trivial the addition of extra stations or subnetworks to an existing solution.

Application of Ambizap greatly improves the analysis of crustal movement in regions such as the western North America (Figure 4), which have dense overlapping GPS networks. For example, a network solution from one day of the ~1000 station Plate Boundary Observatory can be produced in about 7 min on a 40-cpu cluster (4.5 min PPP + 2.5 min Ambizap).

A future development (in collaboration with JPL) is to integrate the algorithm into global network processing such that the station coordinate solution will benefit from the improved orbits, clocks, Earth rotation, and geocenter resulting from ambiguity resolution.

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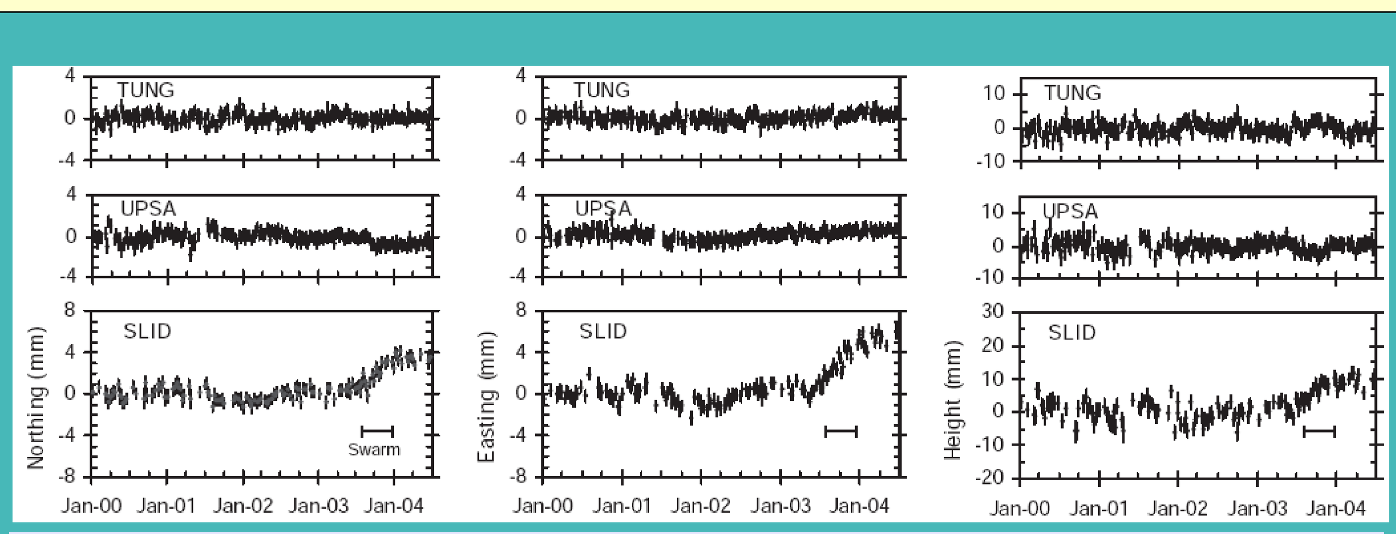


Figure 1: Transient observed at GPS station SLID (as compared to regional stations) caused by a deep-crustal intrusion of magma, in a non-volcanic area [*Smith et al.*, 2004]. To detect such ~mm-scale transients is is critical to perform carrier phase ambiguity resolution, which can be prohibitively costly for large networks, and so leading to inconsistency between regional and global-scale network solutions.

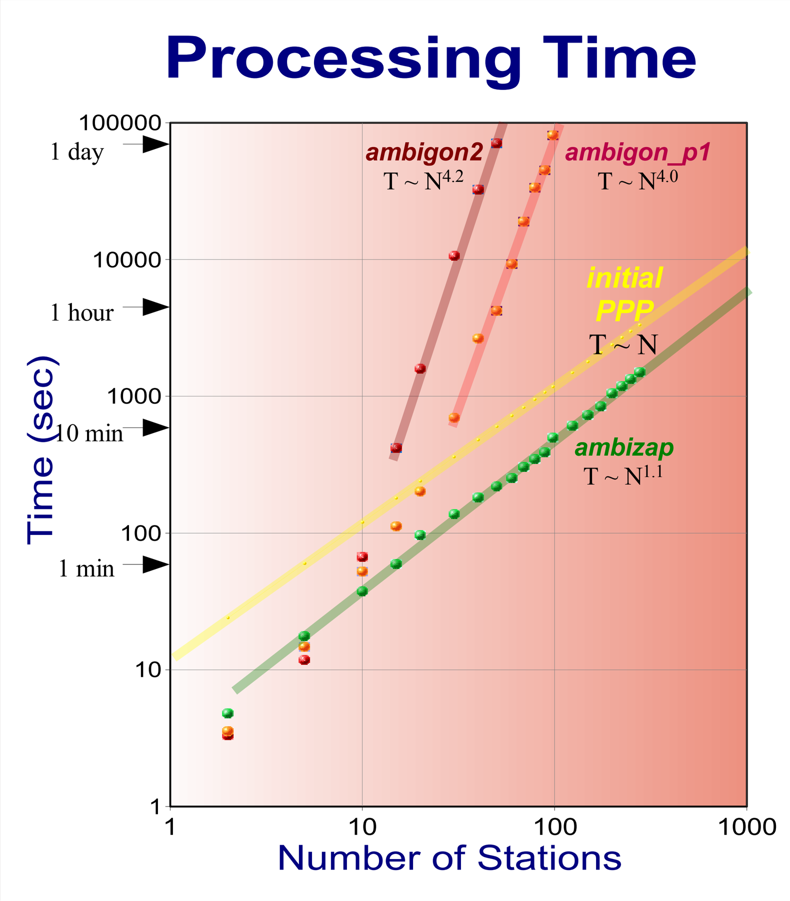


Figure 2. Processing time versus number of stations for currently used algorithms (red) and the new *Ambizap* algorithm (green) described here. The current algorithms shows tends to 4[th] power behavior for large networks, whereas the new algorithm remains approximately linear with processing time. For comparison, PPP is also shown (yellow), which is a necessary preliminary step for all algorithms.

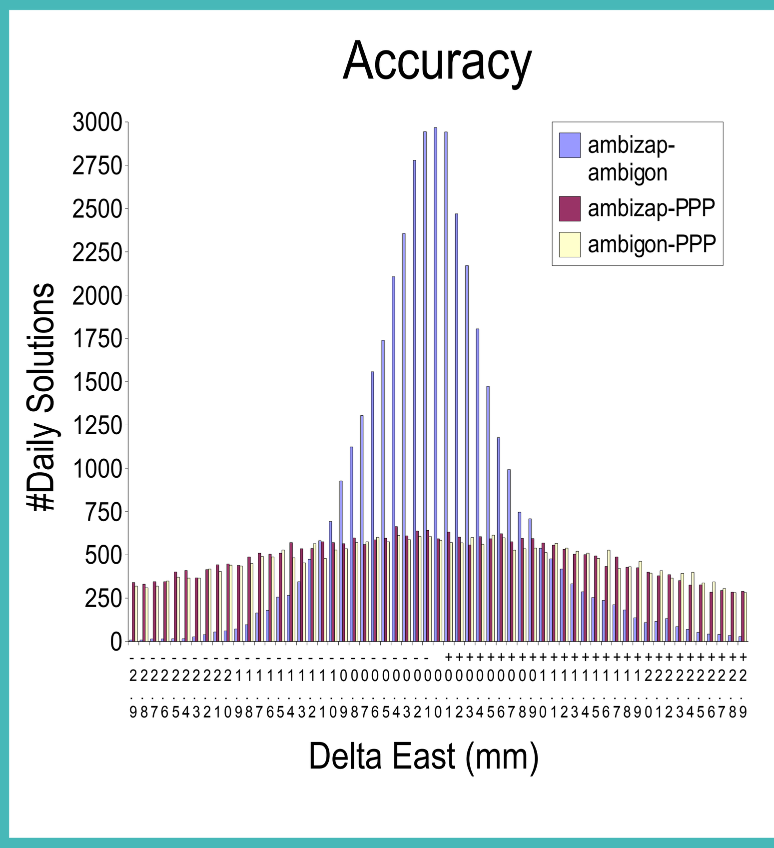
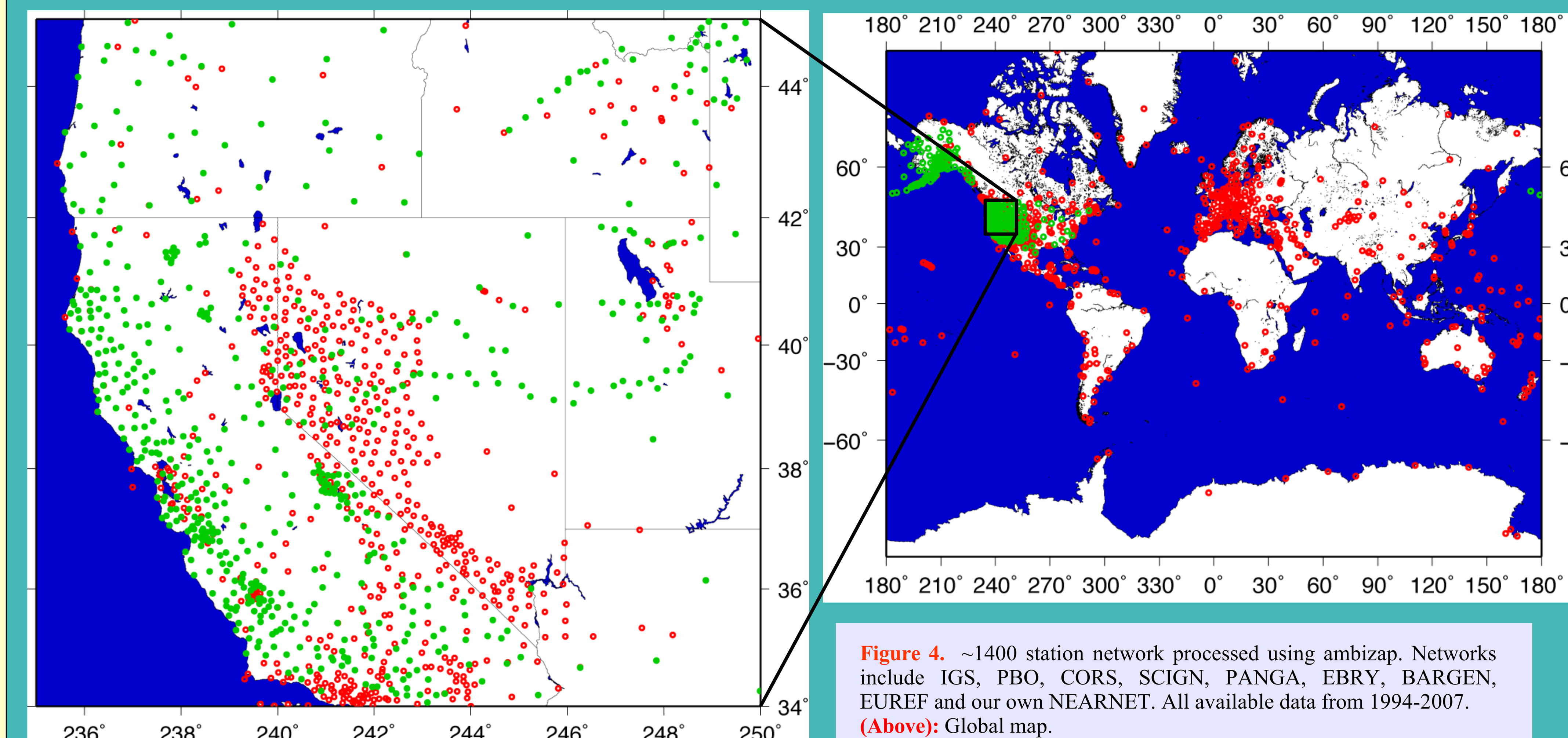


Figure 3. Accuracy of the new algorithm (Ambizap) as assessed by comparison with the current algorithm (Ambigon). Also shown for comparison are agreements of both algorithms with initial PPP. The East component is the one most influenced by ambiguity resolution. The RMS difference between Ambizap – Ambigon is 0.78 mm as compared to 3.3 mm RMS for Ambizap-PPP and 3.4 mm for Ambigon -PPP.



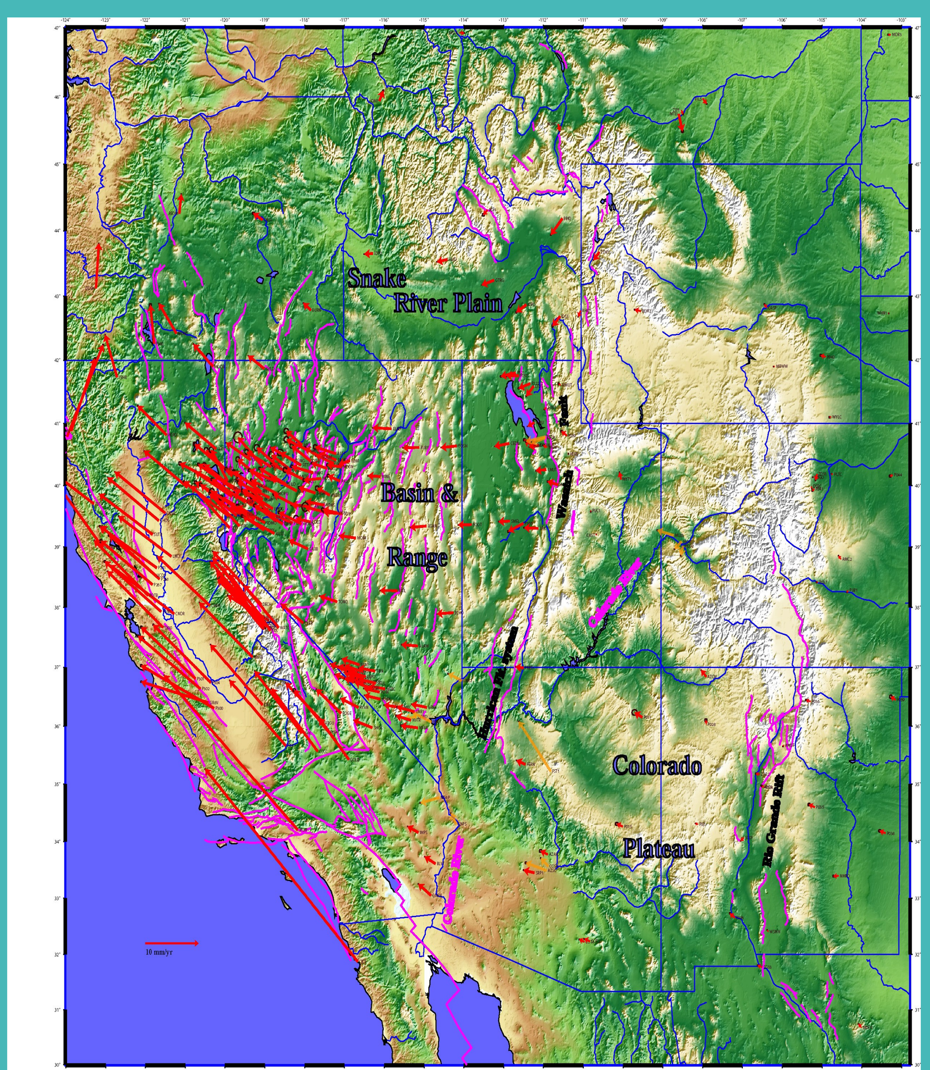


Figure 4. ~1400 station network processed using ambizap. Networks include IGS, PBO, CORS, SCIGN, PANGA, EBRY, BARGEN, EUREF and our own NEARNET. All available data from 1994-2007.
(Above): Global map.
(Upper Left): Western US map.
(Lower Left): Resulting velocity solutions in our realization of a stable North American Reference Frame (SNARF) for stations > 2.5 yr of data.

ACKNOWLEDGMENTS
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CURRENT STATUS AND FUTURE PROSPECTS

- Ambiguity resolution of ~700 station networks (including PBO) takes ~1 hour on one ~3 GHz cpu for 24 hours of data (Figure 3). Cluster processing is linear, and thus takes ~1.5 minutes on our 40-cpu cluster.
- "Networks" are no longer a meaningful concept in the processing, except in the sense that the resulting solutions relate to one dense, global network. Thus no decisions are required at any stage as to "which subnetwork?" a station belongs. This greatly facilitates the administration of data processing for new PBO sites coming on line every week.
- All data we have in hand since 1994 from IGS + SCIGN + BARGEN + BARD + PANGA + EBRY + EUREF + CORS + NEARNET were processed in 7 days on a 40-cpu cluster (PPP + ambizap). See Figure 4. We now routinely process a ~1400-station network Regular weekly processing takes only ~2 hrs.
- Ambizap has been upgraded to allow for the addition of extra stations or subnetworks to an existing solution without having to reprocess data from stations in an existing solution. The resulting solutions agree to << 1 mm with reprocessed network solutions.
- Progress has been initiated toward implementation of Ambizap by JPL into a future official release of GIPSY OASIS II, following the use of PPP engine "gd2p.pl".
- A preliminary design has been developed to interface Ambizap with full-covariance solutions involving global network processing and GPS orbit determination. This will allow for ~1000 station routine analysis as part of the IGS Analysis Center at JPL.