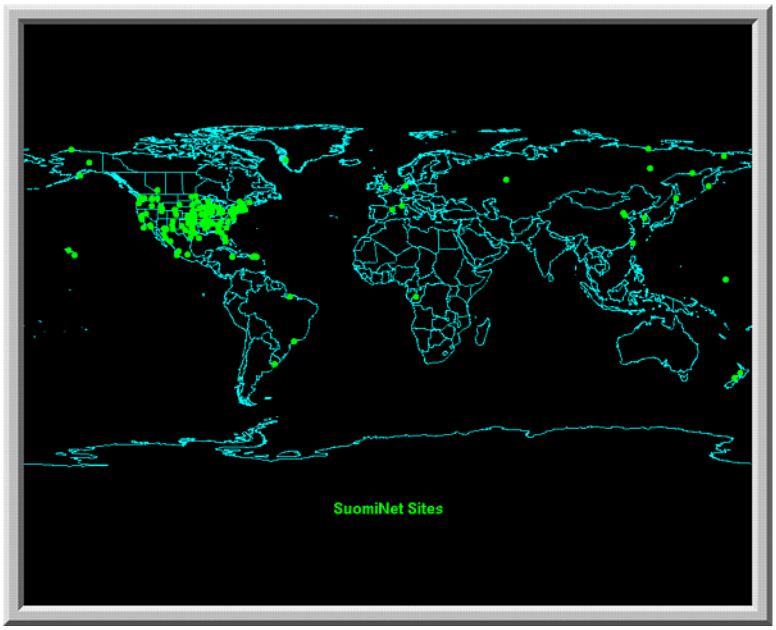
GPS Receiver and Antenna Testing Report for SuomiNet



Mike Jackson, Chuck Meertens, Victoria Andreatta, Teresa Van Hove

University NAVSTAR Consortium, Boulder CO

UNAVCO
University NAVSTAR Consortium

Table of Contents

List of Tables

List of Figures

1.0 Introduction

SuomiNet is a university-based, real-time, national Global Positioning System (GPS) network being developed for atmospheric research and education. Funding for the network comes from the National Science Foundation (NSF) and with cost share from collaborating universities. The network is based on a dense network of GPS Receivers located at member universities that will measure phase delays induced in GPS signals by the ionosphere and neutral atmosphere. These delays can be converted into integrated water vapor (if surface pressure data are available) and total electron content (TEC), along each GPS ray path [Ware et al., 2000] and used as input into numerical atmospheric models. The University NAVSTAR Consortium (UNAVCO) in Boulder was tasked with developing a receiver bid specification, evaluation of receivers submitted by manufactures responding to the bid, and providing a receiver technical evaluation to the SuomiNet Steering Committee for the GPS portion of the procurement. This document represents the culmination of the receiver bid specification and evaluation process.

Manufacturers who responded to the bid specification and provided systems are listed in Table 1-1.

Table 1-1: Receiver and antenna pairs tested.

Manufacturer	Receiver	Antenna
Magellan-Ashtech	Ashtech u-Z	ASH701945.02B (Ashtech Choke RIng)
Javad Positioning Systems	JPS Legacy	ASH701945.02B (Ashtech Choke RIng)
Javad Positioning Systems	JPS Legacy	JPS Regant DD E (dual-depth Choke Ring)
Javad Positioning Systems	JPS Legacy	JPS Regant SD E (single-depth Choke Ring)
Trimble Navigation Ltd.	Trimble 4700	TRM33429.00+GP (Microcentered)
Trimble Navigation Ltd.	Trimble 4700	TRM29659.00 (Choke Ring)

Approximately 60% of the SuomiNet participants have registered as dual use atmospheric and geodetic sites. For this reason, manufactures were asked to submit for testing a standard geodetic antenna and, if available, an IGS compatible, Dorne Margolin element Choke Ring antenna. For this reason we also tested the Javad receiver with a voltage compatible ASH701945.02B Ashtech Choke Ring antenna.

A fully deployed SuomiNet system will consist of a GPS receiver and antenna, surface meteorologic package, and a PC computer running the LINUX operating system. The receiver will stream GPS observables and MET data to the computer where UNAVCO (JStream) and UCAR (LDM) developed software will package and transport the data to a processing facility. Thus, manufacturers' proprietary data download and data processing software was not evaluated during this test.

The report is organized into the following sections: test configuration, zero baseline results, and short baseline results. Each section is followed by a short summary which highlights conclusions for each section.

2.0 Test Configuration

All receiver tests were conducted on the roof of the UNAVCO building to simulate the typical environment for the SuomiNet deployment. Figure 2-1 shows the roof top mounting system and benchmark names used during the SuomiNet tests. Figure 2-2 shows a view of the test area looking to the north (benchmark UV06 is to the far right in the photo).

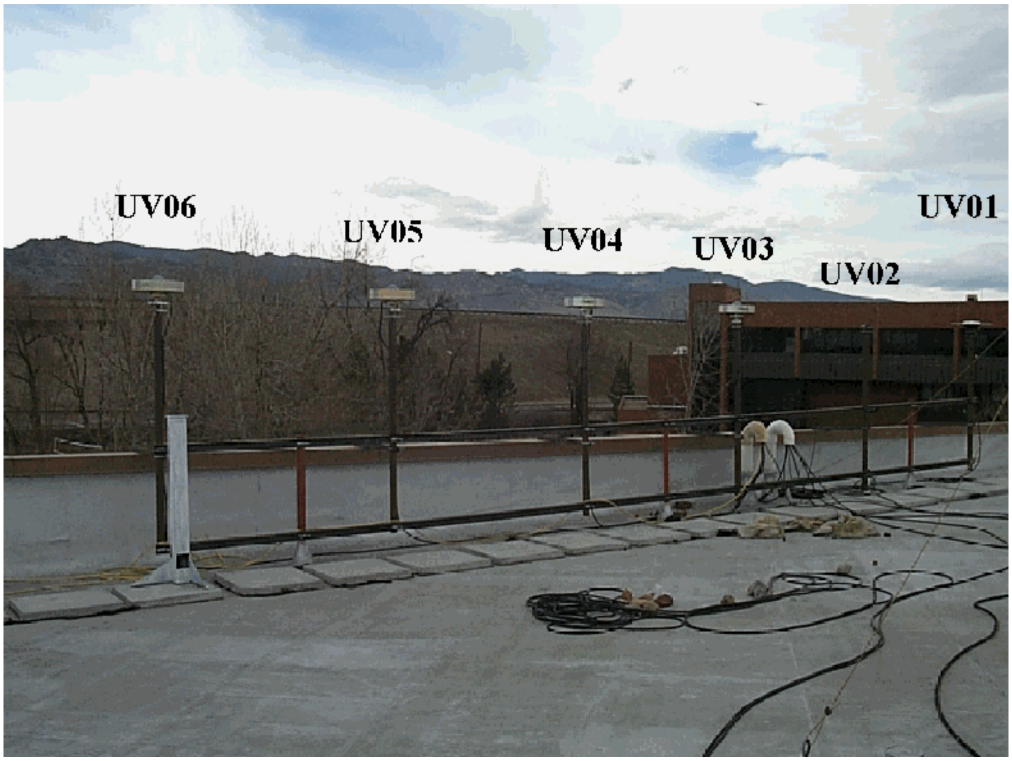


Figure 2-1: Benchmark location and antenna mounting system on the roof of the UNAVCO building. An Ashtech ZXII with antenna ASH700936A_M was run on benchmark UV06 during the entire testing phase. Benchmark UV05 was used for all zero baseline testing while UV04 and UV03 were used for short baseline tests. Benchmarks UV02 and UV01 were not used.

Figure 2-2: UNAVCO SuomiNet test area looking to the north. Station UV06 is at the far right.

Receiver and antenna tests were conducted in a similar manner to those published in the UNAVCO Academic Research Infrastructure (ARI) Receiver and Antenna Test Report [Rocken et. al, 1996]. Where possible, each receiver/antenna was tested using manufactures default settings. Data were collected at 1 and 15 second collection intervals and a zero-degree elevation cutoff. Only results from the 15 second data are reported here. Data were taken over a 50 day period with 24 hour data files (15 second data) and 2 hour data files (1 second data). Data streaming protocols were tested during the evaluation but in most cases data were logged internally to the receiver memory and downloaded using the manufacturers software. Figures 2-3 through 2-7 show the receivers tested during the evaluation. Table 2-1 presents a summary of receivers and firmware tested.

Figure 2-3: Ashtech u-Z GPS receiver with Ashtech ASH701945.02B Choke Ring antenna.

Figure 2-4: Javad Positioning Systems Legacy receiver with JPS Regant DD E (Dual Depth Choke Ring) antenna. The Legacy receiver was also tested with the JPS Regant SD E (Single Depth Choke Ring) antenna (not shown)

Figure 2-5: Javad Positioning Systems Legacy receiver with ASH701945.02B Ashtech Choke Ring antenna.

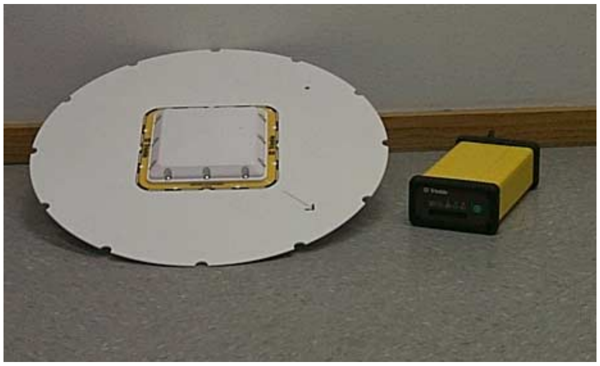


Figure 2-6: Trimble 4700 receiver with TRM33429.00+GP Microcentered antenna.

Figure 2-7: Trimble 4700 with TRM29659.00 Trimble Choke Ring antenna.

Table 2-1:Summary of Receiver and Antennas Tested

Receiver	Part Number	Firmware	Antenna	Part Number
JPS Legacy	01-001001-01	2.0	JPS Regant DD E	01-003002-01
JPS Legacy	01-001001-01	2.0	JPS Regant SD E	01-003002-02
JPS Legacy	01-001001-01	2.0	ASH701945.02B	701945-02
Trimble 4700	35846-15	0.25	TRM29659.00	29659-00
Trimble 4700	35846-15	0.25	TRM33429.00+GP	33429-20
Ashtech u-Z	800851-20	UF48	ASH701945.02B	701945-02
Ashtech Z-XII3	700845-10H	CC00-1D02	ASH701945.02B	701945-02
Ashtech Z-XII3	700845-10D	CC00-1D02	ASH701945.02B	701945-02

Table 2-2 presents a day-by-day summary of the data files acquired during the test period, the type of test (short baseline or zero baseline), the receiver/antenna pair used, and the marker number.

Table 2-2:Summary of Daily Files Collected

Day	Test	Receiver	Antenna	Sampling Interval	File Name	Mark	File Name	Mark
012	Short Baseline	JPS Legacy	JPS Regant DD E	15 sec.	L00794*	UV04	L00795*	UV03
013	Short Baseline	JPS Legacy	JPS Regant DD E	15 sec.	L00794*	UV04	L00795*	UV03
014	Short Baseline	JPS Legacy	JPS Regant DD E	15 sec.	L00794*	UV04	L00795*	UV03
015	Short Baseline	JPS Legacy	JPS Regant DD E	15 sec.	L00794*	UV04	L00795*	UV03
018	Short Baseline	JPS Legacy	JPS Regant DD E	1 sec.	L00794*	UV04	L00795*	UV03
021	Short Baseline	JPS Legacy	JPS Regant SD E	15 sec.	L00794*	UV04	L00795*	UV03
021	Zero Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d50079*	UV05	d10430*	UV05
022	Short Baseline	JPS Legacy	JPS Regant SD E	15 sec.	L00794*	UV04	L00795*	UV03
022	Zero Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d50079*	UV05	d10430*	UV05
023	Short Baseline	JPS Legacy	JPS Regant SD E	15 sec.	L00794*	UV04	L00795*	UV03
023	Zero Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d50079*	UV05	d10430*	UV05
024	Short Baseline	JPS Legacy	JPS Regant SD E	15 sec.	L00794*	UV04	L00795*	UV03
024	Zero Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d50079*	UV05	d10430*	UV05
024	Short Baseline	JPS Legacy	JPS Regant SD E	1 sec.	L00794_1s*	UV04	L00795_1s*	UV03
024	Zero Baseline	Ashtech Z-XII3	ASH701945.02B	1 sec.	d50079_1s*	UV05	d10430_1s*	UV05
025	Short Baseline	JPS Legacy	ASH701945.02B	15 sec.	L00794*	UV04	L00795*	UV03
026	Short Baseline	JPS Legacy	ASH701945.02B	15 sec.	L00794*	UV04	L00795*	UV03
027	Short Baseline	JPS Legacy	ASH701945.02B	15 sec.	L00794*	UV04	L00795*	UV03
027	Zero Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV05	trim175719*	UV05
027	Short Baseline	JPS Legacy	ASH701945.02B	1 sec.	L00794_1s*	UV04	L00795_1s*	UV03
028	Zero Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV05	trim175719*	UV05
028	Short Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d10430*	UV03	d50079*	UV04
029	Zero Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV05	trim175719*	UV05
029	Short Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d10430*	UV03	d50079*	UV04
030	Zero Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV05	trim175719*	UV05
030	Short Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d10430*	UV03	d50079*	UV04

Table 2-2:Summary of Daily Files Collected (cont.)

Day	Test	Receiver	Antenna	Sampling Interval	File Name	Mark	File Name	Mark
031	Zero Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV05	trim175719*	UV05
031	Zero Baseline	Trimble 4700	TRM33429.00+GP	1 sec.	trim177932_1s*	UV05	trim175719_1s*	UV05
031	Short Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d10430*	UV03	d50079*	UV04
032	Short Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d10430*	UV03	d50079*	UV04
032	Zero Baseline	JPS Legacy	JPS Regant DD E	15 sec.	L00794*	UV05	L00795*	UV05
033	Short Baseline	Ashtech Z-XII3	ASH701945.02B	15 sec.	d10430*	UV03	d50079*	UV04
033	Short Baseline	Ashtech Z-XII3	ASH701945.02B	1 sec.	d10430_1s*	UV03	d50079_1s*	UV04
033	Zero Baseline	JPS Legacy	JPS Regant DD E	15 sec.	L00794*	UV05	L00795*	UV05
034	Zero Baseline	JPS Legacy	JPS Regant DD E	15 sec.	L00794*	UV05	L00795*	UV05
035	Zero Baseline	JPS Legacy	JPS Regant DD E	15 sec.	L00794*	UV05	L00795*	UV05
035	Zero Baseline	JPS Legacy	JPS Regant DD E	1 sec.	L00794_1s*	UV05	L00795_1s*	UV05
036	Zero Baseline	JPS Legacy	JPS Regant SD E	15 sec.	L00794*	UV05	L00795*	UV05
037	Zero Baseline	JPS Legacy	JPS Regant SD E	15 sec.	L00794*	UV05	L00795*	UV05
038	Zero Baseline	JPS Legacy	JPS Regant SD E	15 sec.	L00794*	UV05	L00795*	UV05
039	Zero Baseline	JPS Legacy	JPS Regant SD E	15 sec.	L00794*	UV05	L00795*	UV05
039	Short Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV04	trim175719*	UV03
040	Zero Baseline	JPS Legacy	JPS Regant SD E	15 sec.	L00794*	UV05	L00795*	UV05
040	Zero Baseline	JPS Legacy	JPS Regant SD E	1 sec.	L00794_1s*	UV05	L00795_1s*	UV05
040	Short Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV04	trim175719*	UV03
041	Short Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV04	trim175719*	UV03
041	Zero Baseline	JPS Legacy	ASH701945.02B	15 sec.	L00794*	UV05	L00795*	UV05
042	Short Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV04	trim175719*	UV03
042	Zero Baseline	JPS Legacy	ASH701945.02B	15 sec.	L00794*	UV05	L00795*	UV05
043	Short Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV04	trim175719*	UV03
043	Zero Baseline	JPS Legacy	ASH701945.02B	15 sec.	L00794*	UV05	L00795*	UV05
044	Short Baseline	Trimble 4700	TRM33429.00+GP	15 sec.	trim177932*	UV04	trim175719*	UV03
044	Zero Baseline	JPS Legacy	ASH701945.02B	15 sec.	L00794*	UV05	L00795*	UV05
045	Zero Baseline	JPS Legacy	ASH701945.02B	1 sec.	L00794_1s*	UV05	L00795_1s*	UV05
046	Short Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV04	trim175719*	UV03
047	Short Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV04	trim175719*	UV03
048	Short Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV04	trim175719*	UV03
050	Short Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV04	trim175719*	UV03
051	Short Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV04	trim175719*	UV03
052	Short Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV04	trim175719*	UV03
052	Short Baseline	Trimble 4700	TRM29659.00	1 sec.	trim177932_1s*	UV04	trim175719_1s*	UV03
055	Zero Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV05	trim175719*	UV05
056	Zero Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV05	trim175719*	UV05
056	Short Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV04	ash5002*	UV03
057	Zero Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV05	trim175719*	UV05
057	Short Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV04	ash5002*	UV03
058	Zero Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV05	trim175719*	UV05
058	Short Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV04	ash5002*	UV03
059	Zero Baseline	Trimble 4700	TRM29659.00	1 sec.	trim177932_1s*	UV05	trim175719_1s*	UV05

Table 2-2:Summary of Daily Files Collected (cont.)

Day	Test	Receiver	Antenna	Sampling Interval	File Name	Mark	File Name	Mark
059	Short Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV04	ash5002*	UV03
060	Zero Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV05	trim175719*	UV05
060	Short Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV04	ash5002*	UV03
061	Zero Baseline	Trimble 4700	TRM29659.00	15 sec.	trim177932*	UV05	trim175719*	UV05
061	Short Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV04	ash5002*	UV03
061	Short Baseline	Ashtech u-Z	ASH701945.02B	1 sec.	ash5001_1s*	UV04	ash5002_1s*	UV03
063	Zero Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV05	ash5002*	UV05
064	Zero Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV05	ash5002*	UV05
065	Zero Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV05	ash5002*	UV05
067	Zero Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV05	ash5002*	UV05
068	Zero Baseline	Ashtech u-Z	ASH701945.02B	15 sec.	ash5001*	UV05	ash5002*	UV05
068	Zero Baseline	Ashtech u-Z	ASH701945.02B	1 sec.	ash5001_1s*	UV05	ash5002_1s*	UV05

After the raw data files were downloaded they were converted to RINEX using manufactures supplied data converters. Ashtech uZ data files were converted using both the smoothed pseudorange (Ashtech's preferred method) and unsmoothed pseudorange option. Each Ashtech data record contains a field with smoothing parameters which can be applied to the raw pseudorange values. Pseudorange Smoothing provides lower overall pseudorange RMS values, but also produces epoch to epoch correlations in the data. Other manufacturers translators provide raw pseudorange values, therefore, where appropriate, we present tests based on both the Ashtech smoothed and unsmoothed pseudoranges. All RINEX files were quality checked using teqc [Estey and Meertens, 1999] using an elevation cutoff of 10, 5 and 0 degrees. Short and zero baselines were processed using the Bernese GPS software.

Receiver phase and pseudorange performance were tested using the Bernese software, a double differencing based, high precision software package. For all tests the first station was held fixed and the coordinates of the second station were solved for. Data were preprocessed to identify and fix any cycle slips. The number of slips seen in the differenced observation files was consistent with the slips shown in the qc/teqc testing, thus no statistics from this processing step are included in the report.

After pre-processing standard geodetic solutions using an elevation cut-off of 10° were performed for the phase data: L1, L2, L3 (ion-free comb) and the pseudorange data. Precision and accuracy of the geodetic solutions were examined. No troposphere values were estimated in the geodetic runs, however L1 and L2 ambiguities were resolved and these ambiguities were introduced for the L3 runs.

In addition to the geodetic solutions, zenith atmospheric delay differences were estimated between the 2 antennas on the short baselines. Two antennas at the same height and separated by only 1.9 meters experience the same atmospheric delay, so any estimated delay difference reflects error sources such as multipath. For this estimation no elevation cut-off was applied and all the data were used. Coordinates of both stations were held fixed, with the second station coordinates taken from the previous phase geodetic solutions.

3.0 Receiver Tracking and Data Quality Tests

Receiver tracking was assessed by compiling teqc statistics for RINEX files on short and zero baseline data files at high (90-10) and low (10-5, 5-0) elevation angles. We compare observed data volume vs. cycle slip count, pseudorange + multipath noise, and phase noise for the different satellite tracking windows.

3.1 Observed Data vs. Cycle Slips

In the following figures we show plots of expected data (based on total data acquisition time), observed data, and number of cycle slips for the elevation ranges 90°-10°, 10°-5°, and 5°-0°. The data are from both zero and short baseline tracking. The data are normalized to the expected number of observations then converted to log base 10 so that the number of cycle slips can be represented on the same graph as the number of data observations (i.e. a value of 100% = 2). For this analysis, cycle slips are determined using two methods. First, if the root-mean square of the MP1 and MP2 linear combinations exceed a threshold value, a cycle slip is counted [Estey and Meertens, 1999]. Slips detected using MP1 and MP2 constitute either a problem with the pseudorange or a cycle slip larger than a few hundred cycles. Second, a cycle slip is flagged if the IOD, or time derivative of the ionosphere delay exceeds 400 cm/minute [Estey and Meertens, 1999].

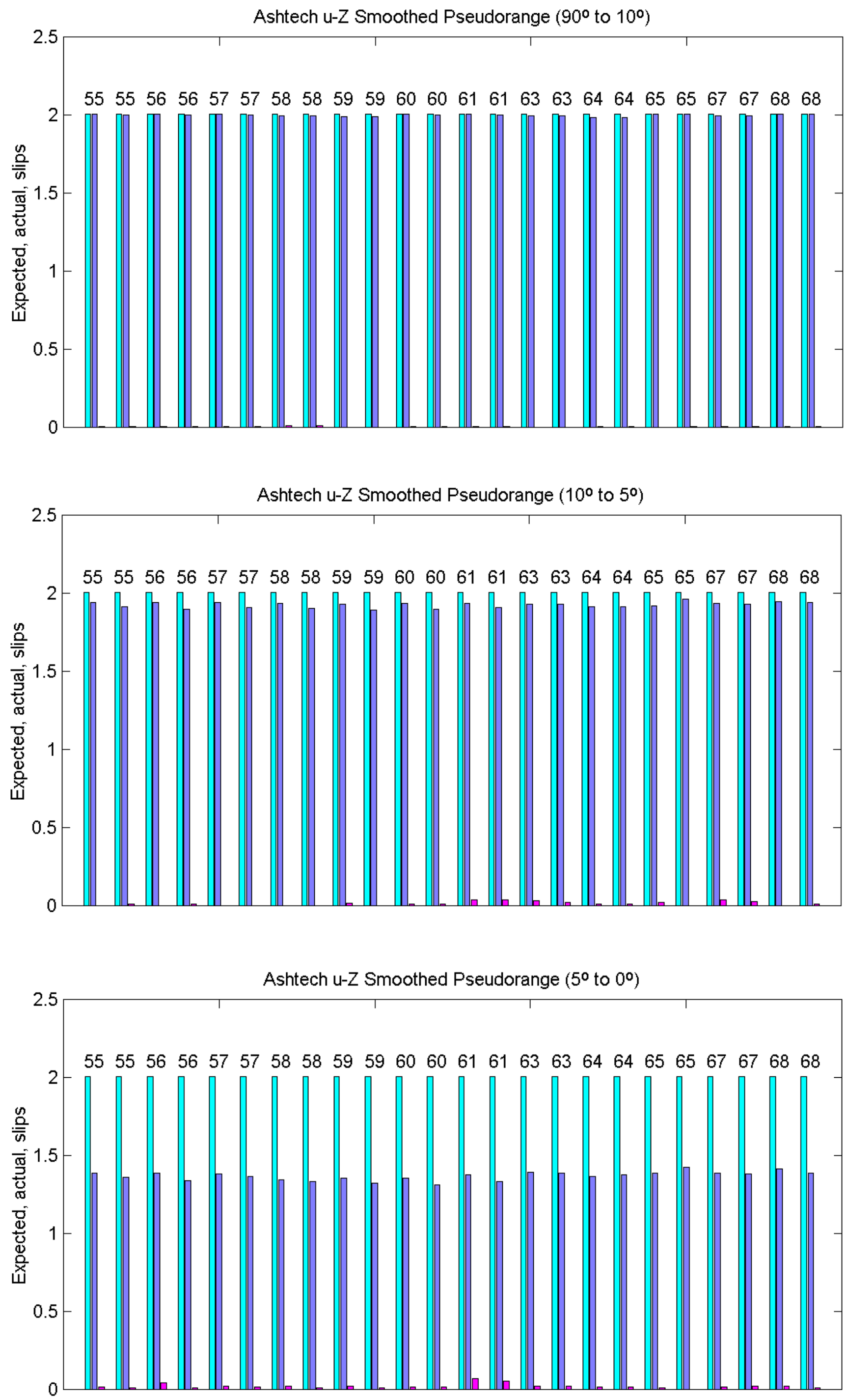


Figure 3-1: Ashtech u-Z smoothed pseudorange data and the Ashtech ASH701945.02B antenna. Expected data (light blue), observed data (dark blue), and cycle slips (magenta) over the elevation range 90°-10° (top), 10°-5° (middle), and 5°-0°(bottom). Acquisition day is shown at the top of each bar.

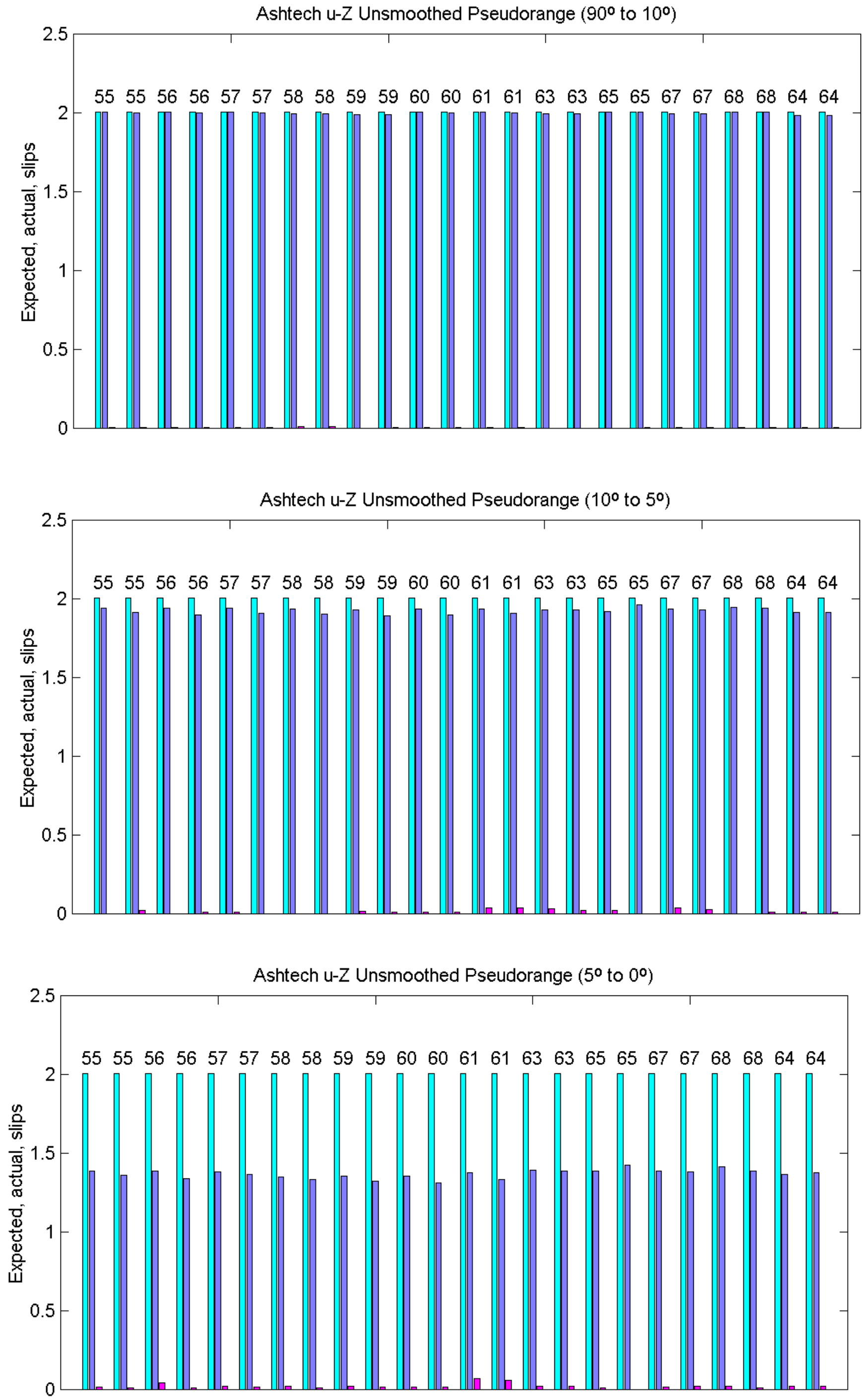


Figure 3-2: Ashtech u-Z with unsmoothed pseudorange data and the Ashtech ASH701945.02B antenna. Expected data (light blue), observed data (dark blue), and cycle slips (magenta) over the elevation range 90°-10° (top), 10°-5° (middle), and 5°-0°(bottom). Acquisition day is shown at the top of each bar.

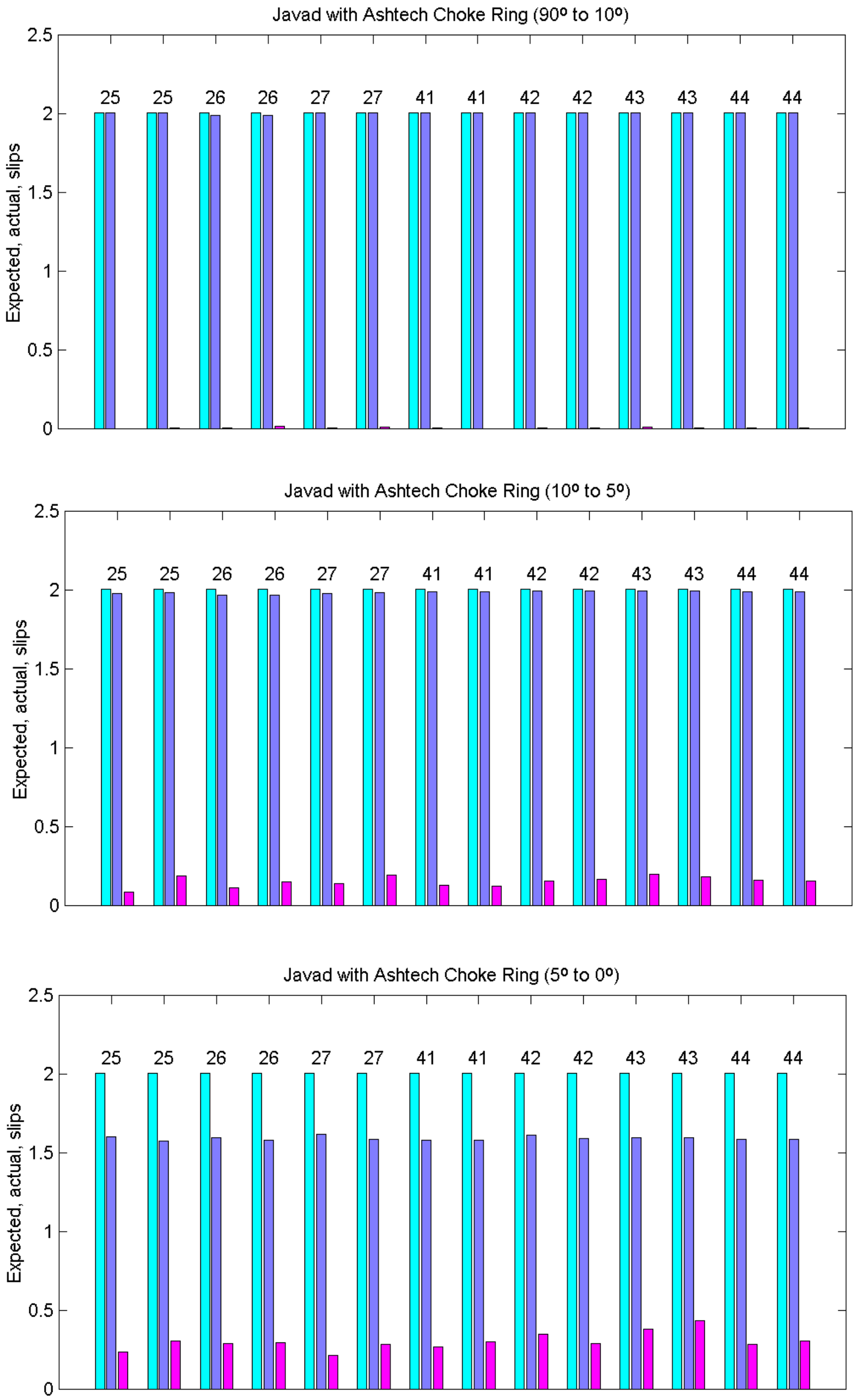


Figure 3-3: Javad Positioning Systems Legacy Receiver with Ashtech ASH701945.02B antenna. Expected data (light blue), observed data (dark blue), and cycle slips (magenta) over the elevation range 90°-10° (top), 10°-5° (middle), and 5°-0 °(bottom).

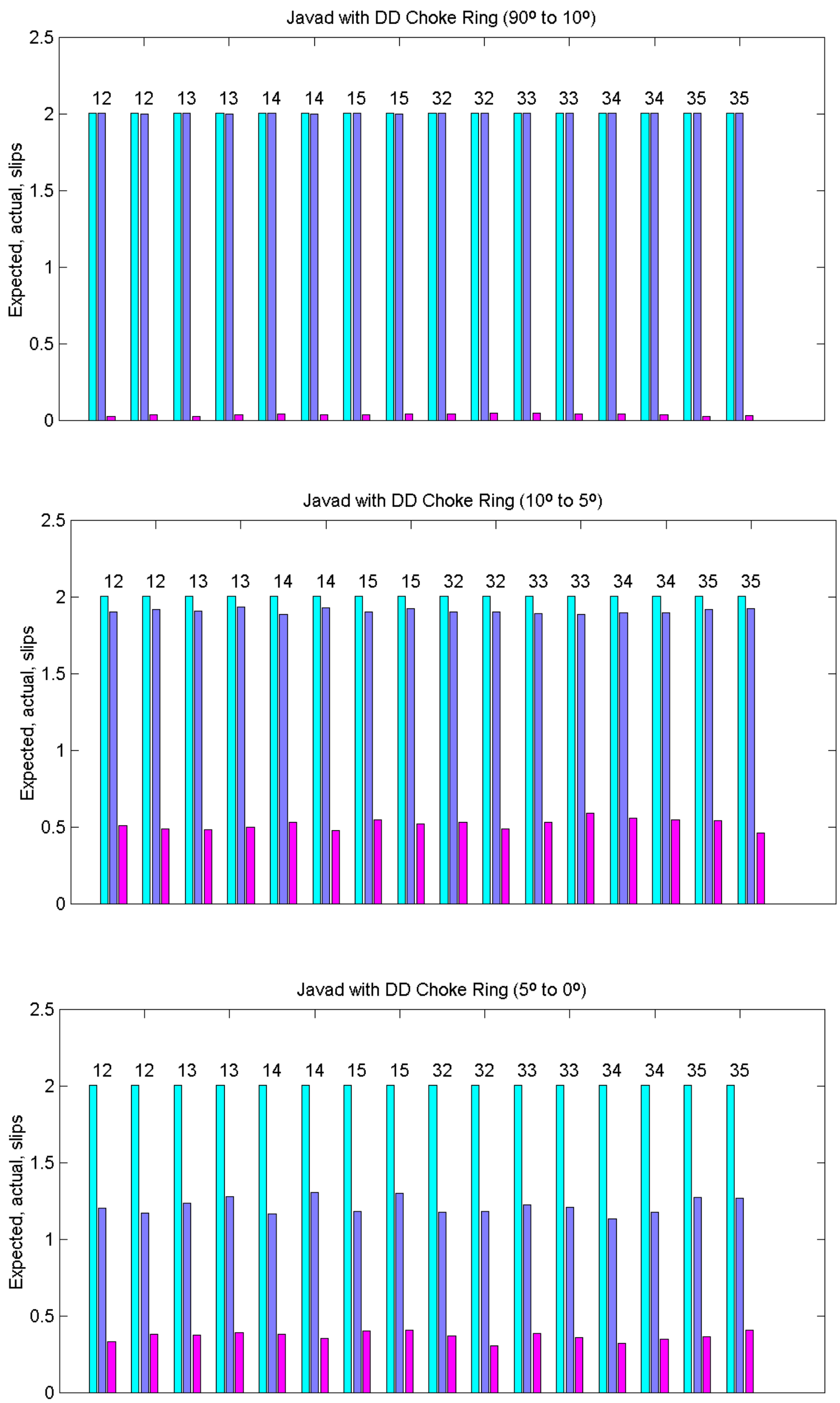


Figure 3-4: Javad Positioning Systems Legacy Receiver with JPS Regant Dual-Depth Choke Ring antenna. Expected data (light blue), observed data (dark blue), and cycle slips (magenta) over the elevation range 90°-10° (top), 10°-5° (middle), and 5°-0 °(bottom).

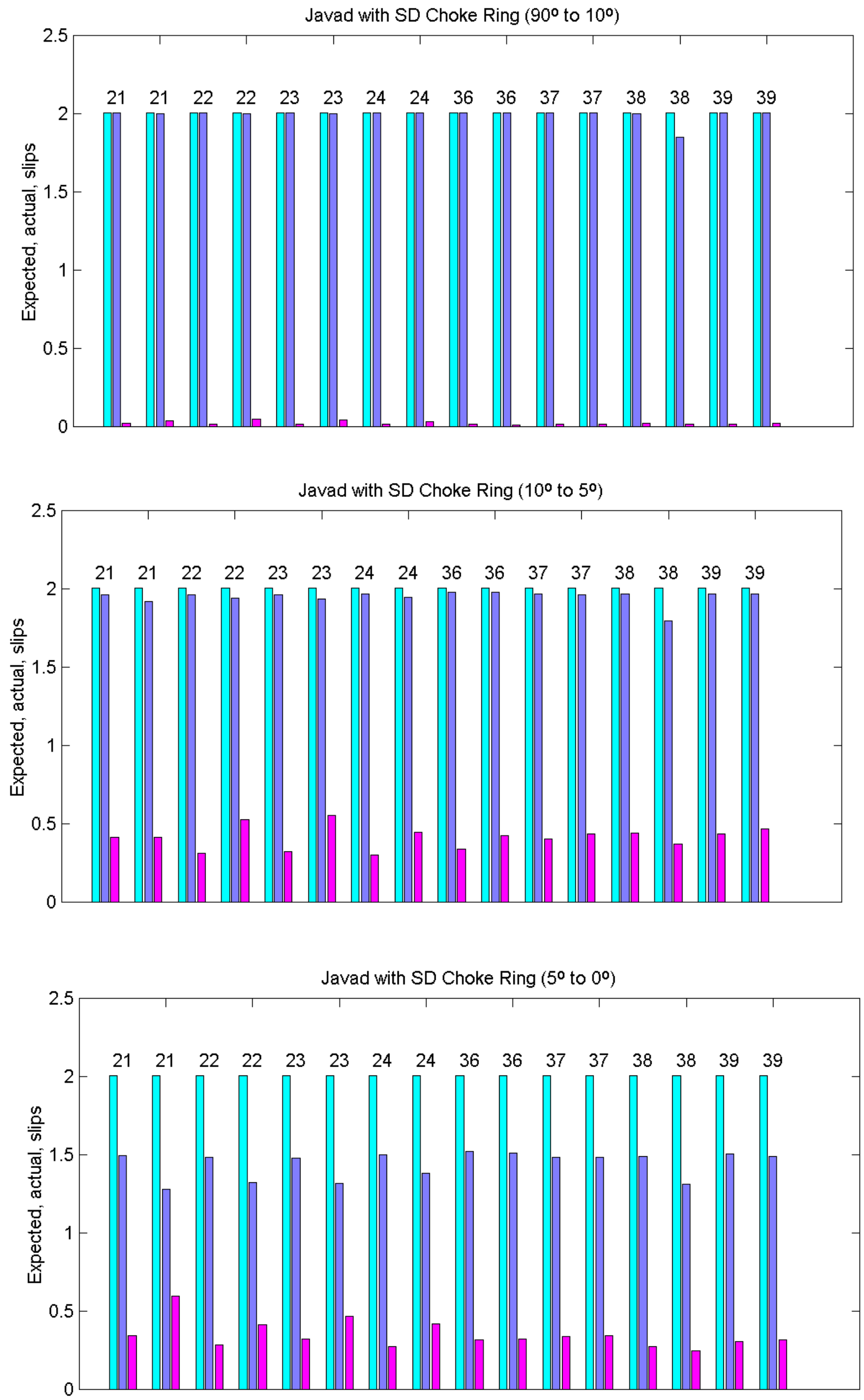


Figure 3-5: Javad Positioning Systems Legacy Receiver with JPS Regant Single-Depth Choke Ring antenna. Expected data (light blue), observed data (dark blue), and cycle slips (magenta) over the elevation range 90°-10° (top), 10°-5° (middle), and 5°-0 °(bottom).

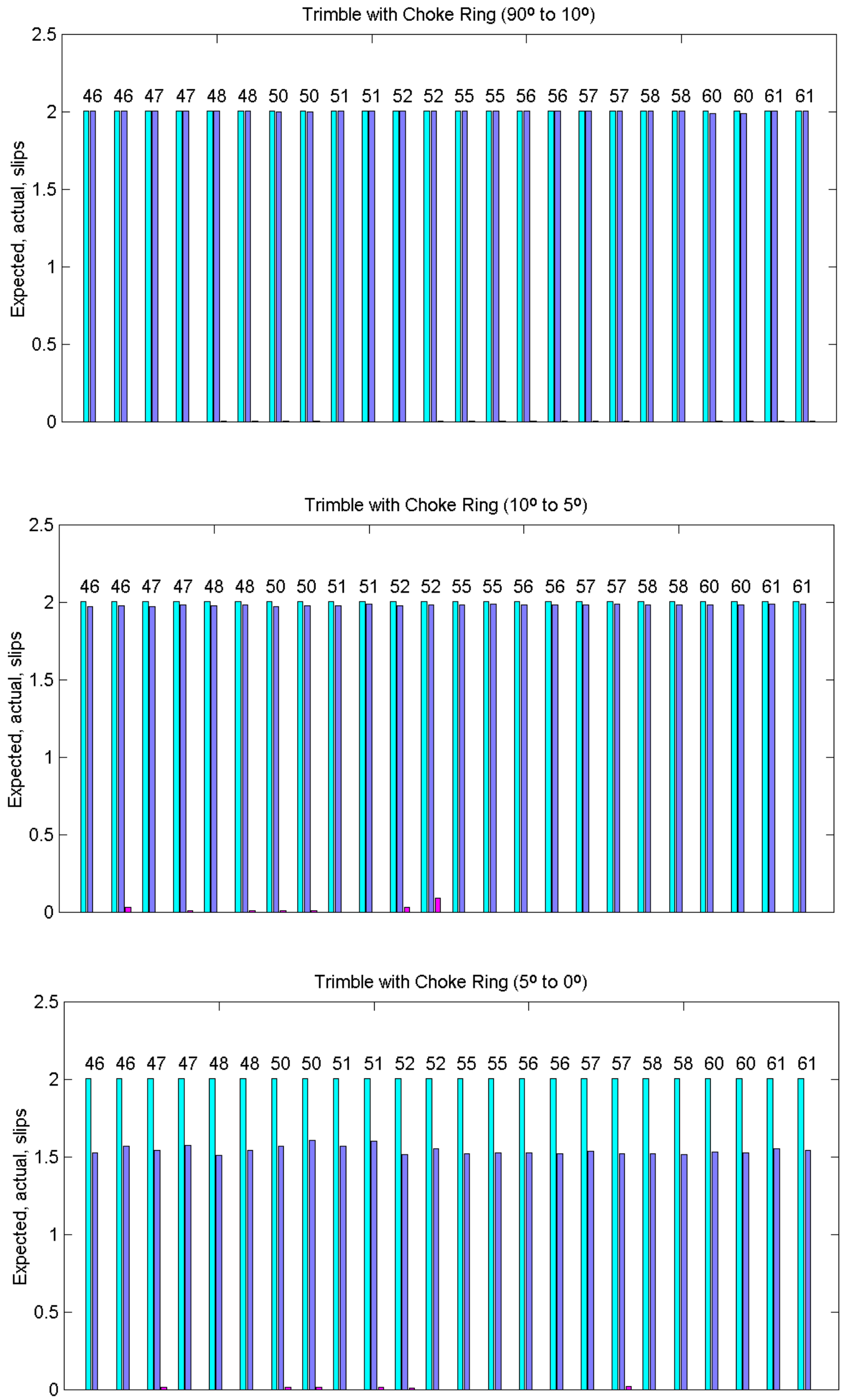


Figure 3-6: Trimble 4700 Receiver with TRM29659.00 Trimble Choke Ring antenna. Expected data (light blue), observed data (dark blue), and cycle slips (magenta) over the elevation range 90°-10° (top), 10°-5° (middle), and 5°-0 °(bottom).

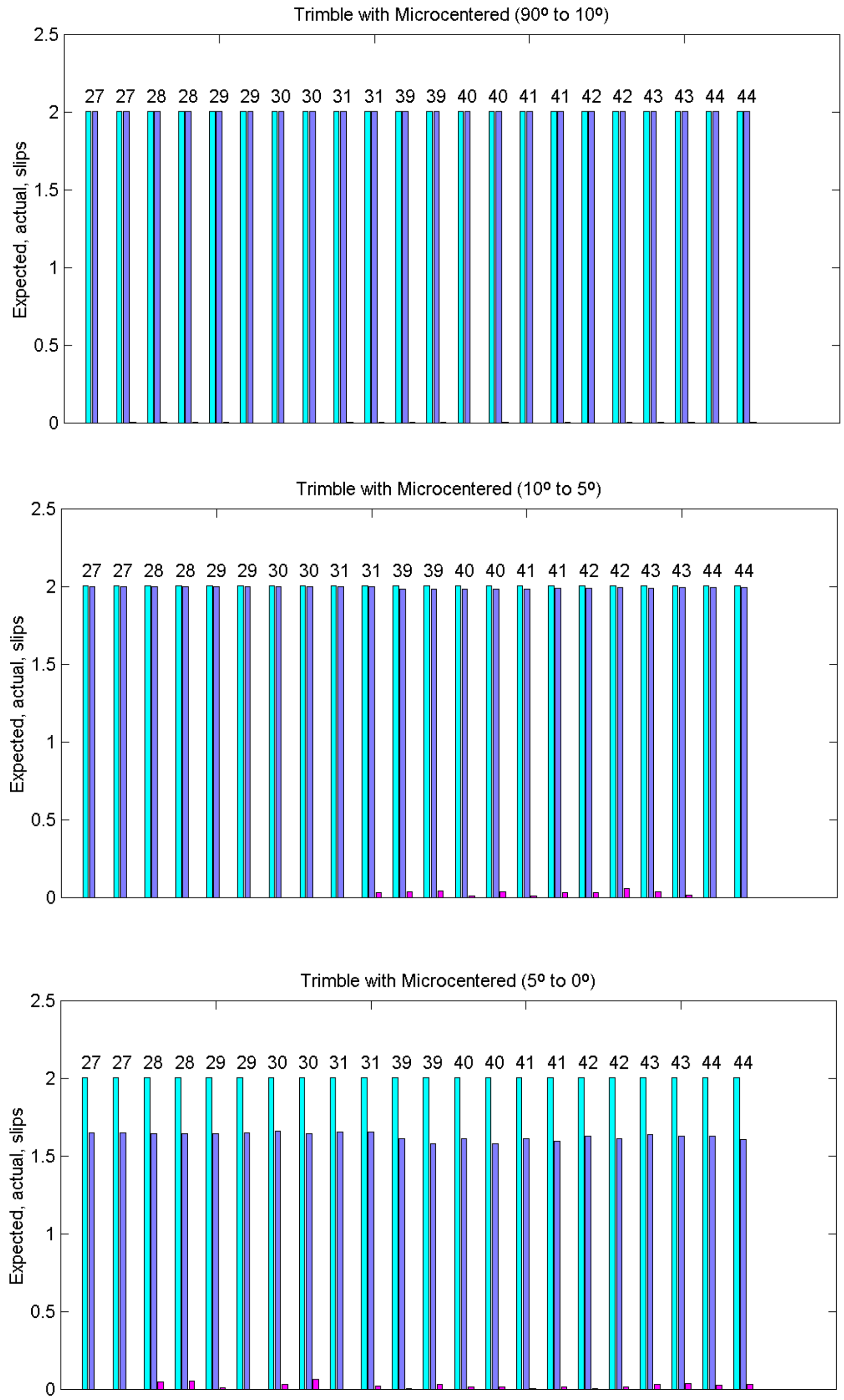


Figure 3-7: Trimble 4700 Receiver with TRM33429.00+GP Trimble Microcentered antenna. Expected data (light blue), observed data (dark blue), and cycle slips (magenta) over the elevation range 90°-10° (top), 10°-5° (middle), and 5°-0°(bottom).

The following tables present a summary of cumulative slips for each receiver over all data sets tested for the elevation ranges 90°-10°, 10°-5°, and 5°-0°. Note that the lower expected values for the Javad receiver/antenna combinations are not due to poor tracking, rather smaller data sets were taken so that the Javad receiver could be tested with the DD, SD, and Ashtech Choke Ring antenna.

Table 3-1: Total Expected and Observed data and Cycle Slips for the elevation interval 90° - 10°. Values in parentheses show percent of observed to expected and percent of slips to observed.

Receiver	Antenna	Expected	Observed	Slips
Ashtech u-Z (s)	Ashtech ASH701945.02B	1021287	1007963 (98.7)	84 (0.01)
Ashtech u-Z (u)	Ashtech ASH701945.02B	1021165	1007841 (98.7)	88 (0.01)
JPS Legacy	Ashtech ASH701945.02B	604040	600845 (99.5)	64 (0.01)
JPS Legacy	JPS DD Choke	695166	694102 (99.8)	625 (0.09)
JPS Legacy	JPS SD Choke	662375	647854 (97.8)	311 (0.05)
Trimble 4700	Trimble Choke	1019510	1015818 (99.6)	54 (0.01)
Trimble 4700	Trimble Microcentered	928395	928138 (100.0)	44 (0.00)

Table 3-2:Total Expected and Observed data and Cycle Slips for the elevation interval 10° - 5° degrees. Values in parentheses show percent of observed to expected and percent of slips to observed.

Receiver	Antenna	Expected	Observed	Slips
Ashtech u-Z (s)	Ashtech ASH701945.02B	128786	106941 (83.0)	35 (0.03)
Ashtech u-Z (u)	Ashtech ASH701945.02B	128753	106915 (83.0)	39 (0.04)
JPS Legacy	Ashtech ASH701945.02B	77441	74304 (95.5)	326 (0.44)
JPS Legacy	JPS DD Choke	91502	73420 (80.2)	2116 (2.88)
JPS Legacy	JPS SD Choke	85579	75962 (88.8)	1390 (1.83)
Trimble 4700	Trimble Choke	130313	124128 (95.3)	17 (0.01)
Trimble 4700	Trimble Microcentered	117324	114803 (97.9)	44 (0.04)

Table 3-3:Total Expected and Observed data and Cycle Slips for the elevation interval 5° - 0° degrees. Values in parentheses show percent of observed to expected and percent of slips to observed.

Receiver	Antenna	Expected	Observed	Slips
Ashtech u-Z (s)	Ashtech ASH701945.02B	138911	30985 (22.3)	60 (0.19)
Ashtech u-Z (u)	Ashtech ASH701945.02B	138874	30983 (22.3)	64 (0.21)
JPS Legacy	Ashtech ASH701945.02B	88137	33619 (38.1)	908 (2.70)
JPS Legacy	JPS DD Choke	101142	15777 (15.6)	1349 (8.55)
JPS Legacy	JPS SD Choke	96364	26626 (27.6)	1135 (4.26)
Trimble 4700	Trimble Choke	141475	48150 (34.0)	12 (0.02)
Trimble 4700	Trimble Microcentered	135990	56632 (41.6)	67 (0.12)

The bar charts and the summary tables indicate that the Javad receiver with the JPS Regant DD Choke Ring antenna show the greatest number of slips over all elevation ranges with a large (8.55%) percentage of slips in the 5°-0° degree range. In addition, the Javad Legacy with the JPS SD Choke Ring antenna also show a large number of cycle slips in all three elevation ranges. The Javad receiver with the Ashtech Choke Ring show the least number of slips for all the Javad receiver/antenna combinations, but a significantly greater number of slips than the other vendors.

We find no significant difference between the number of slips found in the Ashtech uZ with Ashtech Choke Ring (smoothed or unsmoothed) and the Trimble 4700 with either antenna in the ranges of 90°-10° and 10°-5°. However, the Trimble 4700 with the Micro-centered, and particularly the Trimble Choke Ring antenna, showed a greater percentage of actual to expected observations and a lower percentage of slips to actual observations in the low elevation range of 5°-0°.

3.2 MP1 and MP2 Tracking Statistics

3.2.1 MP1 and MP2 90°-10° elevation window

The following tables and graphs provide a summary of teqc MP1 and MP2 tracking statistics taken over the test period. First we present graphs and statistics for MP1 and MP2 for the elevation range 90°-10°. Note, for these graphs we simply report MP1 and MP2 as derived from the teqc summary line. Next we present MP1 and MP2 cycle slip statistics for the elevation ranges 10°-5° and 5°-0°. These graphs (Figures 3-9 - 3-14) and statistics (Tables 3-4 - 3-9) are normalized to the number of observations present in the particular elevation range. Multipath tracking plots (MP1 and MP2) are shown in Figures 3-15 - 3-20.

The teqc program scans each RINEX file and compiles statistics about the data, including number of observations, loss of lock indicator (LLI), slips according to MP and IOD detection parameters, and average MP1 and MP2 values. MP1 is a linear combination of C1, L1 and L2, MP2 is a linear combination of C2, L1, and L2 (see Estey and Meertens, 1999). MP1 and MP2 reflect pseudorange multipath plus receiver noise. TEQC also creates plot files of the ionosphere delay, first derivative of ionosphere delay, MP1, MP2, and elevation for each SV.

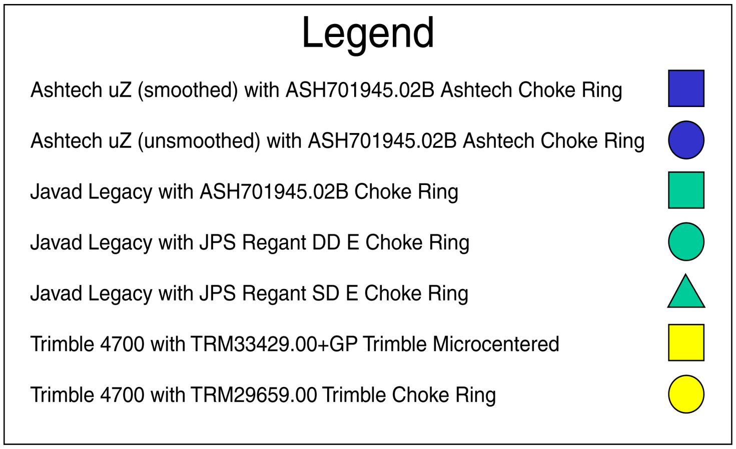


Figure 3-8: Legend for all scatter plots presented in this report. Ashtech uZ with smoothed pseudorange and the ASH701945.02B Ashtech Choke Ring antenna are shown as blue squares. Ashtech uZ with unsmoothed pseudorange and the ASH701945.02B Ashtech Choke Ring antenna are shown as blue circles.The Javad Legacy receiver with JPS Regant DD E, JPS Regant SD E, and Ashtech ASH701945.02B Choke ring antenna are shown as green circles, triangles, and squares respectively. The Trimble 4700 with TRM33429.00+GP Microcentered antenna and TRM29659.00 Choke Ring antenna are shown as yellow squares and circles respectively.

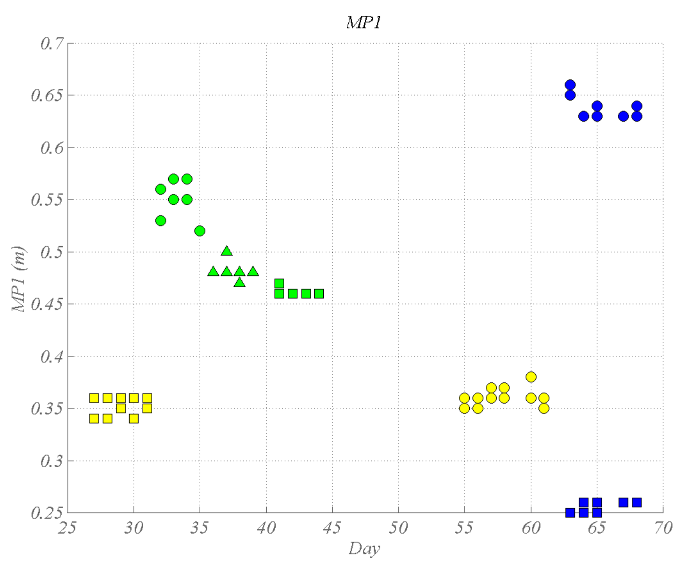


Figure 3-9: Zero baseline MP1 values for each receiver/antenna pair in the elevation range 90°–10°. MP1 is a linear combination of C1, L1 and L2 and provides an estimate of pseudorange multipath.

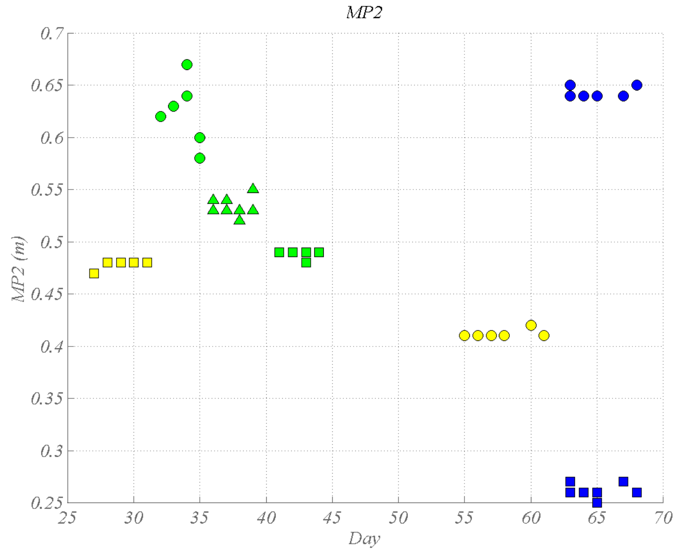


Figure 3-10: Zero baseline MP2 values for each receiver/antenna pair in the elevation range 90°–10°. MP2 is a linear combination of P2, L1 and L2 and provides an estimate of pseudorange multipath.

The Ashtech uZ with smoothed pseudoranges shows the lowest (best) values for MP1 (Table 3-4) followed by the Trimble 4700 with Microcentered and Choke Ring antennas. The Javad Legacy receiver, with the Ashtech Choke Ring, Regant SD, and Regant DD antennas in that order show next highest values. The Ashtech uZ with unsmoothed pseudoranges shows the highest (worst) overall values for MP1. See Figure 3-15 and 3-16 for a trace of MP1 and MP2 values with time for all receiver/antenna pairs.

Table 3-4:Summary of MP1 for zero baseline data in elevation range 90°–10°.

Receiver	Antenna	Mean	RMS	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.26	<0.01	0.25	0.26
Ashtech u-Z (u)	ASH701945.02B	0.64	0.01	0.63	0.66
JPS Legacy	ASH701945.02B	0.46	<0.01	0.46	0.47
JPS Legacy	JPS Regant DD E	0.55	0.02	0.52	0.57
JPS Legacy	JPS Regant SD E	0.48	0.01	0.47	0.50
Trimble 4700	TRM33429.00+GP	0.35	0.01	0.34	0.36
Trimble 4700	TRM29659.00	0.36	0.01	0.35	0.38

Table 3-5:Summary of MP2 for zero baseline data in elevation range 90°–10°

Receiver	Antenna	Mean	RMS	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.26	0.01	0.25	0.27
Ashtech u-Z (u)	ASH701945.02B	0.64	<0.01	0.64	0.65
JPS Legacy	ASH701945.02B	0.49	<0.01	0.48	0.49
JPS Legacy	JPS Regant DD E	0.62	0.03	0.58	0.67
JPS Legacy	JPS Regant SD E	0.53	0.01	0.52	0.55

Table 3-5:Summary of MP2 for zero baseline data in elevation range 90°–10°

Receiver	Antenna	Mean	RMS	Min	Max
Trimble 4700	TRM33429.00+GP	0.48	<0.01	0.47	0.48
Trimble 4700	TRM29659.00	0.41	<0.01	0.41	0.42

The Ashtech uZ with smoothed pseudoranges shows the lowest (best) values for MP2 followed by the Trimble 4700 with Choke Ring antenna. The Trimble 4700 with Microcentered antenna and the Javad Legacy receiver with Ashtech Choke Ring antenna show similar results. The highest values (worst) are from the Javad Legacy receiver with JPS DD Choke Ring antennas and the Ashtech uZ with unsmoothed pseudoranges.

3.2.2 MP1 and MP2 slips in 10°-5° elevation window

The following graphs present the tracking statistics for MP1 and MP2 slips, normalized to the number of observations for the elevation range 10°-5°.

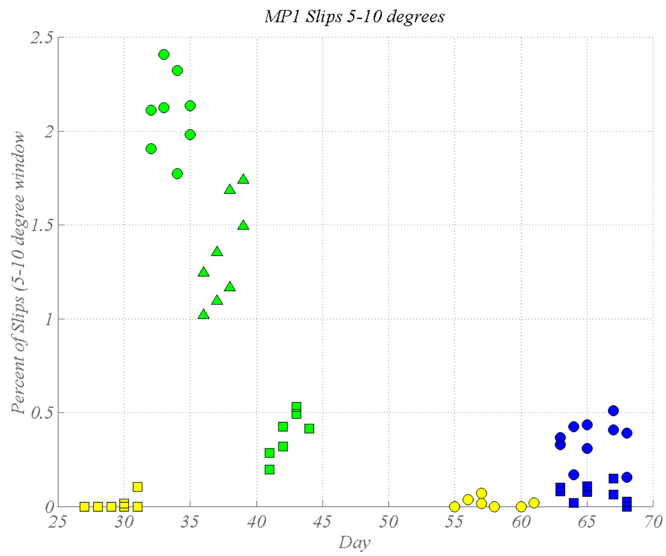


Figure 3-11: Plot of MP1 slips for zero baseline observations for the 10°-5° tracking window. Values are represented as a percentage of observations acquired in the 10°-5° tracking window.

Table 3-6:Summary of MP1 tracking statistics for zero baseline data in the elevation range 10°–5°. Values indicate % of slips within the elevation range.

Receiver	Antenna	Mean	RMS	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.07	0.05	<0.01	0.15
Ashtech u-Z (u)	ASH701945.02B	0.35	0.11	0.16	0.51
JPS Legacy	ASH701945.02B	0.39	0.10	0.20	0.53
JPS Legacy	JPS Regant DD E	2.10	0.20	1.77	2.41
JPS Legacy	JPS Regant SD E	1.35	0.25	1.02	1.74
Trimble 4700	TRM33429.00+GP	0.01	0.03	<0.01	0.11
Trimble 4700	TRM29659.00	0.02	0.02	<0.01	0.07

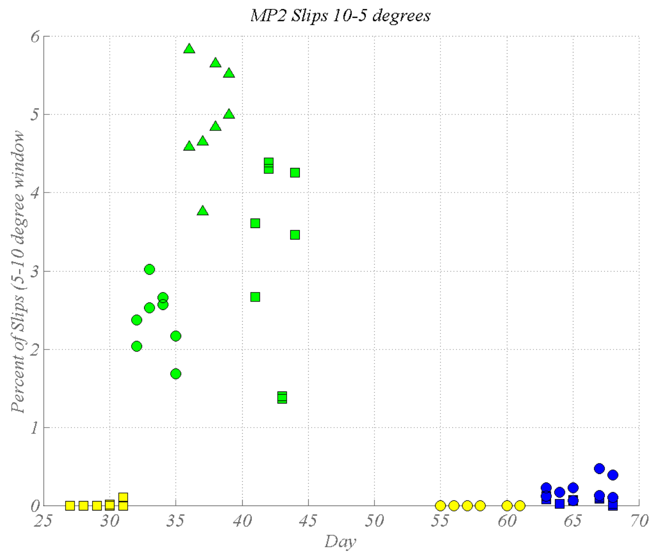


Figure 3-12: Plot of MP2 slips for zero baseline observations for the 10°-5° tracking window. Values are represented as a percentage of observations acquired in the 10°-5° tracking window.

Table 3-7:Summary of MP2 tracking statistics for zero baseline data in the elevation range 10°–5°. Values indicate % of slips within the elevation range.

Receiver	Antenna	Mean	RMS	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.06	0.04	<0.01	0.12
Ashtech u-Z (u)	ASH701945.02B	0.21	0.12	0.07	0.47
JPS Legacy	ASH701945.02B	3.18	1.16	1.36	4.38
JPS Legacy	JPS Regant DD E	2.38	0.39	1.69	3.02
JPS Legacy	JPS Regant SD E	4.98	0.64	3.76	5.82
Trimble 4700	TRM33429.00+GP	0.01	0.03	<0.01	0.11
Trimble 4700	TRM29659.00	<0.01	<0.01	<0.01	<0.01

The Trimble 4700 receiver with TRM33429.00+GP, 4700 with TRM29659.00, and Ashtech uZ with pseudorange smoothing show the lowest overall values for percent MP1 slips in the elevation window 10°-5°. The Ashtech uZ with unsmoothed pseudoranges and Javad Legacy with the Ashtech Choke ring show the next lowest values. The Javad Legacy with SD and DD Choke Ring antennas show the largest day-to-day spread and the worst overall results for percent MP1 slips in the elevation window 10°-5°.

The Trimble 4700 receiver with TRM29659.00 and 4700 with TRM33429.00+GP followed by the Ashtech uZ with pseudorange smoothing show the lowest overall values for percent MP2 slips in the elevation window 10°-5°. The Ashtech uZ receiver with unsmoothed pseudoranges shows the next best results. The Javad Legacy with DD, Ashtech Choke Ring antenna, and SD Choke Ring antennas respectively show the largest day-to-day spread and the worst overall results for percent MP2 slips in the elevation window 10°-5°.

3.2.3 MP1 and MP2 5°-0° elevation window

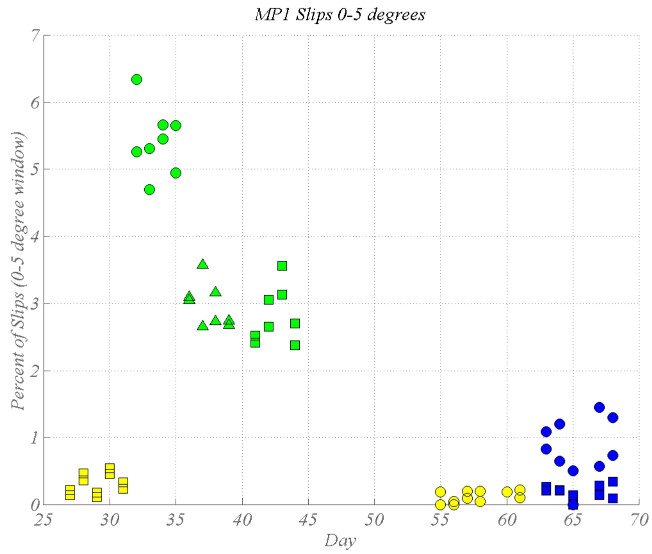


Figure 3-13: Plot of MP1 slips for zero baseline observations for the 5°-0° tracking window. Slips are represented as a percentage of observations acquired in the 5°-0° tracking window.

Table 3-8:Summary of MP1 tracking statistics for zero baseline data in the elevation range 5°–0°. Values indicate % of slips within the elevation range.

Receiver	Antenna	Mean	RMS	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.19	0.10	<0.01	0.35
Ashtech u-Z (u)	ASH701945.02B	0.83	0.41	<0.01	0.35
JPS Legacy	ASH701945.02B	2.80	0.39	2.38	3.56
JPS Legacy	JPS Regant DD E	5.42	0.47	4.70	6.35
JPS Legacy	JPS Regant SD E	2.96	0.30	2.65	3.57
Trimble 4700	TRM33429.00+GP	0.31	0.14	0.11	0.55
Trimble 4700	TRM29659.00	0.13	0.08	<0.01	0.22

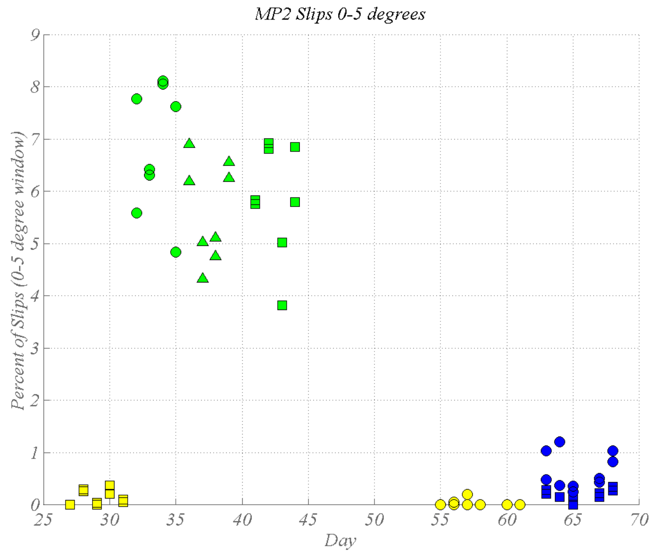


Figure 3-14: Plot of MP2 slips for zero baseline observations for the 5°-0° tracking window. Slips are represented as a percentage of observations acquired in the 5°-0° tracking window.

Table 3-9:Summary of MP2 for zero baseline data in the elevation range 5°–0°. Values indicate % of slips within the elevation range.

Receiver	Antenna	Mean	RMS	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.19	0.09	<0.01	0.35
Ashtech u-Z (u)	ASH701945.02B	0.65	0.33	0.24	1.21
JPS Legacy	ASH701945.02B	5.85	0.99	3.82	6.92
JPS Legacy	JPS Regant DD E	6.84	1.15	4.83	8.12
JPS Legacy	JPS Regant SD E	5.64	0.89	4.32	6.90
Trimble 4700	TRM33429.00+GP	0.13	0.13	<0.01	0.36
Trimble 4700	TRM29659.00	0.02	0.06	<0.01	0.20

The Trimble 4700 receiver with TRM29659.00 antenna and the Ashtech uZ with pseudorange smoothing show the best results for percent MP1 slips in the elevation window 5°-0°. The 4700 with TRM33429.00+GP and the Ashtech uZ with unsmoothed pseudoranges show the next best results. The Javad Legacy with Regant SD and Ashtech Choke Ring antennas show nearly identical results. The Javad Legacy with Regant DD shows the worst performance for percent MP1 slips in the elevation window 5°-0°.

The Trimble 4700 receiver with TRM29659.00 followed by the 4700 with TRM33429.00+GP and Ashtech uZ receiver with smoothed pseudoranges show the best (lowest) overall values for percent MP2 slips in the elevation window 5°-0°. The Javad Legacy with Regant SD, Ashtech Choke Ring, and Regant DD show the highest (worst) results respectively for percent MP2 slips in the elevation window 5°-0°.

3.2.4 MP1 and MP2 tracking plots

Next we present epoch-by-epoch tracking plots of MP1 and MP2 values for over the elevation range 90°-0°.

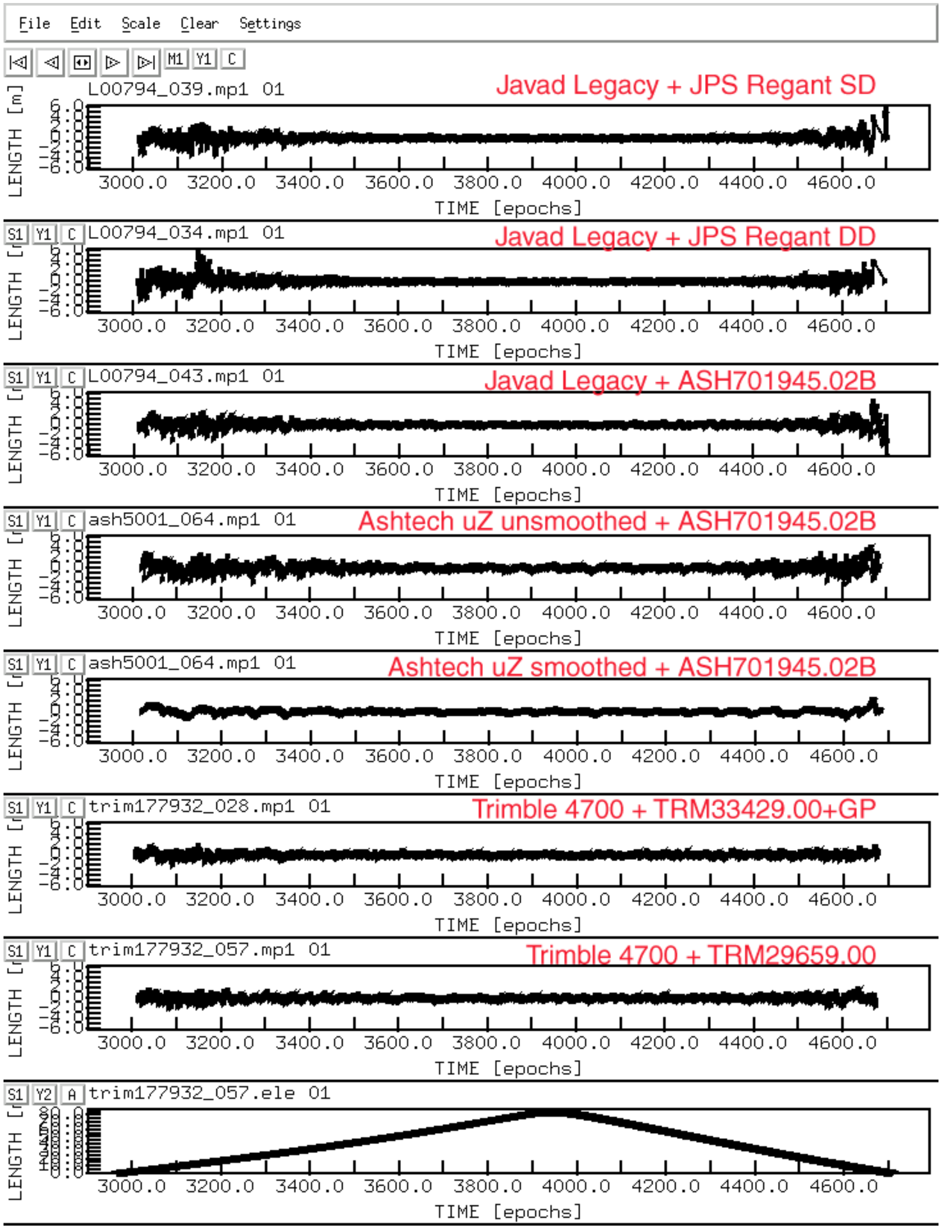


Figure 3-15: 90°-0° MP1 trace for satellite 01. Data are from receivers on the same monument but different days. Traces have been shifted so the tracking geometry is the same. The vertical scale is from -6 to 6 cm. Traces from top to bottom are: Javad Legacy receiver with JPS Regant SD E, JPS Regant DD E, Ashtech ASH701945.02B antennas, Ashtech uZ with unsmoothed pseudorange and ASH701945.02B antenna, Ashtech uZ with smoothed pseudorange and ASH701945.02B antenna, Trimble 4700 with TRM33429.00+GP antenna, and Trimble 4700 with TRM29659.00 antenna. Bottom trace shows satellite elevation over the tracking period.

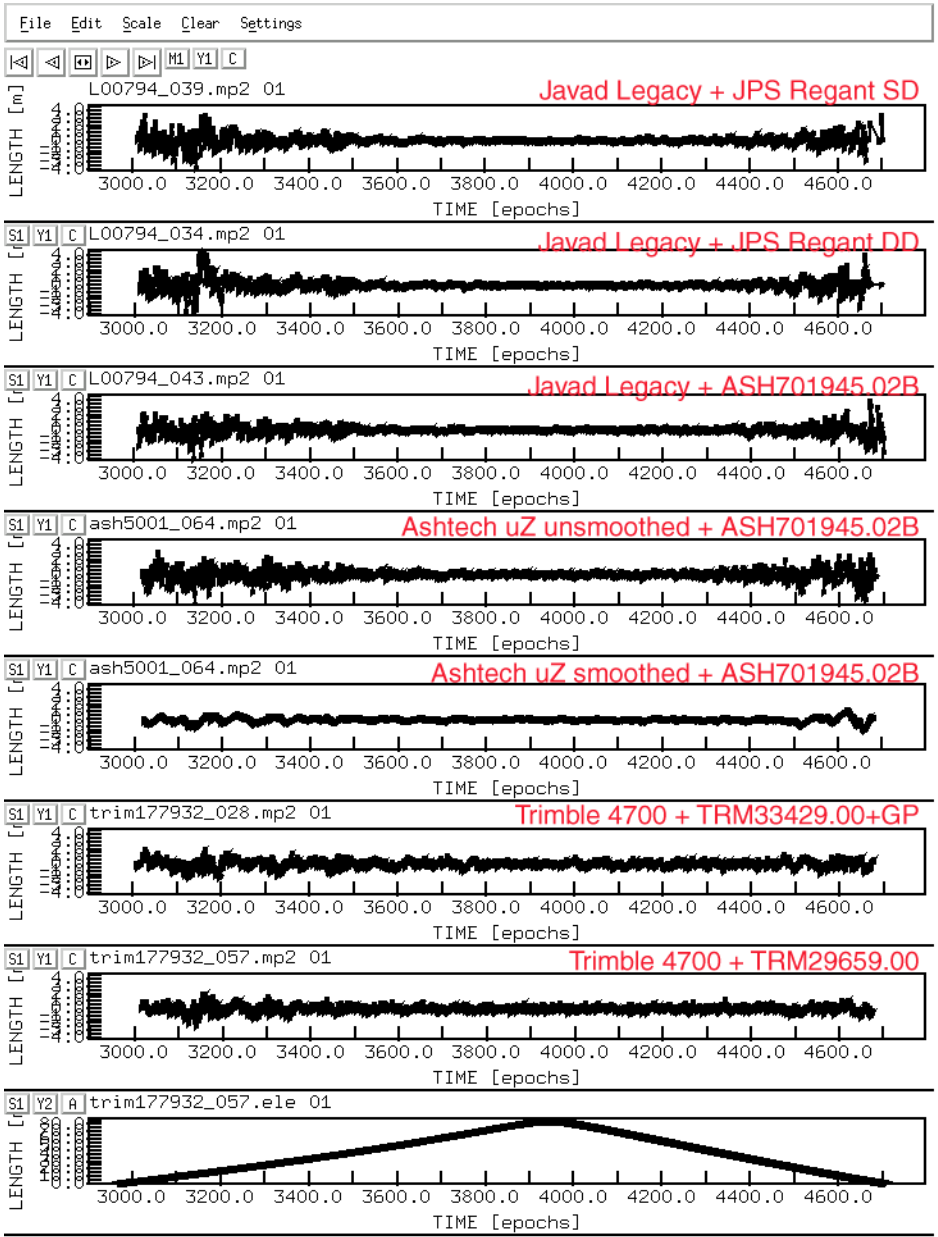


Figure 3-16: 90°–0° MP2 trace for satellite 01. The vertical scale is from -4 to 4 cm.Traces from top to bottom are: Javad Legacy receiver with JPS Regant SD E, JPS Regant DD E, Ashtech ASH701945.02B antennas, Ashtech uZ with unsmoothed pseudorange and ASH701945.02B antenna, Ashtech uZ with smoothed pseudorange and ASH701945.02B antenna, Trimble 4700 with TRM33429.00+GP antenna, and Trimble 4700 with TRM29659.00 antenna. Bottom trace shows satellite elevation over the tracking period.

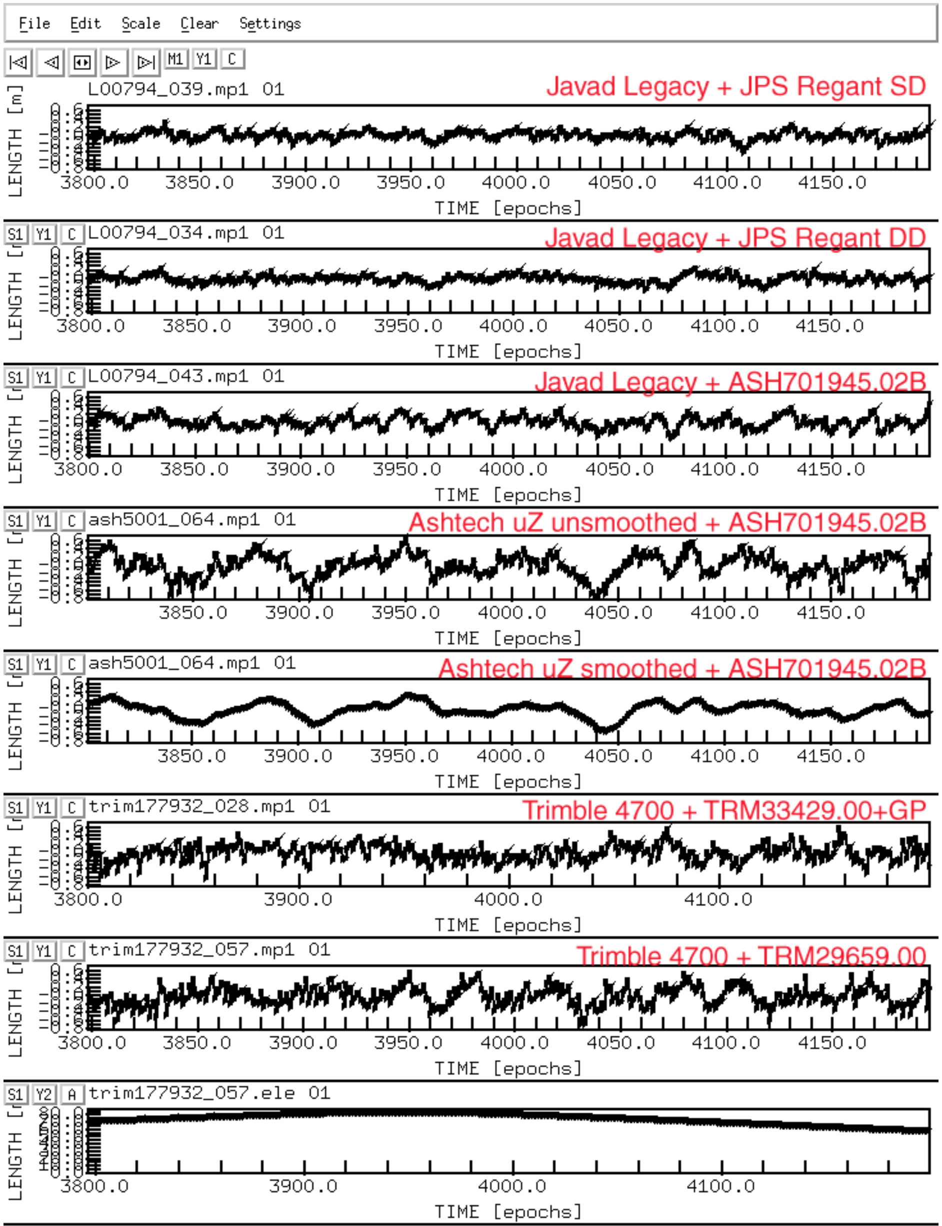


Figure 3-17: Zoom of high elevation MP1 trace for satellite 01. Zoomed area represents tracking from 70°-80°. The vertical scale is from -8 to 6 cm. Traces from top to bottom are: Javad Legacy receiver with JPS Regant SD E, JPS Regant DD E, Ashtech ASH701945.02B antennas, Ashtech uZ with unsmoothed pseudorange and ASH701945.02B antenna, Ashtech uZ with smoothed pseudorange and ASH701945.02B antenna, Trimble 4700 with TRM33429.00+GP antenna, and Trimble 4700 with TRM29659.00 antenna. Bottom trace shows satellite elevation over the tracking period.

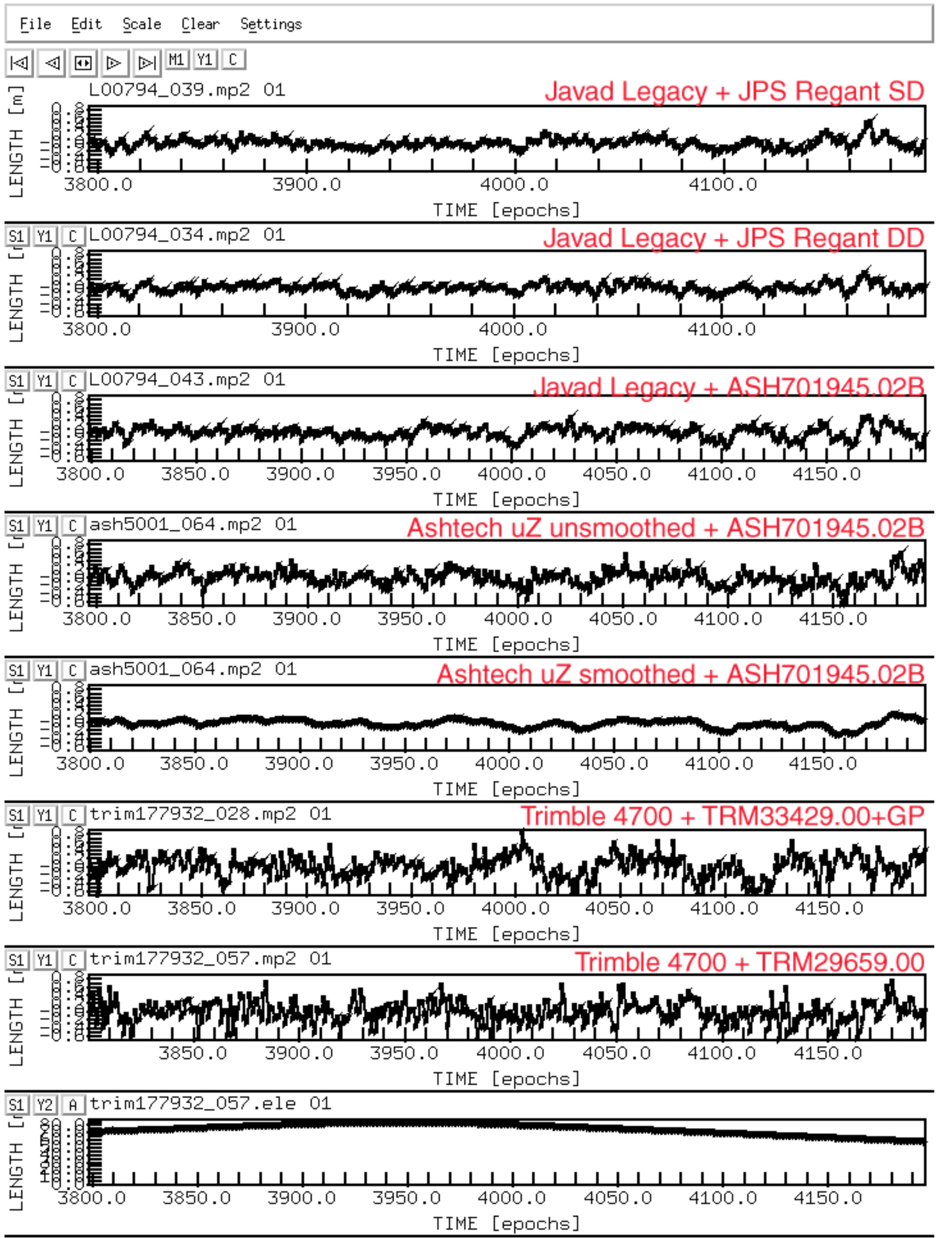


Figure 3-18: Zoom of high elevation MP2 trace for satellite 01. Zoomed area represents tracking from 70°-80°. The vertical scale is from -6 to 8 cm.Traces from top to bottom are: Javad Legacy receiver with JPS Regant SD E, JPS Regant DD E, Ashtech ASH701945.02B antennas, Ashtech uZ with unsmoothed pseudorange and ASH701945.02B antenna, Ashtech uZ with smoothed pseudorange and ASH701945.02B antenna, Trimble 4700 with TRM33429.00+GP antenna, and Trimble 4700 with TRM29659.00 antenna. Bottom trace shows satellite elevation over the tracking period.

3.2.5 Low elevation MP1 and MP2 tracking plots

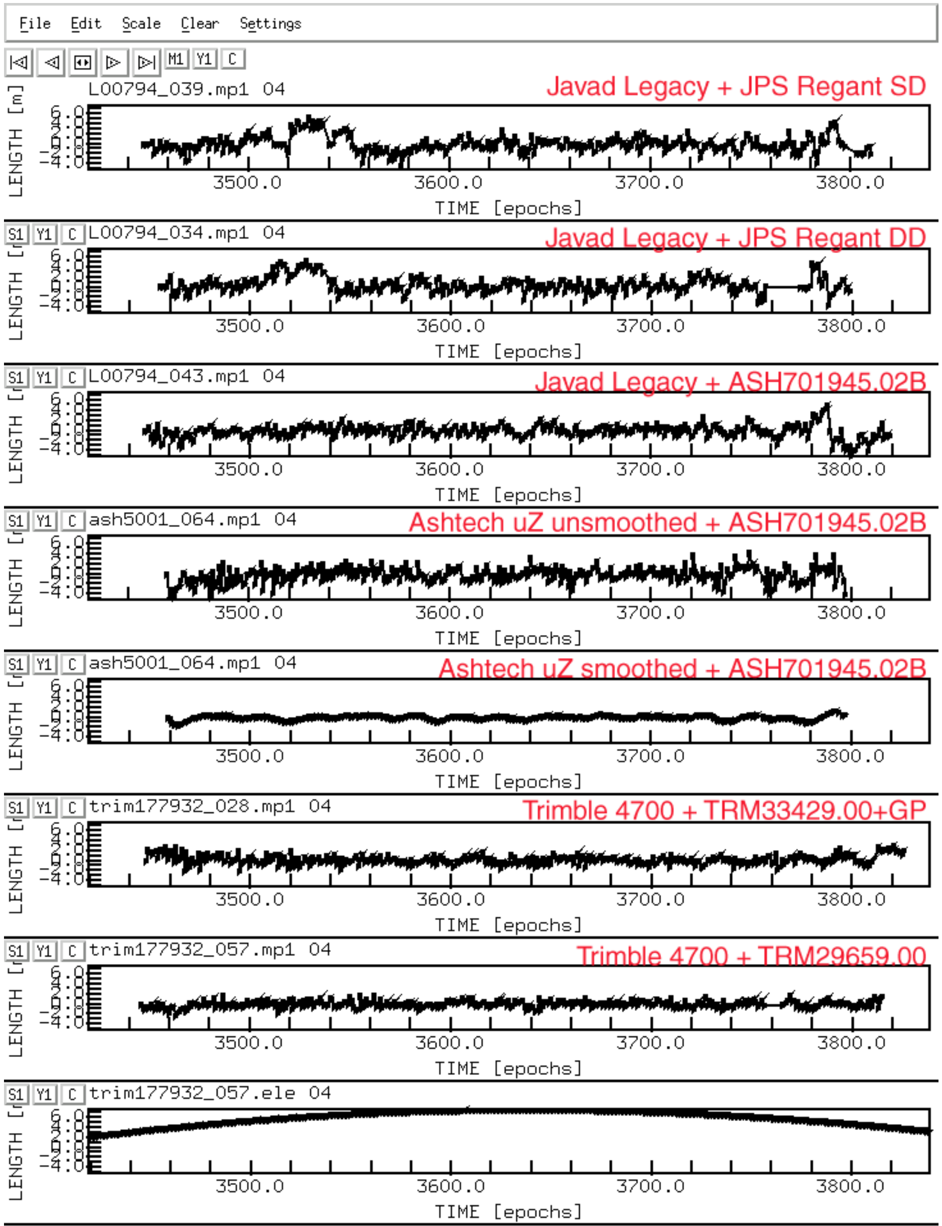


Figure 3-19: Low elevation MP1 trace for satellite 04 over tracking elevation 0°-7°. The vertical scale is from -4 to 6 cm.Traces from top to bottom are: Javad Legacy receiver with JPS Regant SD E, JPS Regant DD E, Ashtech ASH701945.02B antennas, Ashtech uZ with unsmoothed pseudorange and ASH701945.02B antenna, Ashtech uZ with smoothed pseudorange and ASH701945.02B antenna, Trimble 4700 with TRM33429.00+GP antenna, and Trimble 4700 with TRM29659.00 antenna. Bottom trace shows satellite elevation over the tracking period.

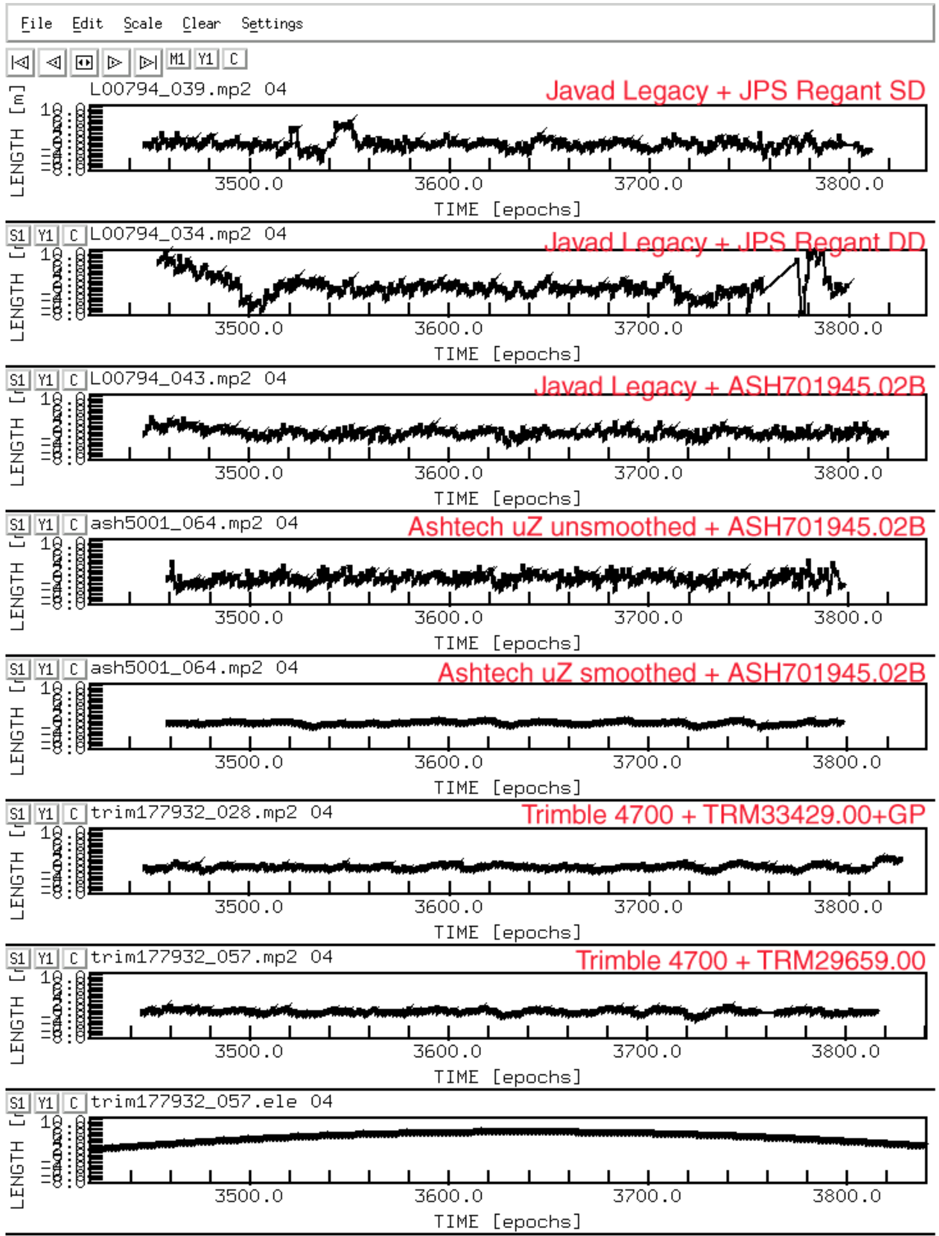


Figure 3-20: Low elevation MP2 trace for satellite 04 over tracking elevation 0°-7°. The vertical scale is from -8 to 10 cm. Traces from top to bottom are: Javad Legacy receiver with JPS Regant SD E, JPS Regant DD E, Ashtech ASH701945.02B antennas, Ashtech uZ with unsmoothed pseudorange and ASH701945.02B antenna, Ashtech uZ with smoothed pseudorange and ASH701945.02B antenna, Trimble 4700 with TRM33429.00+GP antenna, and Trimble 4700 with TRM29659.00 antenna. Bottom trace shows satellite elevation over the tracking period.

The traces presented above provide a qualitative look at MP1 and MP2 tracking statistics over different elevation ranges. The Ashtech uZ receiver shows the best results over the entire elevation range and at low elevation tracking if smoothed pseudoranges are used (Figure 3-17 and 3-18). If unsmoothed pseudorange values are used the Trimble 4700 with TRM29659.00 and TRM33429.00+GP antennas show best overall performance over the entire elevation range. The Javad Legacy receivers provide the overall best performance at high elevation angles (Figure 3-17 and 3-18, also see Manufacturers statement at the end of the report).

3.3 Observations per Slip

The following tables and graphs provide a summary of teqc observation per slip tracking statistics taken over the test period. The graph (Figure 3-21) represents the total number of observations recorded, divided by the combined MP1/MP2 and IOD slips detected over the elevation range. Higher numbers indicate better overall tracking performance. Table 3-10 presents the mean, standard deviation, minimum, and maximum values for the data shown in Figure 3-21.

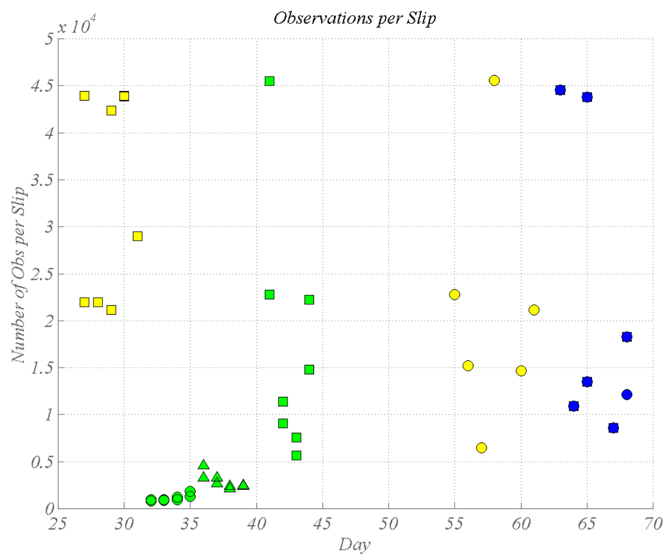


Figure 3-21: Plot of zero baseline, observations per slip for each receiver/antenna pair. High values of Observations per Slip indicate better overall tracking.

As shown earlier in the report (Tables 3-1 through 3-3), pseudorange smoothing does not substantially decrease the number of slips in the data set. Each of the manufacturers show a large spread in the observations per slip data. Based on Table 3-10, the Trimble 4700 with Microcentered antenna show the best overall results, followed by the Ashtech uZ (smoothed and unsmoothed pseudorange) with Choke Ring, Trimble 4700 with Choke Ring, and Javad Legacy with Ashtech Choke Ring.

Table 3-10:Observations per Slip

Receiver	Antenna	Mean	Stdev	Min	Max
Ashtech u-Z (s)	ASH701945.02B	22198	14817	8590	44560
Ashtech u-Z (u)	ASH701945.02B	21587	15087	8589	44553
JPS Legacy	ASH701945.02B	17386	12186	5691	45520
JPS Legacy	JPS Regant DD E	1120	306	841	1832
JPS Legacy	JPS Regant SD E	2887	736	2108	4548
Trimble 4700	TRM33429.00+GP	31907	9854	21180	43908
Trimble 4700	TRM29659.00	20973	12180	6508	45560

3.4 IOD Tracking Statistics

IOD is defined as the time derivative of the ionospheric delay. For our analysis, we assume that a rate of change larger than 400 cm/min in IOD is a phase cycle slip. The following graphs provide a summary of IOD slips converted to percent of observations in the 10°-5° and 5°-0° tracking window. Smaller numbers indicate fewer slips per observation and better phase tracking within the elevation window. Note that pseudorange smoothing has negligible effect on IOD statistics (Tables 3-11 and 3-12).

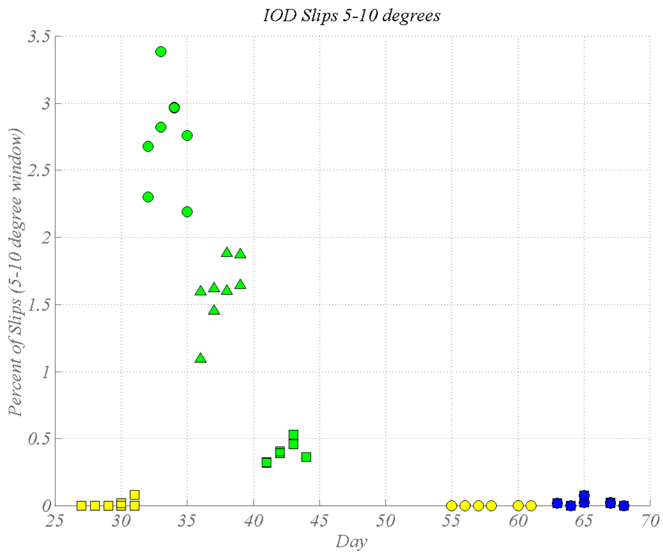


Figure 3-22: Plot of IOD slips for zero baseline observations for the 10°-5° tracking window. Slips are represented as a percentage of observations acquired in the 10°-5° tracking window. See Figure 3-8 for a scatter plot legend.

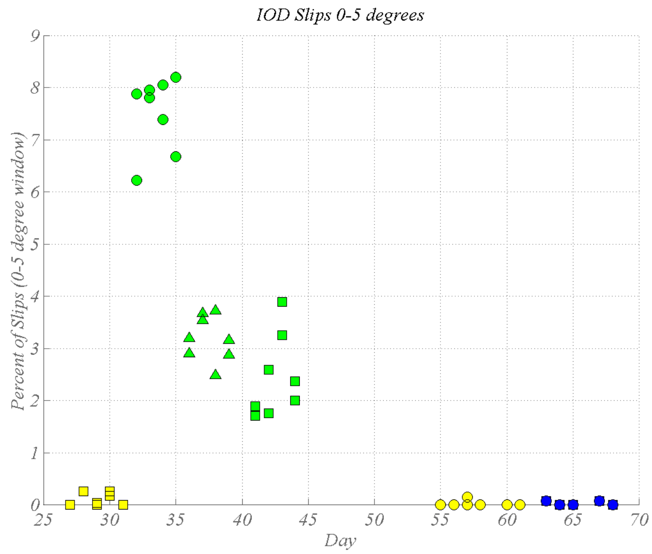


Figure 3-23: Plot of IOD slips for zero baseline observations for the 5°-0° tracking window. Slips are represented as a percentage of observations acquired in the 5°-0° tracking window.

Table 3-11: IOD Slips 10°-5°

Receiver	Antenna	Mean	Stdev	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.02	0.02	<0.01	0.08
Ashtech u-Z (u)	ASH701945.02B	0.02	0.02	<0.01	0.08
JPS Legacy	ASH701945.02B	0.40	0.07	0.32	0.53
JPS Legacy	JPS Regant DD E	2.76	0.36	2.19	3.38
JPS Legacy	JPS Regant SD E	1.60	0.23	1.09	1.88
Trimble 4700	TRM33429.00+GP	0.01	0.02	<0.01	0.08
Trimble 4700	TRM29659.00	<0.01	<0.01	<0.01	<0.01

Table 3-12: IOD Slips 0°-5°

Receiver	Antenna	Mean	Stdev	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.03	0.03	<0.01	0.07
Ashtech u-Z (u)	ASH701945.02B	0.03	0.03	<0.01	0.07
JPS Legacy	ASH701945.02B	2.43	0.73	1.71	3.89
JPS Legacy	JPS Regant DD E	7.52	0.67	6.23	8.20
JPS Legacy	JPS Regant SD E	3.19	0.41	2.48	3.72
Trimble 4700	TRM33429.00+GP	0.10	0.11	<0.01	0.25
Trimble 4700	TRM29659.00	0.01	0.04	<0.01	0.15

The Trimble 4700 with Choke Ring, Trimble 4700 with Microcentered, and the Ashtech uZ (smoothed and unsmoothed) show very low values for percent of IOD slips in the 10°-5° tracking window. The Javad receiver/antenna combinations show higher percentages with the Legacy with the Ashtech Choke ring providing the best results for the group. For IOD slips in the 5-0 degree tracking window the Trimble 4700 with Choke Ring show the best results followed closely by the Ashtech uZ (smoothed and unsmoothed) with Ashtech Choke ring. The Trimble 4700 with Microcentered show slightly worse results. The Legacy with Ashtech Choke ring provide the best results for the Javad receiver/antenna combinations.

4.0 Zero Baseline Tests

For SuomiNet zero baseline tests, two receivers were connected to the same antenna and low-noise amplifier (LNA). Zero baseline tests are conducted to examine receiver performance where all common errors due to multipath, LNA noise, and propagation effects cancel in the GPS processing. Each receiver antenna pair collected data for a minimum of 3-24 hour sessions and the data were quality checked using teqc. All data were processed using the Bernese processing software using IGS rapid orbits. Historically only data down to 15 degrees was used in the zero and short baseline tests (for example see Rocken et. al, 1996), but because low elevation data is important for the atmospheric applications applicable to this report, phase data were processed down to 10 degrees for determining RMS and coordinate repeatability. In the following graphs and tables we present a summary of RMS plots for L1, L2, L3, C1, C2, and C3 zero difference observables, and double difference residual plots. In addition, we estimate the residual troposphere error for the zero baseline solutions.

4.1 Zero difference phase RMS

In the following graphs we show the zero-difference RMS as output from GPSEST in the Bernese software. The SuomiNet receiver bid stated a mandatory receiver specification of 2 mm RMS for L1 and L2 and 6 mm for L3. Note that the values displayed in the zero difference plots can be scaled to double difference values by multiplying by a factor of 2 (also see double difference residual plots shown in Figures 4-10 and 4-11).

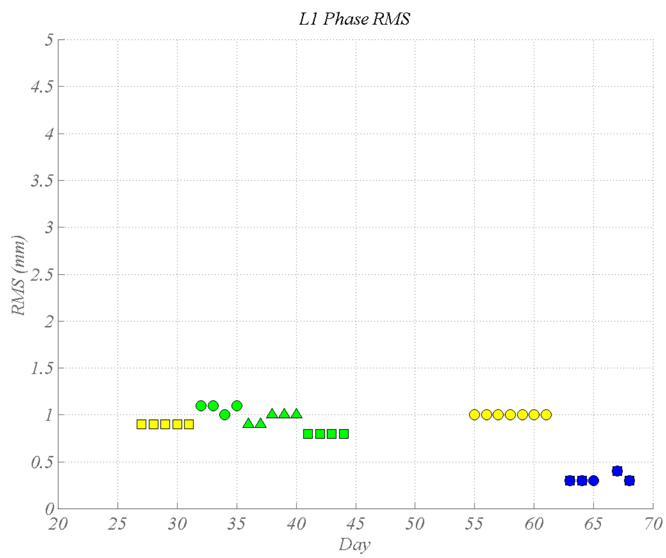


Figure 4-1: Zero difference RMS value for L1 phase zero base line solution. See Figure 3-8 for a scatter plot legend.

Table 4-1:Summary of L1 - zero difference phase RMS (mm)

Receiver	Antenna	Mean	Stdev	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.3	<0.1	0.3	0.4
Ashtech u-Z (u)	ASH701945.02B	0.3	<0.1	0.3	0.4
JPS Legacy	ASH701945.02B	0.8	<0.1	0.8	0.8
JPS Legacy	JPS Regant DD E	1.1	<0.1	1.0	1.1
JPS Legacy	JPS Regant SD E	0.9	<0.1	0.9	1.0
Trimble 4700	TRM33429.00+GP	0.9	<0.1	0.9	0.9
Trimble 4700	TRM29659.00	1.0	<0.1	1.0	1.0

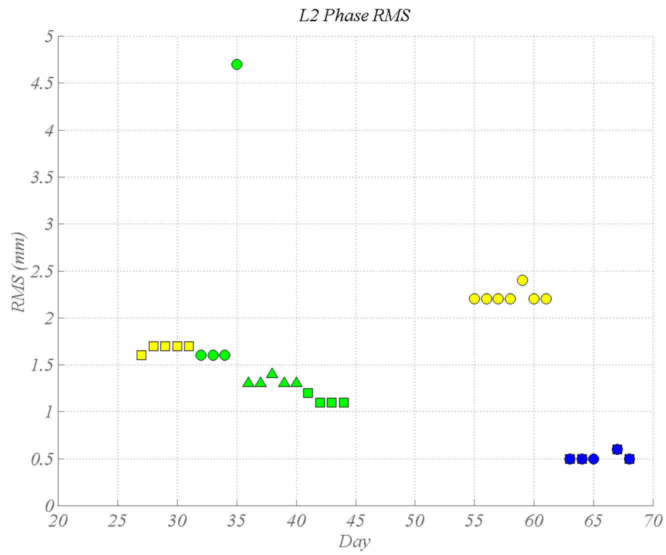


Figure 4-2: Zero difference RMS value for L2 phase zero base line solution.

Table 4-2:Summary of L2 - zero difference phase RMS (mm).

Receiver	Antenna	Mean	Stdev	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.5	<0.1	0.5	0.6
Ashtech u-Z (u)	ASH701945.02B	0.5	<0.1	0.5	0.6
JPS Legacy	ASH701945.02B	1.1	<0.1	1.1	1.2
JPS Legacy	JPS Regant DD E	2.4	1.3	1.6	4.7
JPS Legacy	JPS Regant SD E	1.3	<0.1	1.3	1.4
Trimble 4700	TRM33429.00+GP	1.7	<0.1	1.6	1.7
Trimble 4700	TRM29659.00	2.2	0.1	2.2	2.4

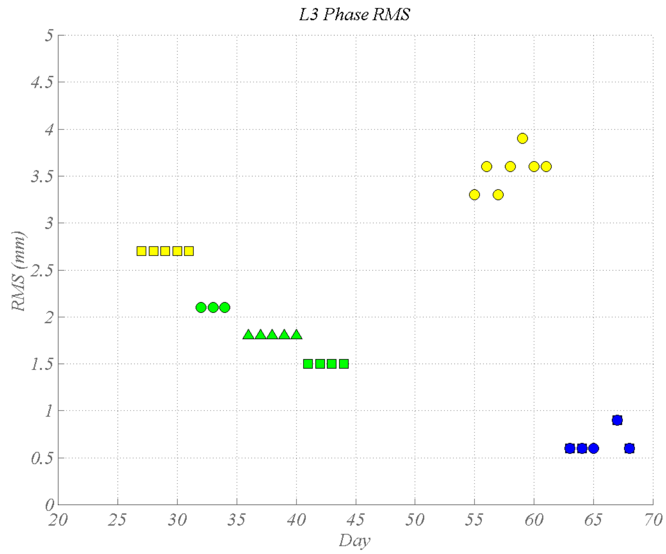


Figure 4-3: Zero difference RMS value for L3 phase zero base line solution.

Table 4-3:Summary of L3 - zero difference phase RMS (mm)

Receiver	Antenna	Mean	Stdev	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.7	0.1	0.6	0.9
Ashtech u-Z (u)	ASH701945.02B	0.7	0.1	0.6	0.9
JPS Legacy	ASH701945.02B	1.5	<0.0	1.5	1.5
JPS Legacy	JPS Regant DD E	3.4	2.2	2.1	7.2
JPS Legacy	JPS Regant SD E	1.8	<0.0	1.8	1.8
Trimble 4700	TRM33429.00+GP	2.7	<0.0	2.7	2.7
Trimble 4700	TRM29659.00	3.6	0.2	3.3	3.9

All receiver and antenna combinations meet or exceed the mandatory requirement for L1 phase RMS. The Ashtech uZ with ASH701945.02B antenna (both smoothed and unsmoothed) show the lowest L1 phase RMS. For L2 phase RMS, the Trimble 4700 with TRM29659.00 and the Javad Legacy with JPS Regant DD E do not meet the mandatory 2 mm specification. The Ashtech uZ with ASH701945.02B antenna (both smoothed and unsmoothed) show the lowest overall L2 and L3 phase RMS. All receivers meet the mandatory L3 phase RMS requirement.

4.2 Zero difference code RMS

In the following graphs we show the zero-difference code RMS as output from GPSEST in the Bernese software. The SuomiNet receiver bid specified a mandatory receiver specification of 30 cm for L1 and L2 and 100 cm zero difference code RMS for L3.

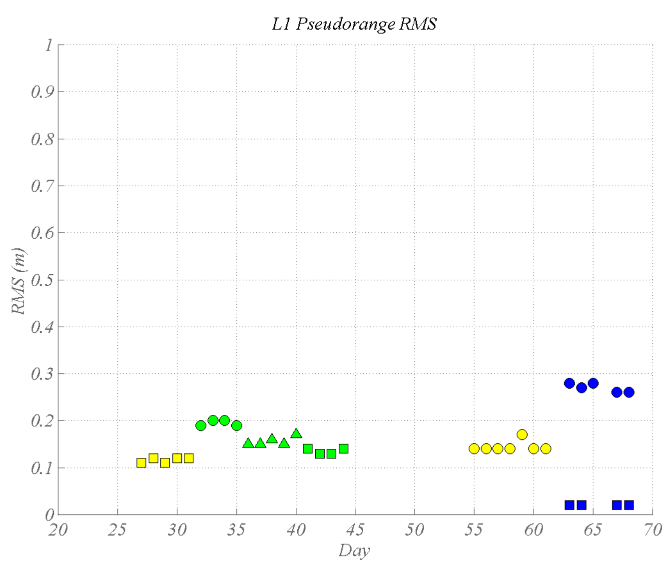


Figure 4-4: Zero difference RMS value for L1 pseudorange zero base line solution. See Figure 3-8 for a scatter plot legend.

Table 4-4:Summary of C1 - zero difference pseudorange RMS (m)

Receiver	Antenna	Mean	Stdev	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.02	<0.001	0.02	0.02
Ashtech u-Z (u)	ASH701945.02B	0.27	0.009	0.26	0.28
JPS Legacy	ASH701945.02B	0.14	0.005	0.13	0.14
JPS Legacy	JPS Regant DD E	0.20	0.005	0.19	0.20
JPS Legacy	JPS Regant SD E	0.16	0.008	0.15	0.17
Trimble 4700	TRM33429.00+GP	0.12	0.005	0.11	0.12
Trimble 4700	TRM29659.00	0.14	0.011	0.14	0.17

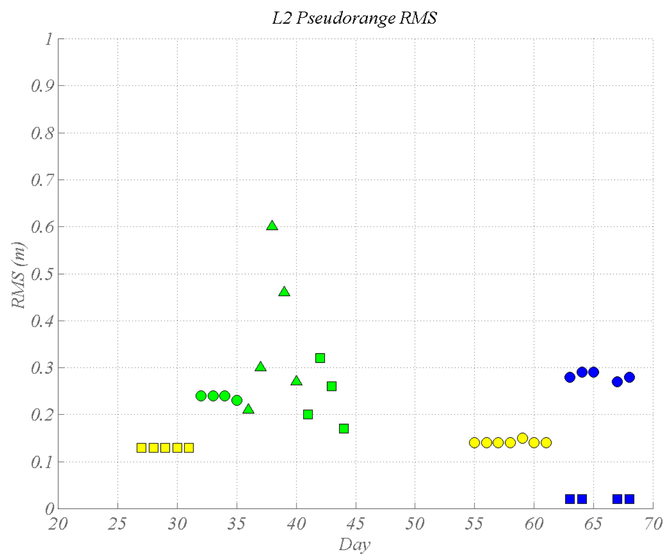


Figure 4-5: Zero difference RMS value for L2 pseudorange zero base line solution.

Table 4-5:Summary of C2 - zero difference pseudorange RMS (m)

Receiver	Antenna	Mean	Stdev	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.02	<0.001	0.02	0.02
Ashtech u-Z (u)	ASH701945.02B	0.28	0.008	0.27	0.29
JPS Legacy	ASH701945.02B	0.24	0.058	0.17	0.32
JPS Legacy	JPS Regant DD E	0.24	0.004	0.23	0.24
JPS Legacy	JPS Regant SD E	0.37	0.143	0.21	0.60
Trimble 4700	TRM33429.00+GP	0.13	<0.001	0.13	0.13
Trimble 4700	TRM29659.00	0.14	0.004	0.14	0.15

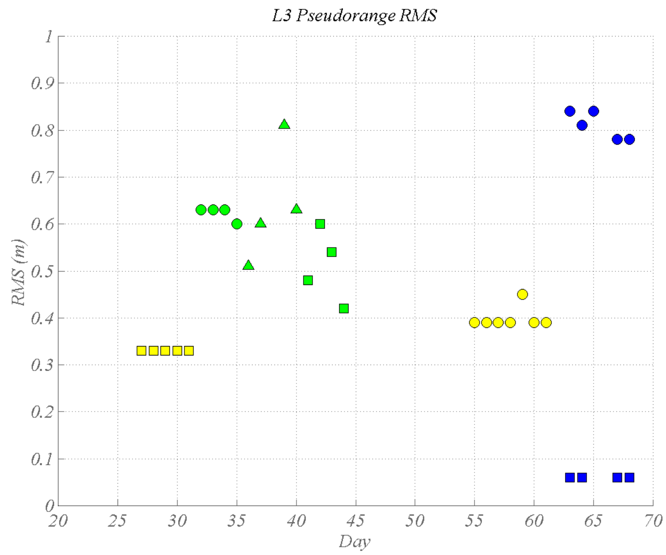


Figure 4-6: Zero difference RMS value for L3 pseudorange zero base line solution.

Table 4-6:Summary of C3 - zero difference pseudorange RMS (m)

Receiver	Antenna	Mean	Stdev	Min	Max
Ashtech u-Z (s)	ASH701945.02B	0.06	<0.001	0.06	0.06
Ashtech u-Z (u)	ASH701945.02B	0.81	0.027	0.78	0.84
JPS Legacy	ASH701945.02B	0.51	0.067	0.42	0.60
JPS Legacy	JPS Regant DD E	0.62	0.013	0.60	0.63
JPS Legacy	JPS Regant SD E	0.71	0.181	0.51	1.02
Trimble 4700	TRM33429.00+GP	0.33	<0.001	0.33	0.33
Trimble 4700	TRM29659.00	0.40	0.021	0.39	0.45

All receiver and antenna combinations meet the mandatory requirement for L1, L2, and L3 code RMS with the exception of the Javad Legacy with JPS Regant SD antenna (L2 code). The Ashtech uZ with smoothed pseudorange shows the lowest (best) values for L1, L2, and L3 code RMS. In general the Trimble 4700 with TRM33429.00 + GP show the next best results, followed by the Javad Legacy with Ashtech Choke Ring and Trimble 4700 with Choke Ring. The Ashtech uZ with unsmoothed pseudorange shows the highest (worst) values for L1 and L2 code RMS.

The graphs presented above show zero difference RMS about a mean value. Below we present the C1, C2, and C3 mean baseline solutions as derived from the zero baseline data. Ideally the mean value should be zero.

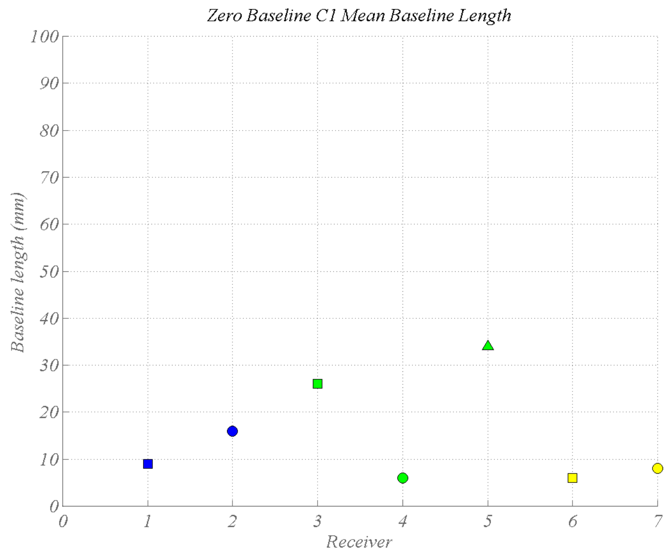


Figure 4-7: Mean zero baseline C1 solutions for all receiver and antenna pairs tested. See Figure 3-8 for scatter plot legend.

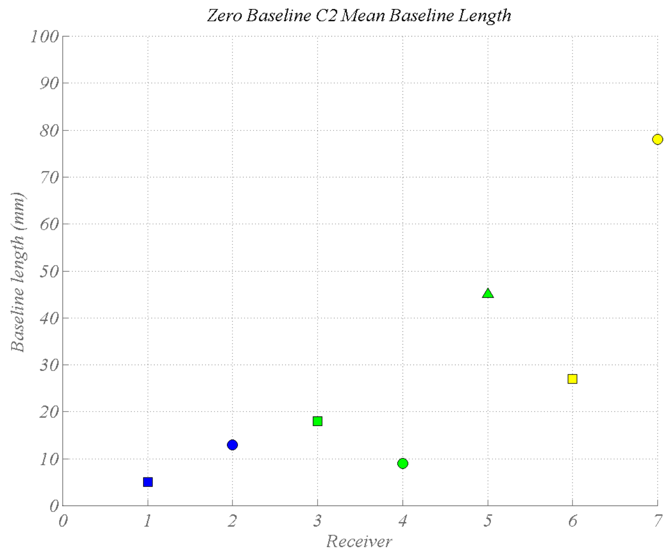


Figure 4-8: Mean zero baseline C2 solutions for all receiver and antenna pairs tested.

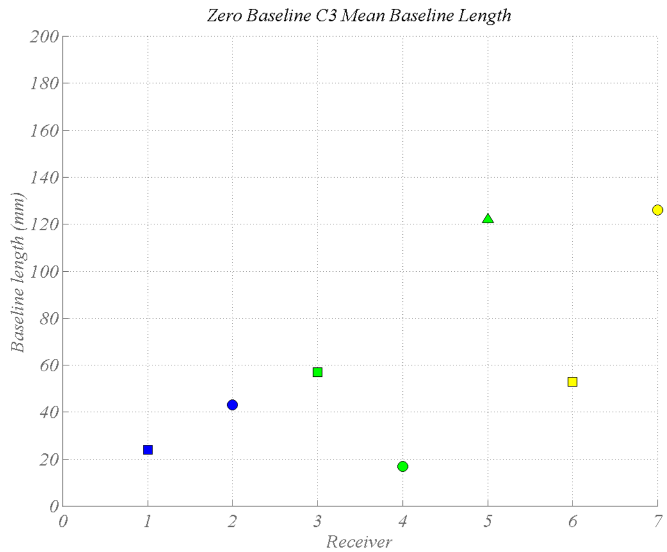


Figure 4-9: Mean zero baseline C3 solutions for all receiver and antenna pairs tested.

Table 4-7:Summary of C1, C2 & C3 mean zero baseline solutions (mm)

Receiver	Antenna	Observable	ZBL Length
Ashtech u-Z (s)	ASH701945.02B	C1	9
Ashtech u-Z (u)	ASH701945.02B	C1	16
JPS Legacy	ASH701945.02B	C1	26
JPS Legacy	JPS Regant DD E	C1	6
JPS Legacy	JPS Regant SD E	C1	34
Trimble 4700	TRM33429.00+GP	C1	6
Trimble 4700	TRM29659.00	C1	8
Ashtech u-Z (s)	ASH701945.02B	C2	5
Ashtech u-Z (u)	ASH701945.02B	C2	13
JPS Legacy	ASH701945.02B	C2	18
JPS Legacy	JPS Regant DD E	C2	9
JPS Legacy	JPS Regant SD E	C2	45
Trimble 4700	TRM33429.00+GP	C2	27
Trimble 4700	TRM29659.00	C2	78
Ashtech u-Z (s)	ASH701945.02B	C3	24
Ashtech u-Z (u)	ASH701945.02B	C3	43
JPS Legacy	ASH701945.02B	C3	57
JPS Legacy	JPS Regant DD E	C3	17
JPS Legacy	JPS Regant SD E	C3	122
Trimble 4700	TRM33429.00+GP	C3	53
Trimble 4700	TRM29659.00	C3	126

The Javad Legacy with JPS Regant DD antenna and the Trimble 4700 with TRM33429.00+GP provide values closest to zero for C1 baseline solutions. The Ashtech uZ with smoothed pseudorange and Ashtech Choke Ring antenna followed by The Javad Legacy with JPS Regant DD antenna show values closest to zero for C2 baseline solutions. The Javad Legacy with JPS Regant DD show values closest to zero for C3 baseline solutions.

4.3 Zero Baseline Carrier Phase Double Difference Residuals

In the following two figures we show representative plots of zero baseline double difference L3 phase residuals. Figure 4-10 shows residuals for all satellite pairs while Figure 4-11 shows isolated residuals for satellite 23-21 pair.

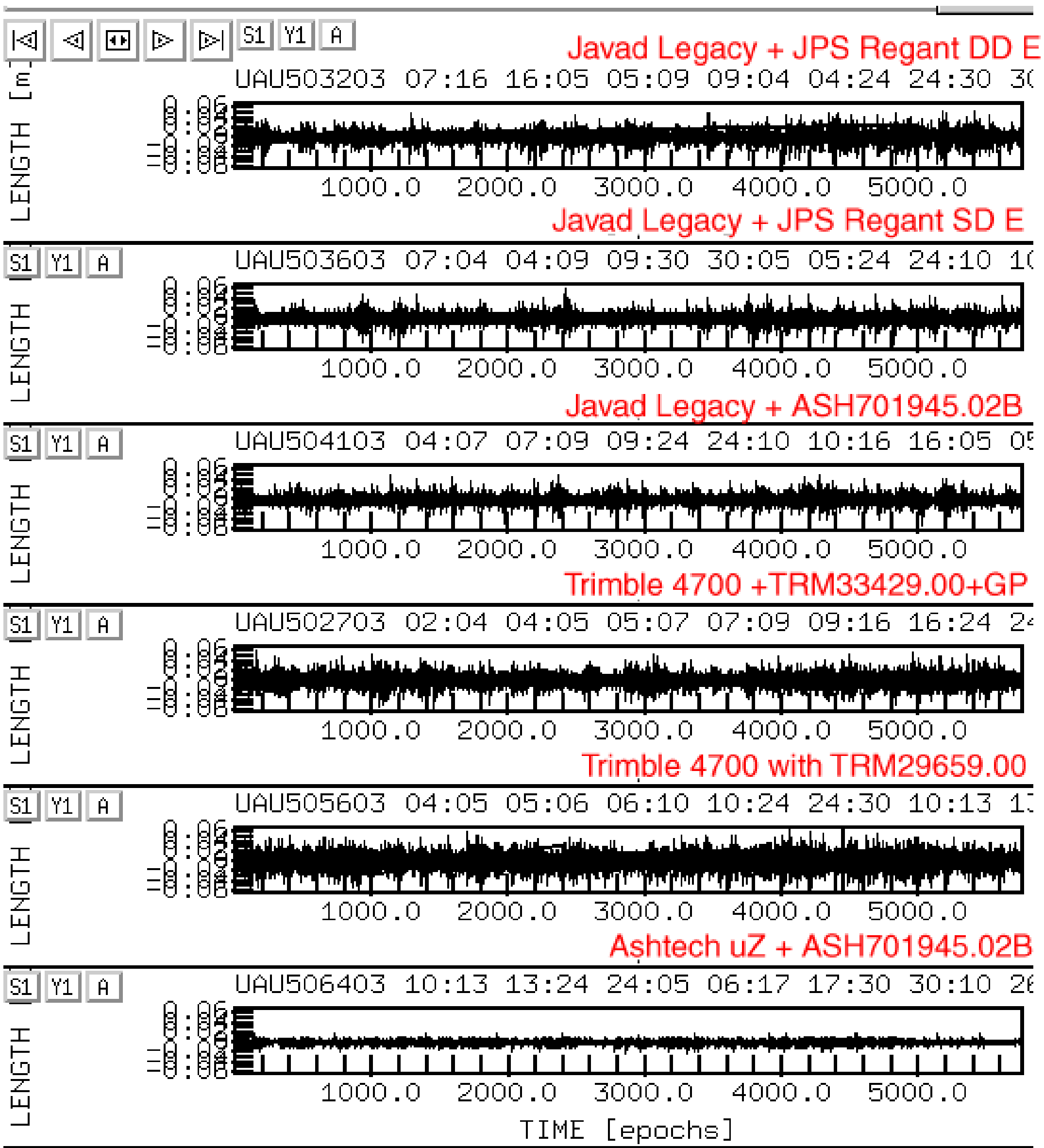


Figure 4-10: Plot of L3 zero baseline double difference residuals for all satellites. Scale is 6 to -6 cm. Traces are, from top to bottom Javad Legacy with JPS Regant DD E, Javad Legacy with JPS Regant SD E, Javad Legacy with ASH701945.02B, Trimble 4700 with TRM33429.00+GP, Trimble 4700 with TRM29659.00, and Ashtech uZ with ASH701945.02B.

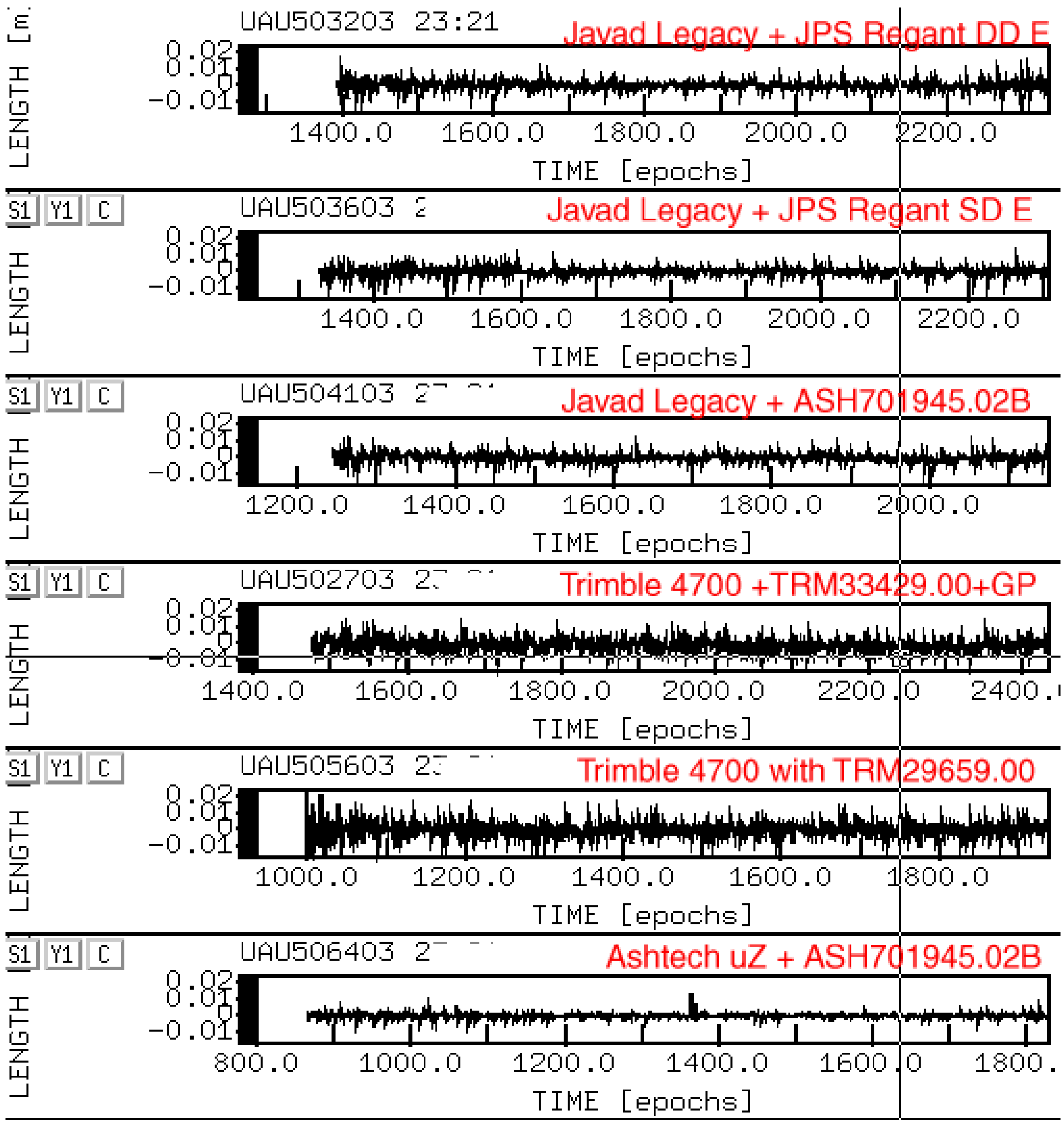


Figure 4-11: Plot of L3 zero baseline double difference residuals for satellites 23 and 21. Scale is 2 to -1 cm. Traces are, from top to bottom Javad Legacy with JPS Regant DD E, Javad Legacy with JPS Regant SD E, Javad Legacy with ASH701945.02B, Trimble 4700 with TRM33429.00+GP, Trimble 4700 with TRM29659.00, and Ashtech uZ with ASH701945.02B.

Qualitatively, Figures 4-10 and 4-11 indicate the Trimble 4700 receiver shows larger zero baseline double difference residuals than the other receiver/antenna combinations. The Ashtech uZ receiver shows the lowest L3, zero baseline double difference residual values.

4.4 Zero Baseline Troposphere delay.

The following graph shows residual tropospheric delay values for zero baseline data sets. Because both receivers are connected to the same antenna, the residual troposphere value should be near zero. Zero baseline GPS data were processed and L3 hourly troposphere parameters estimated and reduced to a single daily residual delay value. In all cases the residual troposphere value was < 0.1 mm.

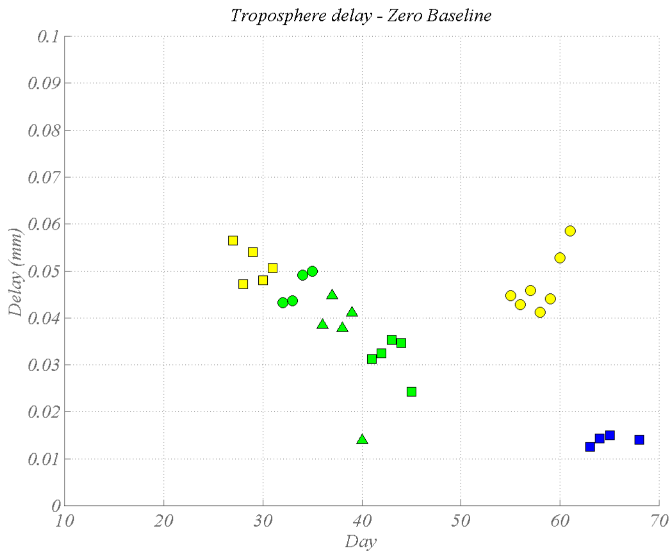


Figure 4-12: Residual Troposphere delay based on L3 zero baseline solutions. See Figure 3-8 for scatter plot legend

5.0 Short Baseline Tests

Short baseline tests were conducted on the roof of the UNAVCO building on station marks UV04 and UV03 (Figure 2-1). Each receiver antenna pair collected data for a minimum of 3-24 hour sessions with data quality checked using teqc. All data were processed using the Bernese processing software with IGS rapid orbits. In the following graphs and tables we present a summary of coordinate solutions and troposphere bias parameters for the short baseline data.

5.1 Short baseline solution precision

In the following section we present L1, L2, and L3 repeatability results for a ~1.912 m baseline on the roof of the UNAVCO building. All precision values are derived from L1, L2, and L3 Bernese network solutions.

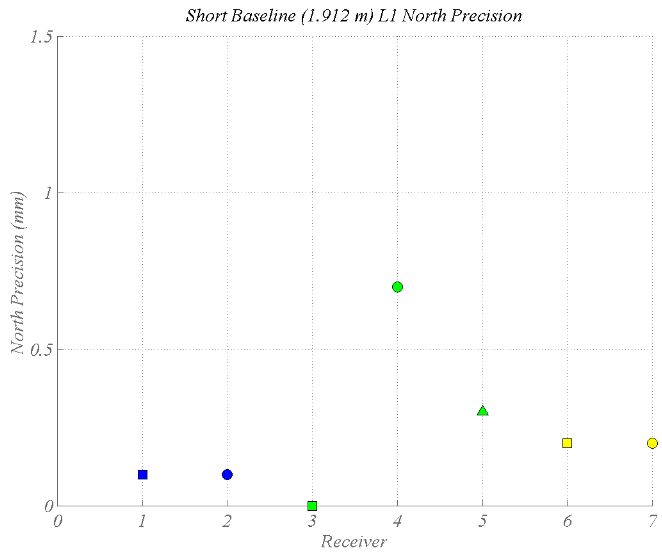


Figure 5-1: North component of the L1 short baseline solution precision for each receiver/antenna tested. A minimum of 3-24 hour data sets were processed and combined into a network solution. See Figure 3-8 for a scatter plot legend.

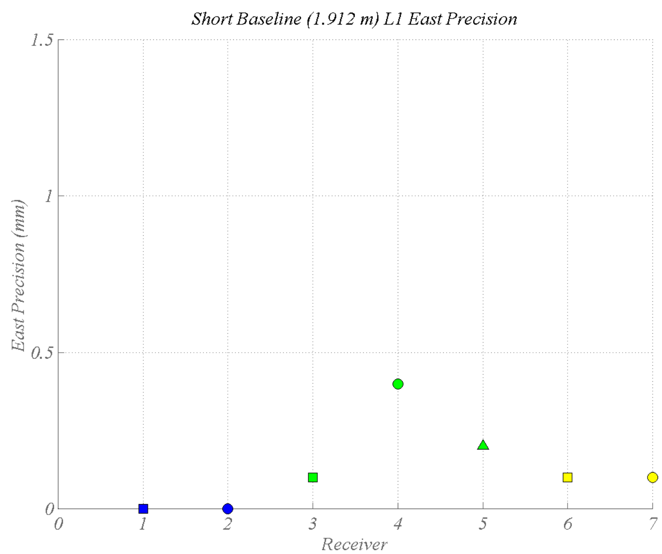


Figure 5-2: East component of the L1 short baseline solution precision for each receiver/antenna tested. A minimum of 3-24 hour data sets were processed and combined into a network solution.

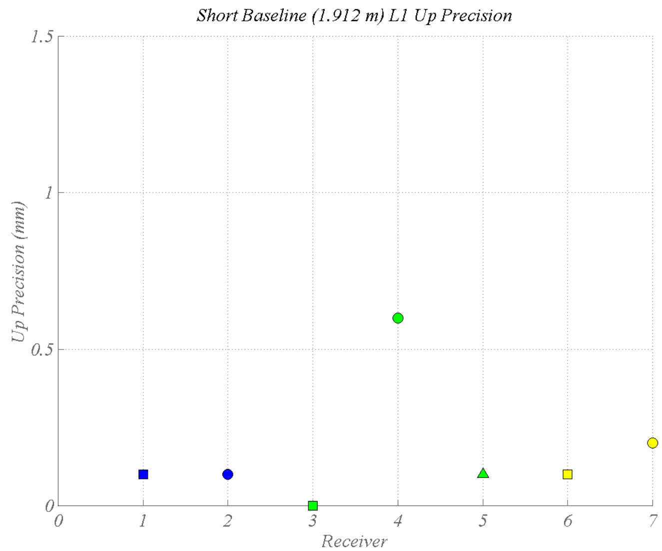


Figure 5-3: Up component of the L1 short baseline solution precision for each receiver/antenna tested. A minimum of 3-24 hour data sets were processed and combined into a network solution.

Table 5-1: L1 Phase Short baseline solution RMS (mm).

Receiver	Antenna	North	East	Up	Norm
Ashtech u-Z (s)	ASH701945.02B	0.1	<0.1	0.1	0.14
Ashtech u-Z (u)	ASH701945.02B	0.1	<0.1	0.1	0.14
JPS Legacy	ASH701945.02B	<0.1	0.1	<0.1	<0.1
JPS Legacy	JPS Regant DD E	0.7	0.4	0.6	1.00
JPS Legacy	JPS Regant SD E	0.3	0.2	0.1	0.37
Trimble 4700	TRM33429.00+GP	0.2	0.1	0.1	0.24
Trimble 4700	TRM29659.00	0.2	0.1	0.2	0.30

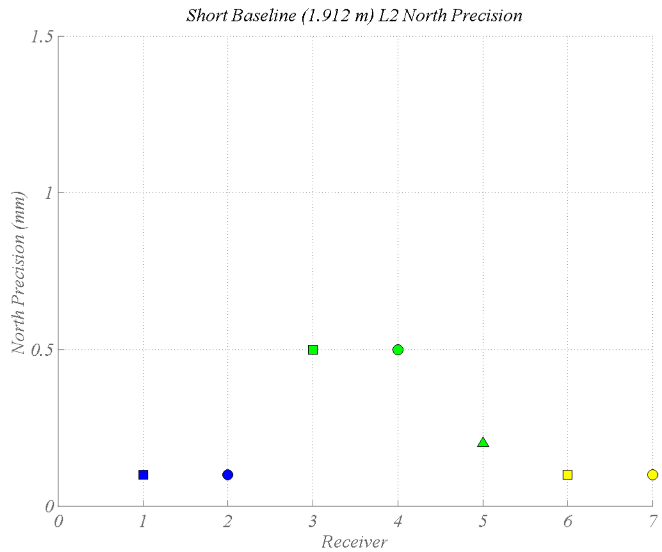


Figure 5-4: North component of the L2 short baseline solution for each receiver/antenna tested. A minimum of 3-24 hour data sets were processed and combined into a network solution.

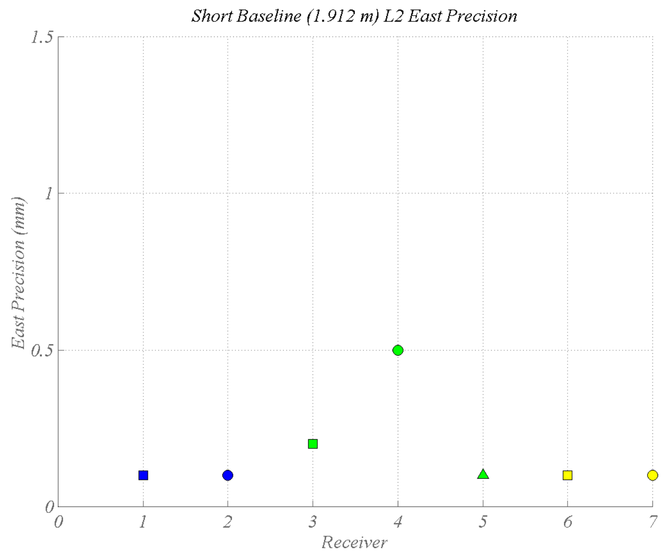


Figure 5-5: East component of the L2 short baseline solution precision for each receiver/antenna tested. A minimum of 3-24 hour data sets were processed and combined into a network solution.

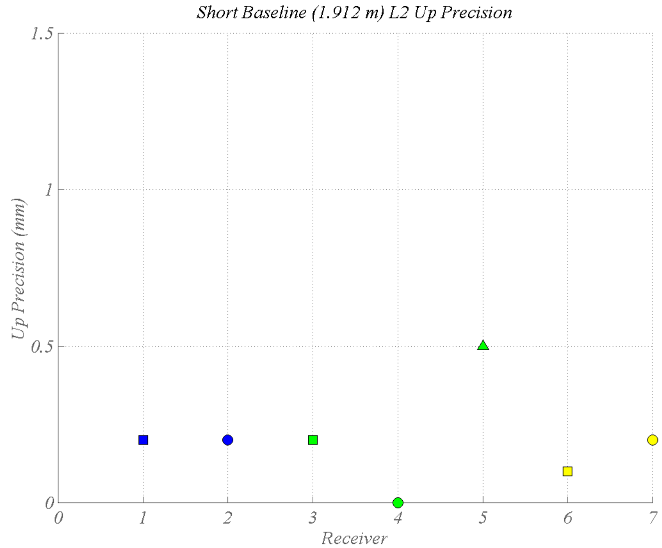


Figure 5-6: Up component of the L2 short baseline solution precision for each receiver/antenna tested. A minimum of 3-24 hour data sets were processed and combined into a network solution.

Table 5-2:L2 Phase Short baseline solution RMS (mm).

Receiver	Antenna	North	East	Up	Norm
Ashtech u-Z (s)	ASH701945.02B	0.1	0.1	0.2	0.24
Ashtech u-Z (u)	ASH701945.02B	0.1	0.1	0.2	0.24
JPS Legacy	ASH701945.02B	0.5	0.2	0.2	0.57
JPS Legacy	JPS Regant DD E	0.5	0.5	<0.1	0.71
JPS Legacy	JPS Regant SD E	0.2	0.1	0.5	0.55
Trimble 4700	TRM33429.00+GP	0.1	0.1	0.1	0.17
Trimble 4700	TRM29659.00	0.1	0.1	0.2	0.24

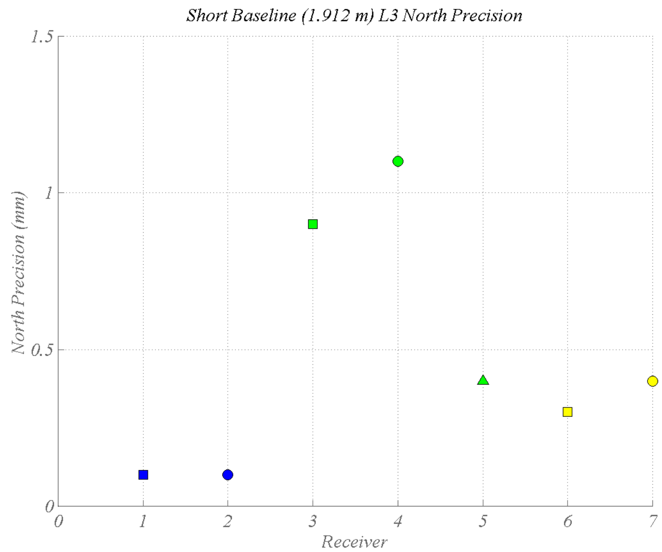


Figure 5-7: North component of the L3 short baseline solution precision for each receiver/antenna tested. See Figure 3-8 for a scatter plot legend.

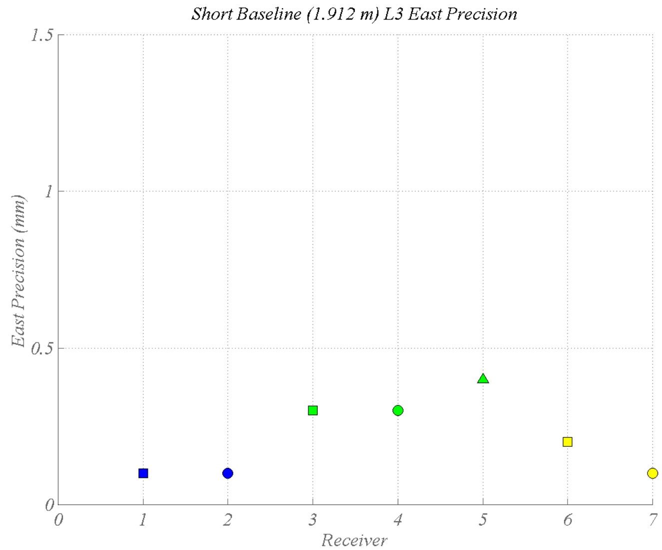


Figure 5-8: East component of the L3 short baseline solution precision for each receiver/antenna tested.

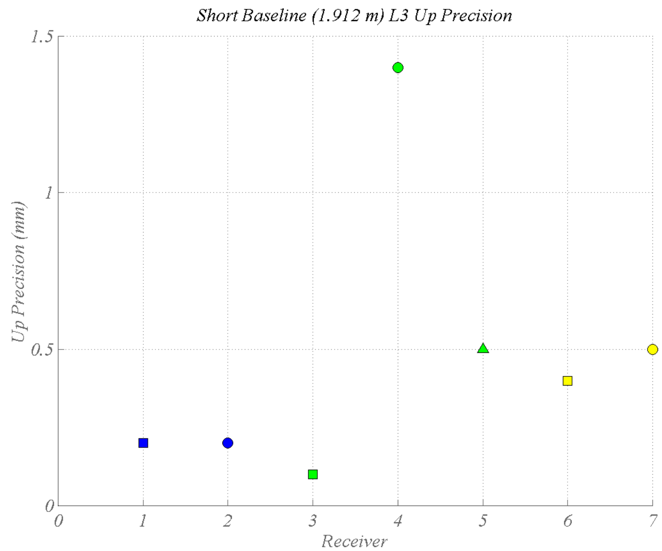


Figure 5-9: Up component of the L3 short baseline solution precision for each receiver/antenna tested.

Table 5-3:L3 Phase Short baseline solution RMS (mm).

Receiver	Antenna	North	East	Up	Norm
Ashtech u-Z (s)	ASH701945.02B	0.1	0.1	0.2	0.24
Ashtech u-Z (u)	ASH701945.02B	0.1	0.1	0.2	0.24
JPS Legacy	ASH701945.02B	0.9	0.3	0.1	0.95
JPS Legacy	JPS Regant DD E	1.1	0.3	1.4	1.81
JPS Legacy	JPS Regant SD E	0.4	0.4	0.5	0.75
Trimble 4700	TRM33429.00+GP	0.3	0.2	0.4	0.54
Trimble 4700	TRM29659.00	0.4	0.1	0.5	0.65

Based on the L1 norm = $\sqrt{(nrms^2 + erms^2 + urms^2)}$ the Javad Legacy with ASH701945.02B followed by the Ashtech uZ with ASH701945.02B antenna shows the best overall results. Based on the L2 norm, the Trimble 4700 with TRM33429.00+GP followed by the Ashtech uZ with ASH701945.02B antenna and Trimble 4700 with Trimble Choke Ring provides the best performance. Based on the L3 norm, the Ashtech uZ followed by the Trimble 4700 with TRM33429.00+GP show the best results.

5.2 Short baseline residual troposphere delay.

Short baseline GPS data were processed and L3 hourly troposphere parameters estimated and reduced to a single daily residual delay value. Smaller delay values (Figure 5-10 and Table 5-4) indicate there is no relative atmospheric delay between the two receivers. Coordinate solutions used only observations above 10°. Troposphere solutions use observations down to 0° and thus are an indicator of receiver performance at low elevation angles.

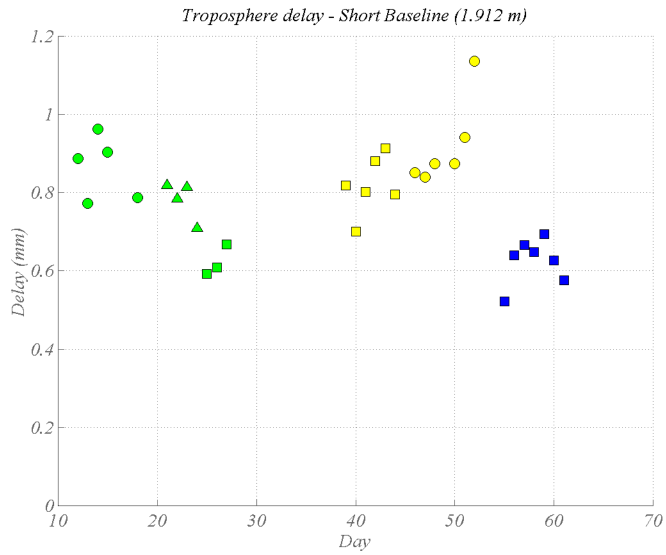


Figure 5-10: Residual Troposphere delay based on L3 short baseline solutions. See Figure 3-8 for scatter plot legend.

Table 5-4:Summary of L3 Short Baseline residual troposphere estimates (mm)

Receiver	Antenna	Mean	RMS	Min	Max
Ashtech u-Z	ASH701945.02B	0.63	0.05	0.52	0.69
JPS Legacy	ASH701945.02B	0.62	0.03	0.59	0.66
JPS Legacy	JPS Regant DD E	0.86	0.07	0.77	0.96
JPS Legacy	JPS Regant SD E	0.78	0.04	0.71	0.82
Trimble 4700	TRM33429.00+GP	0.81	0.07	0.70	0.91
Trimble 4700	TRM29659.00	0.92	0.10	0.84	1.14

The values derived in table 5-4 indicate the level of atmospheric error introduced by the particular receiver/antenna pair. All receivers show similar and acceptable values below 1 mm.

5.3 Short baseline double difference phase residuals.

The following plots provide a qualitative look at double difference residuals for all receiver and antenna pairs. Figure 5-11 shows residuals for all satellite pairs. Figure 5-12 shows residuals for a single double difference satellite pair.

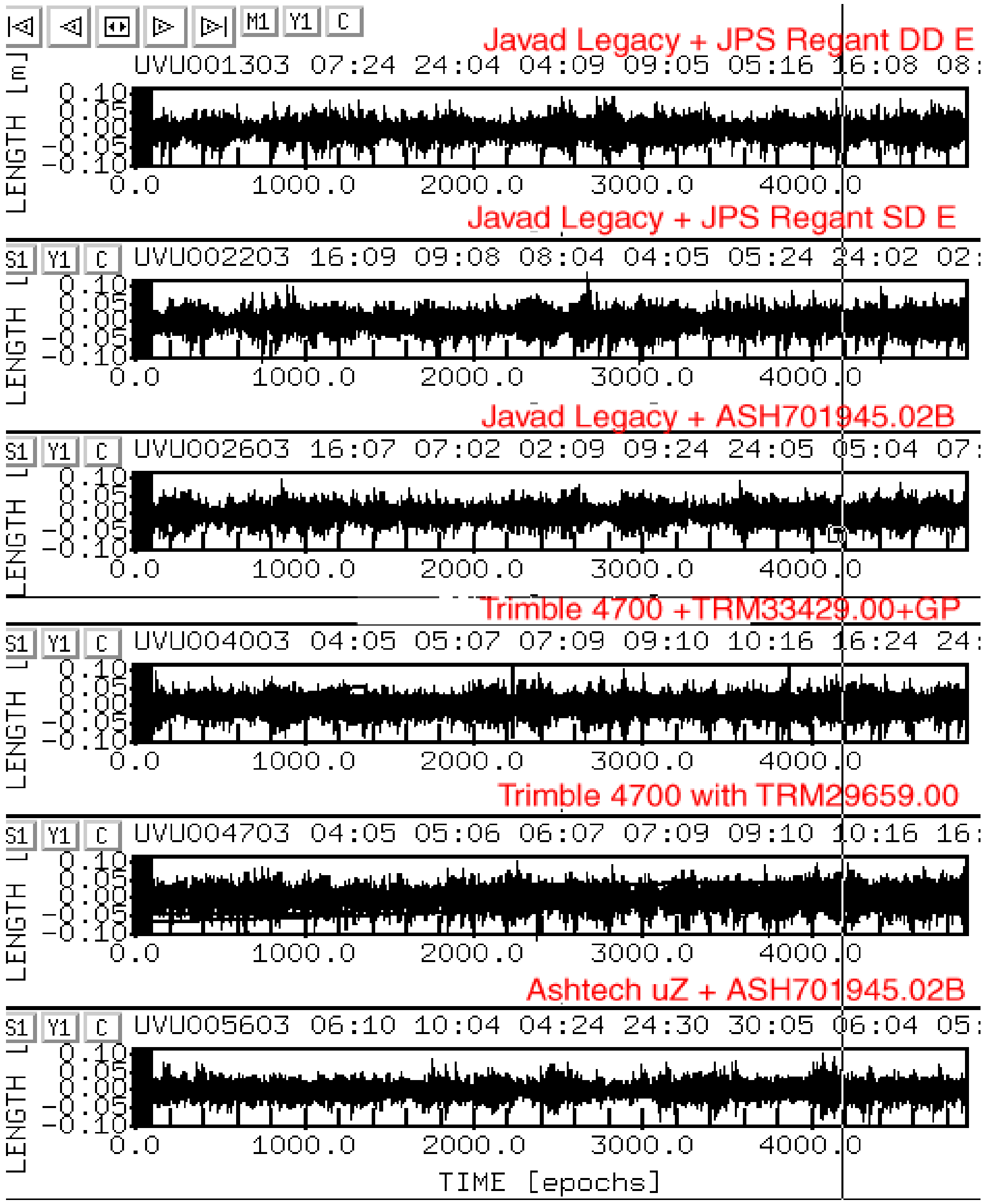


Figure 5-11: Double difference residual plots for all satellites for short baseline L3 solutions. Scale is 10 to -10 cm. Traces are, from top to bottom Javad Legacy with JPS Regant DD E, Javad Legacy with JPS Regant SD E, Javad Legacy with ASH701945.02B, Trimble 4700 with TRM33429.00+GP, Trimble 4700 with TRM29659.00, and Ashtech uZ with ASH701945.02B.

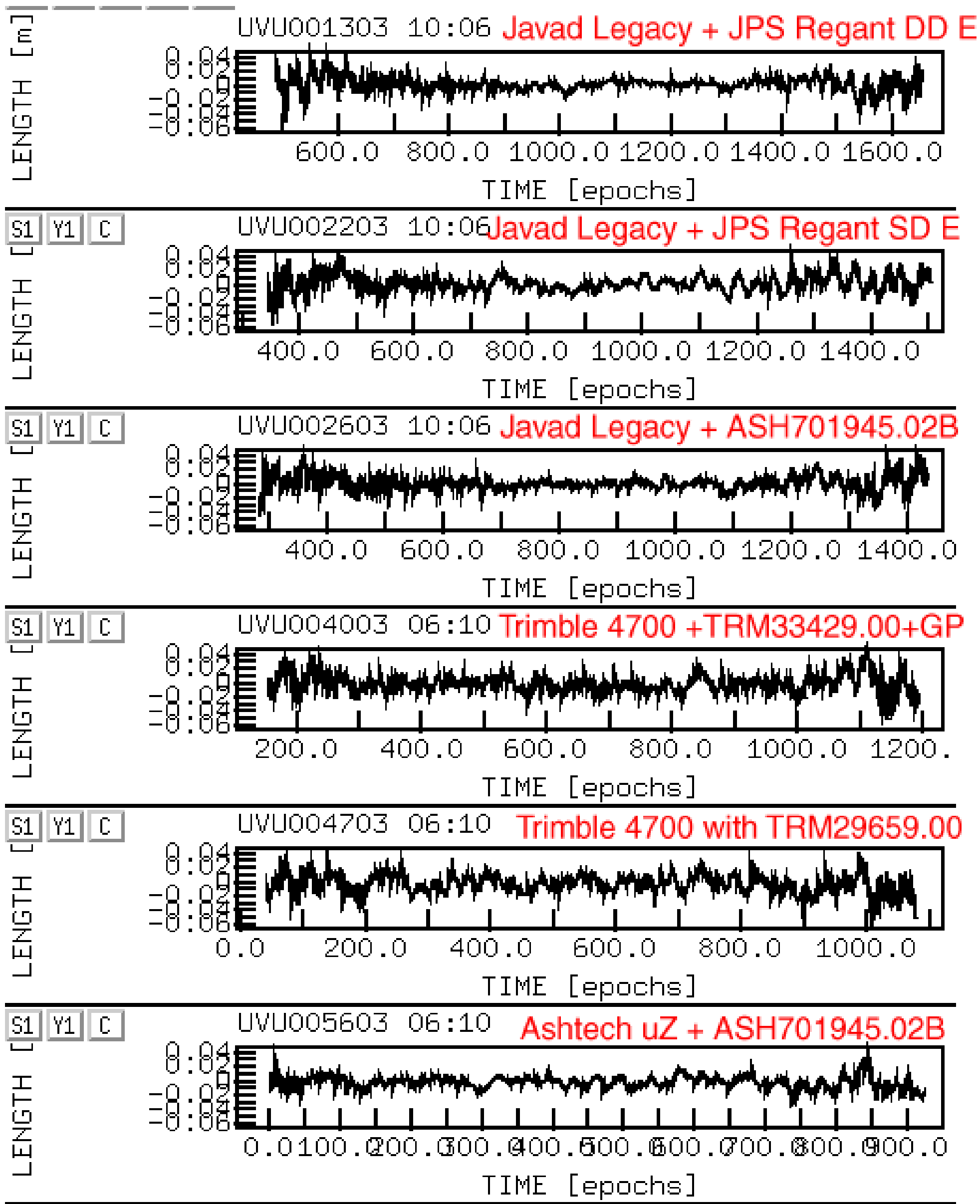


Figure 5-12: Double difference residual plots for short baseline L3 solutions showing SV 10-6 pair. Scale is 4 to -6 cm. Traces are, from top to bottom Javad Legacy with JPS Regant DD E, Javad Legacy with JPS Regant SD E, Javad Legacy with ASH701945.02B, Trimble 4700 with TRM33429.00+GP, Trimble 4700 with TRM29659.00, and Ashtech uZ with ASH701945.02B.

Figure 5-11 and 5-12 indicate low noise levels for the Javad receiver antenna pairs tracking satellites at high elevation angles and higher noise levels at low elevation angles. The Trimble receivers show overall high noise levels. The Ashtech receiver has the overall lowest double difference noise levels.

6.0 Summary

The following table presents a summary of mandatory and desired functionality as called out in the bid specification. Each manufacturers system and antenna is listed with a pass (P) or fail (F) mark.

Table 6-1: Receiver Mandatory Functionality

Receiver	Antenna	L1/L2 Phase and Pseudorange observables	L1 Carrier Phase Precision	L2 Carrier Phase Precision	L3 Carrier Phase Precision	L1 Pseudorange Precision	L2 Pseudorange Precision	L3 Pseudorange Precision	Continuous streaming from 12 SV's	Track SV's to zero degrees	> 3000 observations per slip between 10° - 90°	> 1000 observations per slip between 0° - 10°	Enable - disable code and carrier multipath rejection technology	Stream GPS observables at minimum of 5 Hz	2 serial ports	2 power ports	L1, L2 SNR in dB Hz referenced to a 1 Hz bandwidth	Support input and output of MET measurements	Power up in same configuration when powered down	Environmental specification
[1]Ashtech u-Z	ASH701945.02B	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
JPS Legacy	[2]ASH701945.02B	P	P	P	P	P	P	P	P	P	P	F	P	P	P	P	P	P	P	P
JPS Legacy	JPS Regant DD E	P	P	F	P	P	P	P	P	P	F	F	P	P	P	P	P	P	P	P
JPS Legacy	JPS Regant SD E	P	P	P	P	P	F	P	P	P	F	F	P	P	P	P	P	P	P	P
Trimble 4700	TRM33429.00+GP	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
Trimble 4700	TRM29659.00	P	P	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

[1] Summary for both smoothed and unsmoothed pseudorange data

[2] Antenna is not available from manufacturer

Table 6-2: Desired Functionality

Receiver	Antenna	Stream GPS observables at > 5 Hz	On board logging of GPS observables	3 Serial ports or 2 serial ports and parallel port	Ethernet	Mb removable flashcard	External clock port	external oscillator firmware configuration	Ability to choose satellites observed	Low power consumption (< 7 W)
Ashtech u-Z	ASH701945.02B	P	P	P	F	F	P	F	P	F
JPS Legacy	ASH701945.02B	P	P	P	F	F	P	P	P	P
JPS Legacy	JPS Regant DD E	P	P	P	F	F	P	P	P	P
JPS Legacy	JPS Regant SD E	P	P	P	F	F	P	P	P	P
Trimble 4700	TRM33429.00+GP	F	P	P	F	F	F	F	P	P
Trimble 4700	TRM29659.00	F	P	P	F	F	F	F	P	P

Table 6-3: Antenna mandatory and desired functionality

Receiver	Antenna	L1/L2 antenna	Antenna must be separate from receiver.	L1/L2 "out of band" signal rejection	Antenna phase correction table	Antenna must have ground plane/choke ring	well-defined phase	backlobe gain pattern available	operate the antenna up to 30 m cable	environmental specification	upgrade to IGS DM-T choke ring antenna
Ashtech u-Z	ASH701945.02B	P	P	P	P	P	P	P	P	P	P
JPS Legacy	ASH701945.02B	P	P	P	P	P	P	P	P	P	F
JPS Legacy	JPS Regant DD E	P	P	P	P	P	P	P	P	P	F
JPS Legacy	JPS Regant SD E	P	P	P	P	P	P	P	P	P	F
Trimble 4700	TRM33429.00+GP	P	P	P	P	P	P	P	P	P	P
Trimble 4700	TRM29659.00	P	P	P	P	P	P	P	P	P	P

7.0 Acknowledgments

Funding for receiver specification and testing was made possible through the SuomiNet NSF grant (Scientific Program Order No. 12 (ATM-9977639) to NSF Cooperative Agreement No. ATM-9732665 25) and the AMCS (Antenna Multipath Calibration System) grant (Smithsonian Astrophysical Observatory (SAO) Contract No. SV8-68005). We wish to thank Curt Conquest and Warren Gallaher of the UNAVCO Boulder Facility for their assistance in establishing the roof top mounts, and Amy Rosewater for her assistance in formatting this report. Also thanks to Chris Rocken, John Braun, and Randolph Ware of the UCAR GPS Science and Technology Program for assisting in defining the receiver specification and providing timely reviews. We would also like to thank Jon Siegrist and Sergei Podshivalov of Ashtech Magellan, Jim Nasmith and Javad Ashjaee of Javad Positioning Systems, and Bruce Stephens, Peter Large, Jeff Tait, and Brian Frohring of Trimble Navigation for providing technical assistance during the testing process.

8.0 References

Estey, L., & Meertens, C., (1999). TEQC: The multipurpose toolkit for GPS/GLONASS data. GPS Solutions Vol. 3, No. 1 pp. 44-49.

Rocken, C., Meertens, C., Stephens, B., Braun, J., Van Hove, T., Perry, S., Ruud, O., McCallum, M., & Richardson, J., (1996). UNAVCO Academic Research Infrastructure (ARI) Receiver and Antenna Test Report. UNAVCO Boulder Facility Internal Report.

Ware, R., Fulker, D., Stein, S., Anderson, D., Avery, S., Clark, R., Droegemeier, K., Kuettner, J., Minster, B., Sorooshian, S. (2000). SuomiNet: A Real-Time National GPS Network. Bulletin of the American Meteorological Society Vol 81, No. 4 pp. 677-694.

9.0 Vendor Response to Report

9.1 Javad Positioning Systems

1. After reviewing your report and observing your heavy emphasis on data below 10 degrees, it appears that for your application we should have supplied you with our LegAnt antenna, not RegAnt SD and DD. SD and DD are for high precision geodesy and RTK applications where multipath mitigation is of prime importance. SD and DD are designed to have a very low gain in the horizon (0 to 10 degrees) while they keep their high gain above 10 degrees. Their multipath mitigation capabilities are higher than standard choke rings and have lower gain in the horizon. The data below 10 degrees is still usable (with a few percent of cycle slips that can easily be repaired.) LegAnt uses the same antenna as SD and DD but does not lower the gain in the horizon. It also has good multipath mitigation capabilities, though not as much as SD or DD. With the benefit of hindsight we should have provided you with non-choke ring antennas or antennas with higher gain at the horizon as did Vendor 3. It seemed from the tone of the specification that you were mainly interested in Choke Ring technology We will be glad to provide you with a pair of LegAnts for your test if you are interested.

2. It also appears that we did not inform you to turn on the Co-Op tracking loops for low signal tracking. This feature is turned off as default to save processor power in applications when very low signal tracking is not needed. You can tell us if this was the case. I know that we were supposed to give you instructions for setting the receiver parameters. It seems that we did not specifically state this but in our response to the Technical Specifications para 3.1.3. we did state that "Co-Op Tracking is ideal to achieve this requirement" in reference to tracking all satellites to 0o.

3. Despite all above, in your report the calculation of counting the percentage of "cycle slips to

observed" is misleading. For example, the receivers of the Vendor 1 in your list cannot track satellites when signal strength is below a certain limit and they don't deliver any information. No data, no cycle slip. Even with SD and DD we track weaker signals and report them. Such weaker signals may have more cycle slips. We continue to provide data and leave it to the discretion of the post processing software to either ignore them or repair possible cycle slips. We have higher ratio of "observed to expected". See the table on the bottom of page 15 of your report. We give 16% more measurement (38.1% vs. 22.4%) but 2.5% more cycle slips. We think this is better. Also note that even such low elevation data is useful because the post processing software can easily repair the few percent cycle slips.

4. Furthermore, Inclusion of such data (item 3 above) in your calculation of RMS of pseudo ranges and carrier phases destroys the fairness of the numbers. When others stop giving data on weaker signals they get better RMS!

5. It is a point of discussion that how in a criteria a receiver fails on both of L1 and L2 Pseudo Range precisions but passes on their combination, L3. (Third vendor)

6. The systems that we supplied to you are capable of dual frequency GPS+GLONASS. The antenna bandwidth is wider to accommodate both GPS and GLONASS.

We will be glad to supply you with LegAnts to prove our points.

Best Regards,
Javad Ashjaee
April 27, 2000

9.2 Ashtech Magellan

We are very pleased to have submitted our latest generation Continuous Geodetic Reference Station receiver, the Ashtech µZ-CGRS™, for the SuomiNet equipment evaluation. UNAVCO continues to provide a highly valuable service to the reference station community and to the GPS industry at large by providing comprehensive, independent test results.

This report shows that the Ashtech µZ-CGRS, which incorporates our patented Z-Tracking™ technology, is the only receiver system tested that passed all SuomiNet mandatory requirements (Table 6-1) with an IGS compatible antenna with either raw or carrier-phase-smoothed pseudorange measurements.

The highest accuracy performance of the carrier phase measurements from the Ashtech µZ-CGRS is especially important. This is shown through all possible comparisons in the report, from the zero difference RMS (Figures and Tables 4-1 to 4-3), zero-baseline double difference residuals (Figures 4-10 and 4-11), zero-baseline troposphere delay (Figure 4-12), short-baseline repeatability (Figures 5-1 to 5-9 and Tables 5-1 to 5-3), short-baseline residual troposphere delay (Figure 5-10 and Table 5-4) to the short-baseline phase residuals (Figures 5-11 and 5-12).

In addition, the Ashtech µZ-CGRS has a very low number of cycle slips through all slip comparison criteria by slip percentage (Figures 3-11 to 3-14 and Tables 3-6 to 3-9), observations per slip (Figure 3-21 and Table 3-10) and IOD tracking statistics (Figures 3-22 and 3-23, and Tables 3-11 and 3-12). It is noteworthy that while both high accuracy carrier phase measurements and a low number of cycle slips are critical requirements for all Reference Stations, the Ashtech µZ-CGRS demonstrated high performance in both areas simultaneously. We are extremely proud of this accomplishment, as it validates that Z-Tracking continues to be the premier technique for tracking and for providing the highest quality GPS raw data under Anti-Spoofing (AS) conditions.

The Ashtech µZ-CGRS receiver is designed to support geodetic data collection and to broadcast differential corrections for both code and carrier phase RTK operations. The reference station community often requires both the "raw" and the carrier-phase-smoothed pseudorange measurements to be available in real-time. Therefore, we have designed the Ashtech µZ-CGRS to provide both raw and carrier-phase-smoothed pseudoranges for both post-mission and real-time operations. The carrier-phase-smoothed pseudoranges are generated in real time using smoothing parameters that are derived from the receiver's carrier phase measurements. It is important to note that the carrier phase measurements are not affected by the smoothing of the pseudoranges.

The Ashtech data was converted to RINEX using the UNAVCO TEQC Toolkit, which does not fix or repair cycle slips and does not perform any data smoothing. Therefore, the Ashtech results are the same as the results that would be obtained in real time from the receiver at 10 Hz. Note that the 10 Hz output rate does not reduce the accuracy of the carrier-phase-smoothed pseudoranges.

With the design and performance aspects mentioned above, the Ashtech µZ-CGRS clearly provides the highest level of operational flexibility without compromising quality, and it accommodates all reference station operational needs at the same high performance level. We continue to invest heavily in future receiver designs and the development of next-generation core technology to guarantee that Ashtech Precision Products receivers will continue to be the highest quality available.

Sincerely,
Jonathan Ladd, Senior Vice President
Dr. Mohamed Abousalem, Marketing Manager
Dr. Shaowei Han, Principal Scientist
Robert Lorenz, Principal Engineer
Sergei Podshivalov, Manager, Firmware Development
Dr. Xinhua Qin, Director of Santa Clara Engineering
Jon Siegrist, Senior Product Manager

9.3 Trimble Navigation Ltd.

Trimble wish to thank UNAVCO for the opportunity to participate in this important receiver testing and evaluation campaign, and for the opportunity to comment upon the results. We are delighted to see that the Trimble 4700 receiver with MicroCentered Antenna has passed all the tests for this demanding scientific application, even out-performing the other Choke Ring combinations tested in many test areas - including low elevation tracking performance, cycle slips, and levels of multipath present in the observables.

We are pleased to provide our observations and comments on this testing as follows:

Section 3 Receiver Tracking and Data Quality Tests.

3.1 Observed Data vs. Cycle Slips.

It is clear from the results shown in the report that the Trimble 4700 has by far the lowest number of cycle slips for all elevation angles, and that the results are especially good for the low elevation angle range of 0 to 5 degrees. We would point out that this low elevation tracking performance is especially important for atmospheric research.

We believe that the outstanding performance demonstrated is the result of our continued high investment in GPS research and development and we are very pleased with the results

3.2 MP1 and MP2 Pseudorange Multipath

This is an important parameter as, in practice, multipath is the dominant error source for most GPS data.

Pseudorange data produced by Trimble receivers is unsmoothed, independent and uncorrelated - even at the highest output rate of the receiver (5Hz in this case). When comparing like data (i.e. unsmoothed with unsmoothed), it can clearly be seen that the Trimble 4700 has by far the lowest levels of multipath present on both the L1 and L2 frequencies.

We believe that the very low levels of multipath present in the Trimble data are due to our continued investment in the development of advanced proprietary real-time multipath reduction techniques.

Section 4 Zero Baseline Tests

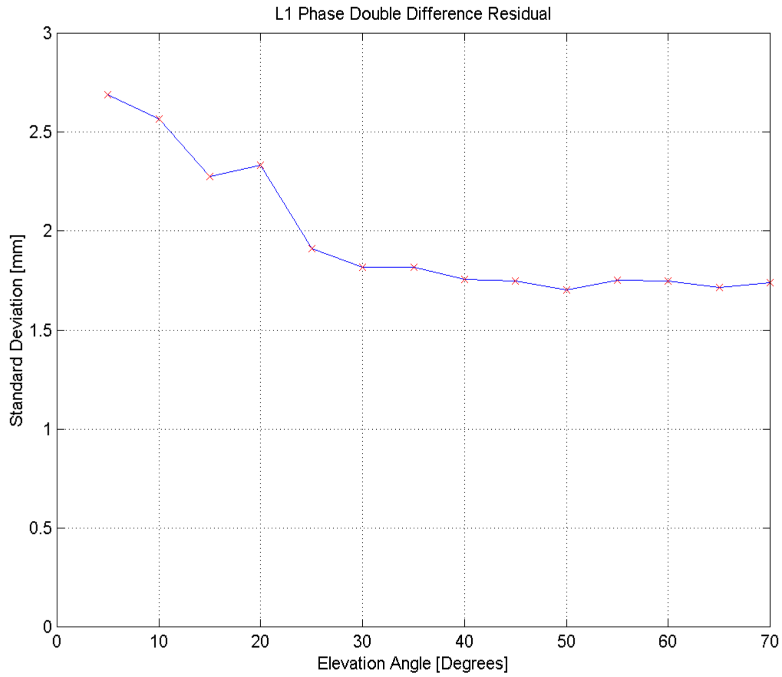
Section 4.1 Zero Difference Phase RMS

Concerning the comparison of zero difference residuals on a zero baseline, we wish to make the following comments:

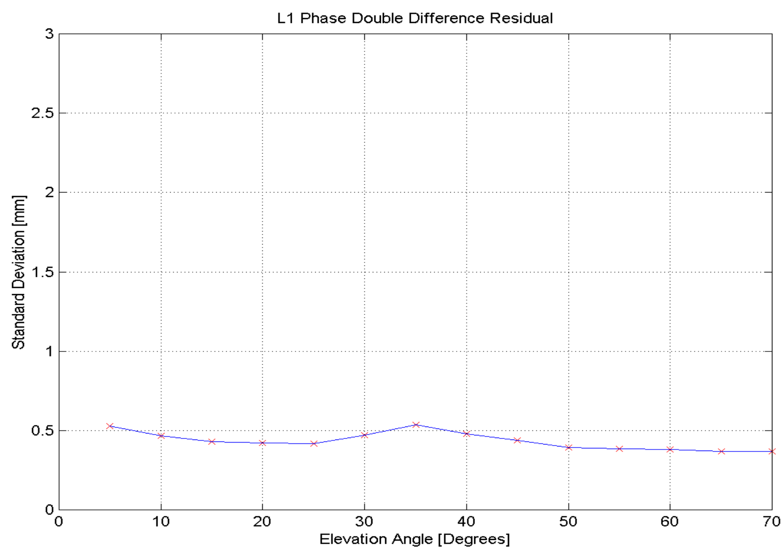
- The magnitude of these RMS values are largely a function of the effective measurement bandwidth.
- Changing the effective measurement bandwidth changes these results.
- Reducing the effective measurement bandwidth reduces the magnitude of the RMS. (Noise is typically proportional to the square root of the measurement bandwidth). But this also reduces the performance of the receiver in the presence of phase dynamics (such as ionospheric scintillation and receiver acceleration and jerk)
- Increasing the effective measurement bandwidth increases the magnitude of these RMS values but also improves the tracking performance of the receiver under conditions of phase dynamics (such as ionospheric scintillation and receiver acceleration and jerk)
- A key aspect of high performance GPS receiver engineering is the strike the right balance between apparent noise and tracking performance. Trimble believes that this balance has been struck for the wide range of applications that the 4700 receiver serves.
- The effective measurement bandwidth of the 4700 receiver can be changed (see paragraph below)
- Trimble fully understands that, to suit the particular needs and specialist applications of the SuomiNet scientific project, a different effective measurement bandwidth may be required. We confirm that Trimble can deliver 4700 receivers with a different effective measurement bandwidth, as required. (Which will also reduce the zero difference RMS values, assuming that the measurement bandwidth is decreased - see below).

To illustrate the effects of changing the effective measurement bandwidth in the 4700 receiver, two 24 hour zero baseline data sets were collected with two pairs of 4700 receivers, identical in all respects except that the measurement bandwidth was reduced by a factor of 15 in one pair of receivers.

The graphs below show the zero baseline double difference (recall the factor of 2 between this and the zero difference) baseline residuals for these two simultaneous data sets, the first plot showing the wider bandwidth (as used in the 4700 receivers tested by UNAVCO) and the second plot showing a much narrower bandwidth:



Trimble Figure 1. Wide Bandwidth Zero Baseline Double Difference Residuals



Trimble Figure 2. Narrow Bandwidth Zero Baseline Double Difference Residuals

From theory, we would expect the standard deviation to reduce by approximately sqrt(15) = ~3.87. This can be observed as being the case. Thus it can be seen that the results of a zero baseline test can be controlled by changing the effective measurement bandwidth. Although a GPS receiver may appear to have lower noise in the measurements when the bandwidth is reduced, the fact that this reduced bandwidth also has an impact on the receiver's ability to track satellites under conditions of receiver dynamics or ionospheric scintillation must also be considered.

Note that the above comments apply to both L1 and L2 measurements.

Section 4.2 Zero Difference code RMS

When like data are compared (unsmoothed data with unsmoothed data), the Trimble data clearly has by far the best pseudorange measurements and lowest pseudorange noise on both L1 and L2 frequencies, and for the C3 combination.

Note that Trimble data is unsmoothed and uncorrelated at the highest measurement output rate (5Hz in this case).

Trimble are delighted with these outstanding results

Environmental Specifications

We confirm that the Trimble 4700 receiver the following environmental operating ranges, as per the mandatory specifications:

- Operating Temperature -40 to +65 Centigrade
- 100% Humidity Proof, Fully Sealed.
- Shockproof for a drop of 1 meter onto a hard surface.

Final Remarks

We thank UNAVCO again for the opportunity to participate in this campaign and for the opportunity to provide our observations and comments on the results. We have no doubt that all who took part found this a very worthwhile exercise and we re-confirm our ongoing and continued commitment to the scientific GPS user community.