Demonstration of Decimeter-level Real-time Positioning of an Airborne Platform

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BIOGRAPHY

Michael Armatys earned a Ph.D. in Aerospace Engineering from the University of Colorado, Boulder in 2001 and currently works for the Orbiter and Radio Metric Systems Group at JPL. His interests include precise positioning and real-time applications of GPS as well as receiver algorithm development.

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Yoaz Bar-Sever is a Technical Group Supervisor at the Jet Propulsion Laboratory, California Institute of Technology. He holds a Ph.D. in Applied Mathematics from the Technion – Israel Institute of Technology (1987), and a Master in Electrical Engineering from the University of Southern California (1993). In 1989 he joined JPL where he has been involved in the development of GPS technology and its geophysical applications.

Robert Meyer works for JPL's Orbiter and Radiometric Systems Group on real-time GPS orbit, LEO orbit determination, time transfer and geodesy applications. Prior to joining JPL he was with Raytheon supporting JPL OD projects and on the research staff at Chevron's R&D company. His interests are in differential GPS, orbit determination, geodesy and time and frequency metrology for both airborne and space flight missions. He holds a BA, Physics from U.C. Santa Cruz.

ABSTRACT

We demonstrate the ability of the NASA Global Differential GPS (GDGPS) System to support 10 to 20 cm accurate real-time airplane positioning, anywhere in the world, independent of local navigational aids or infrastructure. The demonstrations were carried out in a series of flight experiments from February through September 2002. Experiments using the NASA AirSAR DC-8 airplane based at the Dryden Flight Research Center, CA were carried out over the continental United States and used Inmarsat global satellite beams to receive the GDGPS differential correction data stream. Experiments on the NASA P-3 from the Wallops Island Flight Facility, VA were conducted over Greenland using an Iridium modem to receive the GDGPS differential correction data stream. The 1 Hz differential corrections, comprising GPS orbits and clock offsets relative to the GPS broadcast ephemeris, are computed at the GDGPS Operations Center, from the NASA Global GPS Network data.

In addition to the Inmarsat receiver and Iridium modem, the aircraft positioning payload includes a geodetic-quality, 12-channel dual-frequency GPS receiver and a connection from the plane's avionics pressure transducer to receive external pressure. A Linux PC laptop, running JPL's Real Time GIPSY (RTG) software, combines the measurements and differential corrections to estimate the plane position at 1 Hz.

We will discuss the derivation and validation of truth trajectories using post-processing, and describe the performance of the real time positioning system in terms of accuracy, and availability. We will address the operational challenges and the broad potential benefits from this capability.

INTRODUCTION

Since its inception in 1995, JPL's Global Differential GPS (GDGPS) system has seen continuous improvement. Today's system includes a mature network of GPS receivers based on NASA's Global GPS Network (GGN). Sophisticated software transports GPS observables over the Internet to a central processing facility, JPL's GDGPS Operations Center (GOC). The GOC is a multiply-redundant facility providing continuous GDGPS correction messages since 1999.

At the core of the GOC software is the Real-Time GIPSY (RTG) software. Based on the precise models of JPL's GIPSY-OASIS software, RTG ingests GPS observables from the GGN receivers and computes real-time GPS orbits and clocks. Differencing the real-time orbits and clocks with the broadcast orbits and clocks forms the GDGPS correction message. The correction message distribution channels include the open Internet, the Inmarsat global satellite links, or an Iridium modem connection.

Applications of the precise, real-time positioning made possible by GDGPS system abound. Missions that stand to benefit from onboard decimeter-level positioning included airborne and space borne Earth mapping missions, aircraft navigation, precision farming, and many others. JPL's GDGPS makes precise positioning available in areas where it was never before feasible or practical due to lack of local infrastructure.

Past experiments with a wide-area network based on North America have demonstrated sub-meter level positioning capability [*Muellerschoen et al. 1999*]. Network and software enhancements have driven the accuracies down to the decimeter level. Recent experiments show positioning to the 5 cm RMS level. In this paper, we present the current status of the GDGPS system with results from recent flight campaigns.

SYSTEM OVERVIEW

The backbone of NASA Global Differential GPS (GDGPS) System is the NASA Global GPS Network (GGN). The GGN is a global network of GPS receivers streaming data to JPL over the internet using the Real-Time Net Transfer (RTNT) software developed at JPL [*Muellerschoen et al. 2000*]. RTNT transmits phase and range observables to the GDGPS Operations Center (GOC) with latencies typically less than 2 seconds.

At the GOC, the GPS data are filtered to compute real-time GPS satellite orbit positions, clock offsets, and tropospheric delay estimates for each reference site. The computed orbits and clocks are differenced with the broadcast ephemeris orbits and clock values to form the global differential correction message. [*Bar-Sever 2002*].

For aircraft flights, differential corrections are disseminated through two methods: an Inmarsat geo-stationary satellite and an Iridium modem connection. Our commercial partner, Navcom, broadcasts the GDGPS correction messages on Inmarsat satellites. The Inmarsat beams provide coverage to +/- 75 degree latitudes. We establish an Iridium phone connection by dialing into the GDGPS Operations Center at JPL. The polar-orbiting Iridium constellation provides coverage at all latitudes, allowing flight experiments to use corrections over the Earth's poles.

The flight system comprises a rack-mount flight chassis with twice-redundant GPS receivers, a Linux laptop running the RTG software, an aircraft GPS antenna, a connection to the aircraft barometer, and an Inmarsat receiver or Iridium modem. The rackmount chassis houses the GPS receivers, power converters, Inmarsat receiver, and Iridium modem. The GPS receivers used are the Ashtech Z-12 and Navcom's NCT-2000. Both are dual-frequency, 12-channel receivers.

The GPS receivers output P1, P2, L1, and L2 data to the laptop at 1-Hz over a serial connection. The GDGPS corrections are received at 1-Hz with bandwidths of 28 and 44 bytes/second over the Inmarsat satellite link and Iridium phone connection, respectively. 1-Hz pressure measurements from the plane's barometer are used to compute the dry tropospheric delay. Ephemeris data is received from the GPS satellites.

SYSTEM ENHANCEMENTS

Recent hardware and software enhancements to the GDGPS system improve performance over previously published results. JPL's original real-time network is bolstered by the addition of Navcom's 20 real-time receivers to produce the network depicted in Figure 1.

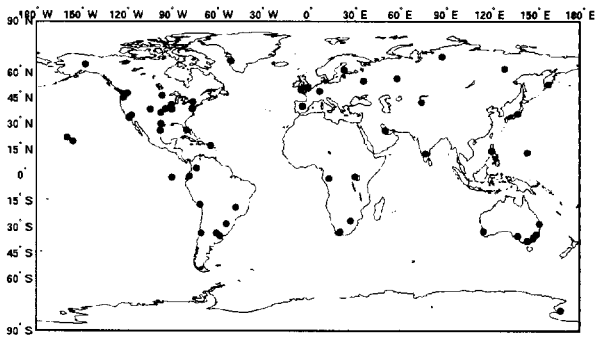

Figure 1: Combined JPL and Navcom 62-station real-time GPS network.

Many changes have occurred in the end-user module of the RTG software. For aircraft flights, a new tropospheric estimation technique computes a height-dependent scale factor for the wet component of the tropospheric delay.

A new filter convergence algorithm was developed for aircraft platforms. The new end-user module resolves the phase biases on the ground before the flight, eliminating the convergence period from the flight data. GPS carrier phase biases are resolved using approximately 15 minutes of GPS data while holding the aircraft position fixed.

Once the phase biases have been resolved and the aircraft is ready to move, a signal is sent to the software to begin kinematic positioning of the aircraft.

The aircraft RTG software has been modified to optimally select the receiver from the multiple-receiver architecture whose data produces the smallest formal errors. The real-time latency of the filter is less than $1/10^{th}$ of a second.

DATA COLLECTION CAMPAIGNS

The aircraft positioning system has been tested on multiple missions. The system flew on the NASA DC-8 in support of JPL's AirSAR mission from February through September of 2002 using Ashtech and Navcom GPS receivers. In the spring of 2002, the system also flew as part of the NASA P3 Ice-Mapping mission over Greenland. This mission exploited the Iridium satellite constellation as a means of retrieving GDGPS differential corrections with over 17 hours of data. In December 2002 through February 2003, the system was deployed on the NASA DC-8 for the SOLVE III flights over the northern polar region to profile ozone. The SOLVE III mission uses the Iridium satellite constellation for operation at high latitudes.

In this paper, we present only the data taken over Greenland. The P3 mission provided a rare opportunity to compare the real-time solution to a completely independent GPS solution. The only source of truth reference for the real-time solution on most flights is the post-processed GOA solution. While the GOA solutions are robust and accurate, we desire independent truth data when available. On the Greenland flights, a team of scientists and engineers from Wallops Flight Facility computed post-processed, carrier-phase based local area differential GPS solutions at 2 Hz. We compare the RTG results to the independent Wallops results.

The onboard RTG software produces real-time solutions at 1 Hz. This state space position solution contains the aircraft position in ECEF X, Y, Z coordinates and estimates of the wet component of the tropospheric delay. Data from the aircraft flight for post-processing include the GPS observables in RINEX format and the real-time solution for later comparison.

COMPARISON TO POST-PROCESSED TRAJECTORIES

Nominally, we use JPL's GOA II software as a source of truth for our real-time flights. GOA is JPL's primary orbit determination, point positioning, and ambiguity resolution software. Using GOA, we apply JPL's precise GPS orbit and clock solutions to the GPS data collected in flight to compute a post-processed solution.

Table 1 shows the RMS errors between the real-time solution and GOA solution. The June 1 data provides the best comparison to the GOA solutions. The horizontal components agree to better than 5 cm and the vertical component agrees to better than 10 cm. The solutions on this day provided the best comparison because the Iridium phone connection was most reliable on this day. The system performance on June 4 is similar to the data on June 1. There was only one substantial reset of the Iridium phone connection. All components agree to within 10 cm RMS. May 31 was the first attempt at using the Iridium modem to obtain GDGPS corrections. The Iridium connection was lost on three separate occasions causing large errors in the kinematic solution. The errors remain less than 20 cm even on the worst day.

Table 1: Real-time point solution vs. GIPSY-OASIS solution. Errors are in RMS cm.

Date	# 1 Hz pts	East	North	Vert
31May02	10029	17.3	6.6	11.4
01Jun02	10576	4.4	4.0	7.5
04Jun02	21510	6.8	4.0	9.0

The agreement between the real-time and Wallops post-processed solutions is also very good as is shown in Table 2. The June 1 data provide the best comparison with the horizontal components providing less than 5 cm of RMS error and the vertical RMS error is less than 6 cm. Again, the Iridium modem connection problems on May 31 and June 4 slightly degrade the performance of the GDGPS system. All errors remain less than 20 cm RMS despite the connection problems.

Table 2: Real-time point solution vs. Wallops post-processed solution. Errors are in RMS cm.

Date	# 1 Hz pts	East	North	Vert
31May02	9790	17.2	10.1	13.0
01Jun02	10463	4.5	4.6	5.9
04Jun02	21645	8.0	6.1	12.6

BENEFITS OF FLIGHT SYSTEM

The benefits of the GDGPS system abound. The system provides continuous global coverage eliminating the need for setting up and calibrating base station equipment. The user-equipment is extremely portable consisting of only a laptop, a standard rackmount chassis, a few cables, and antennas. The flight equipment can use any dual-frequency GPS receiver with software interface changes.

SUMMARY

We have demonstrated seamless global performance of JPL's Internet-based Global Differential GPS system and

have shown that the Iridium satellite constellation is a viable platform for disseminating GDGPS differential corrections. We have shown improved performance of JPL's GDGPS system. Current system accuracies are typically better than 10 cm RMS for each coordinate. Recent improvements in real-time accuracies come from network enhancements, and improvements in the end-user RTG software.

ACKNOWLEDGMENTS

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Special thanks to the Wallops team for sharing their post-processed GPS solutions for comparison to the real-time results.

We are grateful to Navcom Technology for broadcasting the GDGPS differential corrections on the Inmarsat L-band global beams, for supplying the precise GPS and L-band receivers, and for general technical support.

REFERENCES

Bar-Sever, Y., R. Muellerschoen, A. Reichert, "The Development and Demonstration of NASA's Global Differential System," Proceedings of ESTC 2002, Pasadena, CA, June, 2002.

Muellerschoen, R. J., W. I. Bertiger, "Flight Tests Demonstrate Sub 50 cms RMS. Vertical WADGPS Positioning," Proceedings of ION GPS 1999, Nashville, TN, September, 1999.

Muellerschoen, R. J., W. I. Bertiger, M. Lough, D. Stowers, D. Dong, "An Internet-Based Global Differential GPS System, Initial Results," Proceedings of ION NTM 2000, Anaheim, CA, January, 2000.

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Benefits

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- **Continuous global coverage**
  - 24/7
  - No need for setting up LADGPS base station/radio link
- **Portable**
  - Flight system includes standard rackmount chassis, Linux laptop, antennas, pressure transducer for dry tropo measurements
- **Flexible**
  - Can be used with any dual-frequency receiver

NASA Global GPS Network

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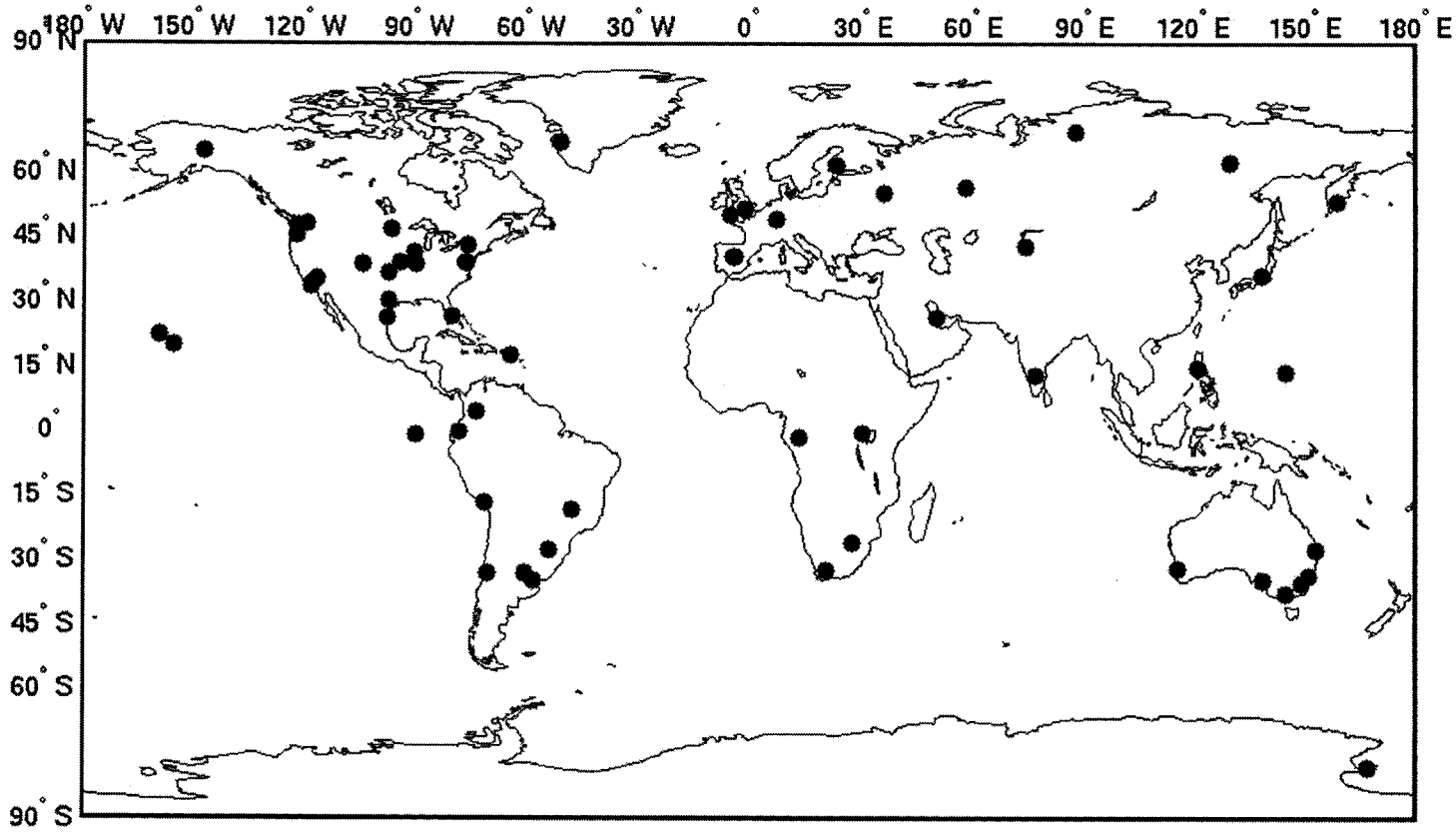

NASA Global GPS Network

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- 62-station subset of the NASA GGN
- Receiver types?
- Use Real-Time Network Transfer (RTNT) software to stream GPS data to operations center
- At the operations center, data fed into RTG (Real-Time GIPSY) to produce real-time GPS satellite orbits, 1-Hz GPS clocks, and tropospheric delay estimates at each station.
- Difference orbits and clocks with broadcast orbits and clocks to form GDGPS correction message.
- Distribute corrections using many different protocols

Correction dissemination

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- Over the internet via TCP/UDP connection
- Via dial-up connection to operations center
- Over geosynchronous satellite link through partner Navcom

Recent Enhancements

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- **The following enhancements have improved the accuracy of our airborne system over previously published data:**
  - Additional ground stations
  - Filter enhancements?
  - On-board software enhancements?

Flight Campaigns

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- **NASA P3 ice-mapping flights over Greenland**
  - May and June 2002
  - Used Iridium modem connection
  - Over 17 hours of data
- **NASA DC-8 AirSAR flights over continental U.S.**
  - September 2002
  - Used Inmarsat satellite link
  - Over 9 hours of data

Truth data

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- **GIPSY-OASIS II**
  - JPL's premiere orbit determination, point positioning and ambiguity resolution software
  - Combine GPS observables save during flight with JPL's precise GPS orbits and clocks
- **LADGPS**
  - Available only during Greenland experiments
  - Code-only DGPS system
  - Base station at airport, radio link to aircraft
- **Laser-ranging**
  - Primary instrument on Greenland ice-mapping flights
  - Find crossovers and flight path and compare change in height reported by laser, LADGPS, and GDGPS.

Real-time vs. GIPSY-OASIS Comparisons (cm RMS)

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Date	# 1-Hz Pts	East Comp Error	North Comp Error	Vert CompErr
31May02	17475	6.4	4.9	9.2
02Jun02	17530	1.2	2.1	7.5
04Jun02	26379	4.7	3.6	5.1
11Sep02	16136	1.5	1.0	1.5
18Sep02	6507	0.8	0.5	1.6
20Sep02	11150	0.5	0.7	1.3

Real-time vs. LADGPS Comparisons (cm RMS)

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Date	# 1-Hz Pts	East Comp Error	North Comp Error	Vert CompErr
31May02	17415	6.6	5.2	8.4
02Jun02	17410	2.3	3.2	6.7
04Jun02	27150	4.6	4.3	8.4

GIPSY-OASIS vs. LADGPS Comparisons (cm RMS)

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Date	# 1-Hz Pts	East Comp Error	North Comp Error	Vert CompErr
31May02	17415	1.4	1.9	5.0
02Jun02	17410	1.7	3.1	7.4
04Jun02	27150	5.0	4.9	8.6

Laser-ranging vs. GPS Comparisons (cm RMS)

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Date	System	# of crossings	Height diff
31May02	LADGPS	49	5.5
31May02	Real-Time	42	11.9
31May02	GO	42	6.0
01Jun02	LADGPS	22	4.3
01Jun02	Real-Time	22	7.9
01Jun02	GO	22	5.0

Results

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- The real-time results used in the previous slides were smoothed is post-processing to better reflect the GDGPS correction accuracy
- The true real-time results show a filter convergence period due to unresolved phase biases
- Smoothed results use the exact data used in the real-time solutions.

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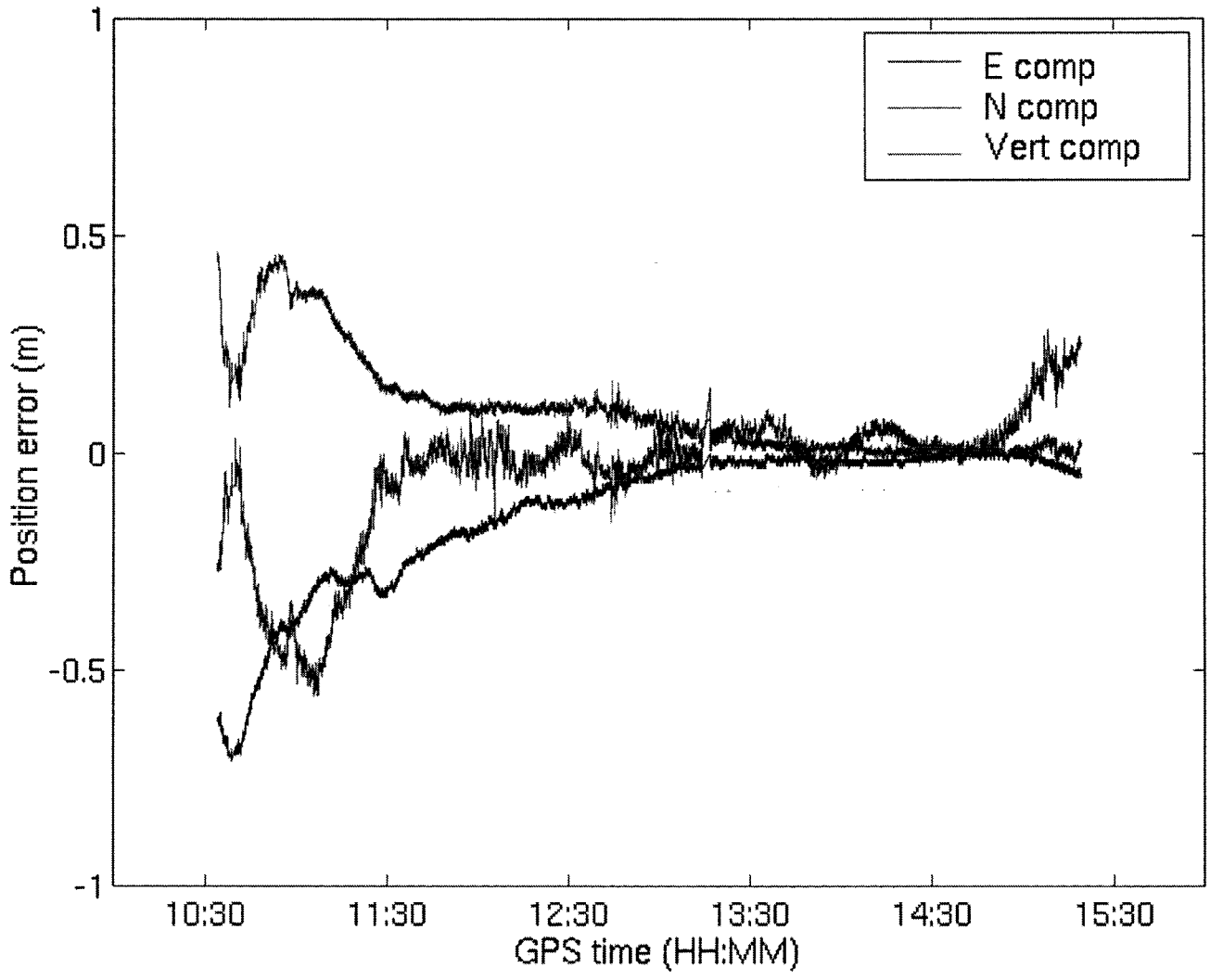

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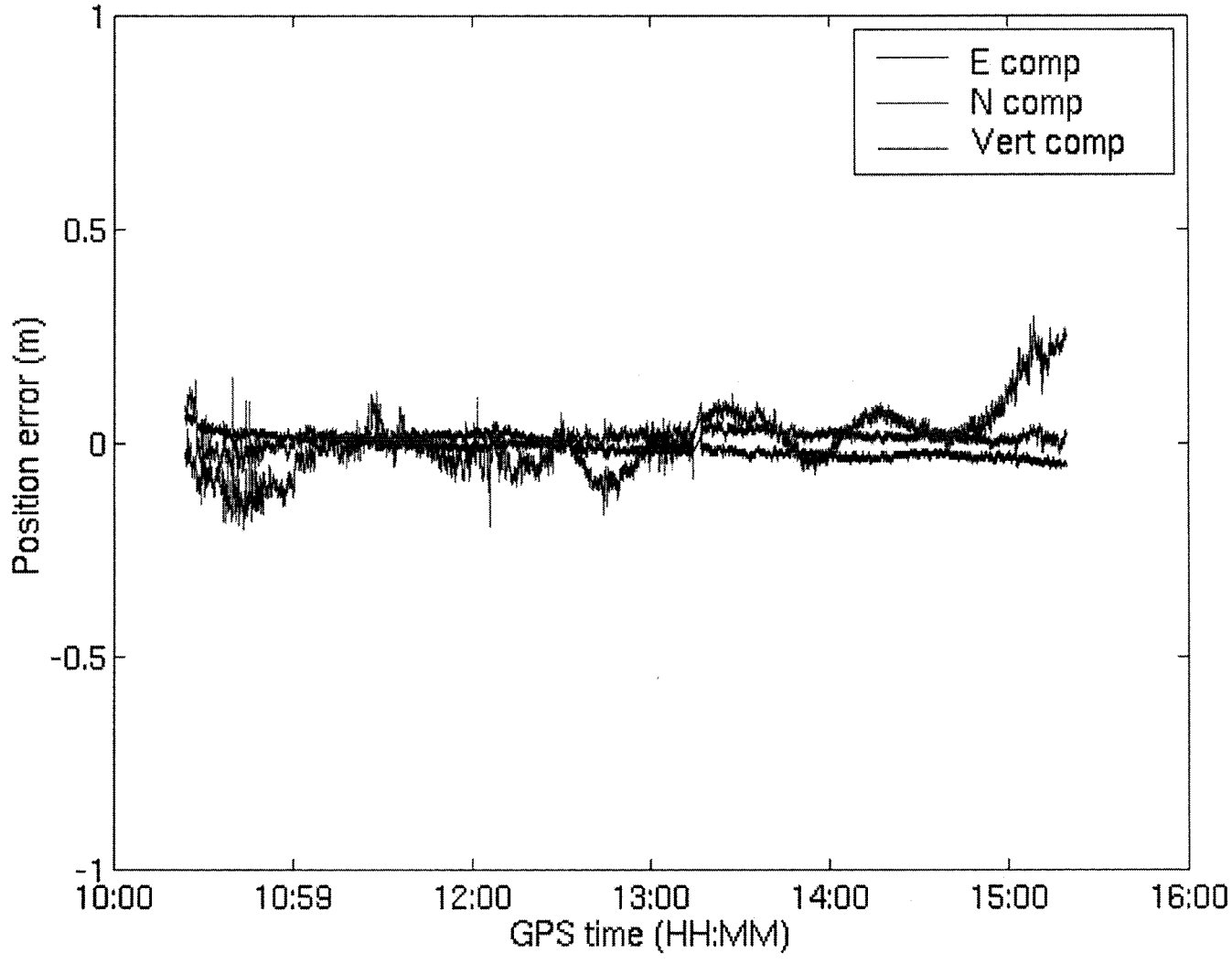

Conclusions

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- We have shown consistent decimeter-level positioning capability with results often sub-decimeter.
- We have demonstrated seamless global performance with operation over vast distances.

Future Work

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- **Employ system to improve filter convergence**
  - Take measurements for 30 minutes on tarmac before flight
  - Estimate phase biases while holding position fixed.
  - When the aircraft is ready to move, send signal to software to begin kinematic positioning.

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Acknowledgements

- Thanks to my co-authors for all of their hard work.
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- Thanks to the Ice-mapping folks for sharing their LADGPS and laser-ranging data.

For more information:

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- **See our website**
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