Capabilities of Currently Available GPS Receivers for Precise Autonomous Positioning[1]

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What accuracies are achievable with different GPS receivers? This is the question most often asked by users of the Canadian Active Control System (CACS) performing GPS point positioning using precise ephemerides and clocks. Users of these CACS products obtain DGPS-like accuracies anywhere in Canada, without access to base station data. This is accomplished by post processing their receiver observations and replacing broadcast satellite orbits and clock parameters with precise orbit and clock information. This approach provides single epoch positioning accuracy at the sub-metre level to users operating receivers with low measurement noise and antennas with good multipath rejection performance.

To assess the positioning accuracy of various GPS receivers (offering raw data in the RINEX format), tests were conducted in static and kinematic mode using this autonomous positioning approach. In static mode, averaging periods of varying length were compared to help determine the optimum occupation period needed to reduce the effect of some of the random errors in the observations. The results provide an indication of the accuracy that can be expected from various receiver types when using CACS for precise point positioning.

INTRODUCTION

Since the introduction of precise GPS point positioning based on precise ephemerides and clocks computed from the CACS (Héroux and Kouba 1995), achievable accuracy has been a primary concern to users. To help provide answers to users, various GPS receivers that provide data in the RINEX format were tested in both static and kinematic mode. This paper examines the results obtained from the receivers tested and draws some overall conclusions on their performance.

The purpose of the Canadian Active Control System is to provide efficient access to modern spatial reference frames (NAD83, ITRF, etc.) and to improve effectiveness and accuracy of GPS applications (Duval et al. 1996). The CACS consists of permanent GPS tracking stations distributed over Canada's landmass. Each station is equipped with a high quality dual frequency GPS receiver and an atomic frequency standard. The data collected daily from these stations and a number of international tracking sites allows for the computation of very precise GPS satellite orbits and clock corrections based on the CACS reference clock. By using these precise ephemerides and clocks instead of the broadcast information along with their own observation data and point positioning software, users can obtain accuracies comparable to DGPS anywhere in Canada without the use of base station data. This is accomplished primarily through the

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removal of the satellite related errors including clock dithering effects introduced by selective availability (SA) - the main source of error in GPS pseudo-range positioning.

GPSPace point-positioning software (GPS Positioning from ACS Clocks and Ephemerides), developed by the Geodetic Survey Division of Geomatics Canada, was used to process the data shown in this paper. It is a PC-compatible program that processes a user's static or kinematic GPS pseudo-range (code) data in RINEX format with the CACS precise satellite clock and ephemeris products. Optional inputs include meteorological data to compensate for tropospheric delay and a single layer model to compensate for ionospheric effects.

METHODOLOGY

From mid January to mid March 1996, tests were carried out at Shirley's Bay test site in Kanata, Ontario. Figure 1 shows the location of the site.

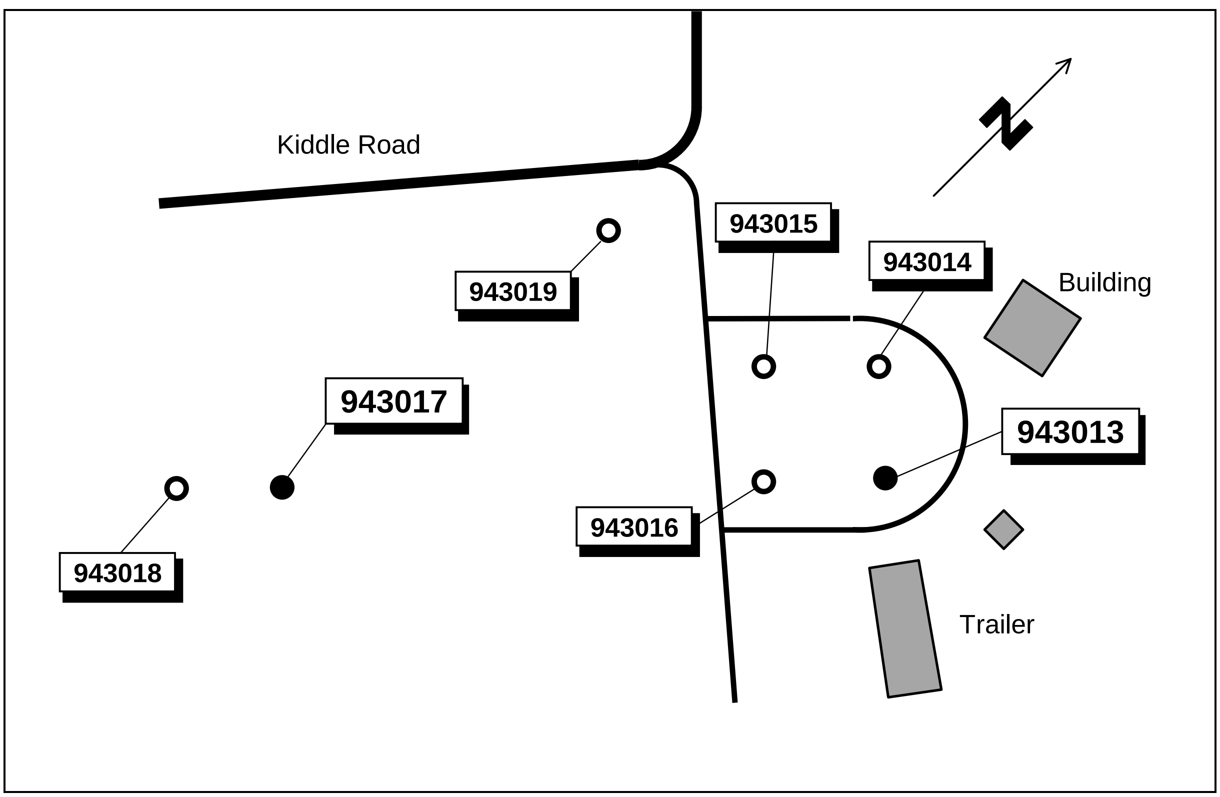


Figure 1 - Location of Shirley's Bay test site in Kanata, Ontario.
(Static tests took place at stations 943013 and 943017.
Note the potential multipath from nearby metal sided buildings at station 943013)

Receivers

A total of thirteen receivers from six different manufacturers were tested. Of the thirteen receivers, ten were single frequency and three were dual frequency. The retail price of the receivers ranges from $4,000 to $32,000. Table 1 gives some general information on the receivers tested.

Receiver (Rx)	Frequency	Pseudo-range is carrier smoothed	Satellites Tracked	Price ($ CDN)
Rx3-L	L1	No	8	4,000
Rx6-L	L1	No	5	4,000
Rx12-L	L1	Yes	8	4,000
Rx8-L	L1	Yes	12	4,700
Rx7-L	L1	No	10	5,000
Rx9-H	L1	Yes	12	7,500
Rx1-H	L1	Yes	12	12,100
Rx4-H	L1	Yes	6	14,000
Rx11-H	L1	Yes	8	16,000
Rx13-H	L1	Yes	12	20,000
Rx5-G	L1 + L2	Yes	9	30,000
Rx10-G	L1 + L2	Yes	12	30,000
Rx2-G	L1 + L2	Yes	12	32,000

Table 1 - General receiver specifications as tested

These particular receivers were chosen because they produce RINEX format data. They differ in price, number of frequencies, number of tracking channels, internal processing software, and antenna type. They were selected because they represent a wide range of currently available GPS receivers.

Static Test

Two separate observing sessions were carried out for the static test of each receiver. The first session was on a pier at which multipath was likely. The second site was in an open field relatively free from the effects of multipath. This procedure was intended to show the possible effects of multipath on GPS measurements. For each session observed the antenna was set up over a pier and left to collect data for a two-hour period at a data rate of 5 seconds with a satellite elevation mask of ten degrees. During the measurement period, meteorological conditions were observed to correct for the effects of the troposphere.

Ideally, receivers should be compared under identical observing conditions. However, this was not possible since the test was conducted over a three-month period when receivers were generously made available by manufacturer representatives or equipment owners. Nevertheless, an attempt was made to schedule the sessions in order to observe under similar satellite geometry. The atmospheric and ground conditions varied from bitter winter weather with temperatures dipping down to -30° Celsius to warm spring days with the temperature reaching +10° Celsius.

Kinematic Test

To assess the positioning accuracy achievable in kinematic mode, a simple procedure was developed to monitor the time varying position of the receiver antenna. The solution was to tether the antenna on a fixed length of rope around a pier with known coordinates. By walking the antenna at pier elevation with the rope taut, the observed differences in latitude and longitude between the antenna and the pier were combined to estimate the radius of the circle. This computed radius could then be compared with the known radius at each measurement epoch to derive error statistics.

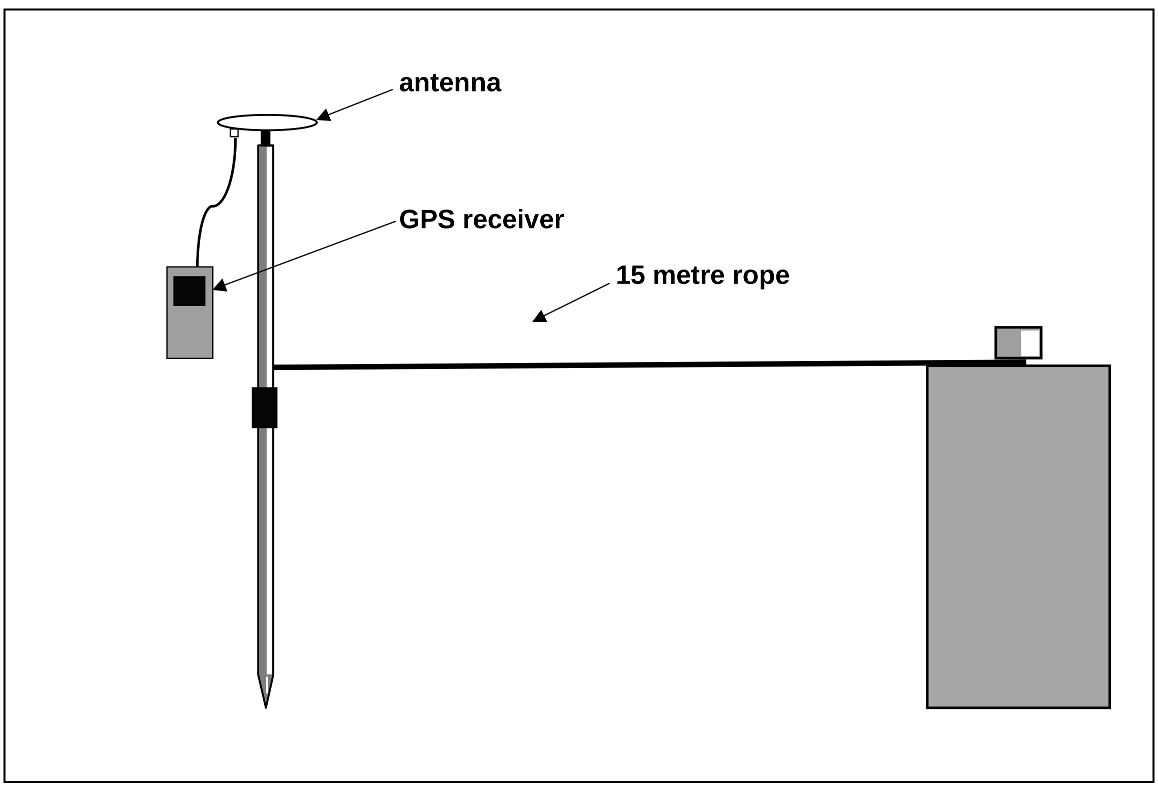


Figure 2 - Setup of the receivers for kinematic tests.

The kinematic test was repeated twice, each under different satellite geometry. For each session, one end of a fully extended rope was attached to a bolt on the pier while the other had a range pole with an antenna attached to it. The antenna then circled the pier five times along a 15 metre radius at a fixed height. The sampling interval was one second and the satellite elevation mask set to ten degrees. Figure 2 depicts the setup for the kinematic tests.

Data Processing

Program *GPSPace* was used to post-process the pseudo-range observations from all tested receivers (NRCan 1995). For comparison, the data was processed using both the broadcast and the precise orbits and clocks publicly available through the Canadian Geodetic Bulletin Board Service which can be accessed via internet at http://www.geod.nrcan.gc.ca.

The output from *GPSPace* yields two files. The summary file shows the input parameters, and observation and position statistics for the complete session. The position file contains information on each epoch processed as shown in Table 2.

Year	HR:MN:SS	GDOP	RES	LAT	LONG	HGT	DLAT	DLONG	DHGT
2/22/96	17:17:00	4	1.1	45 23 59.8676	- 75 55 08.9433	51.436	4.429	1.374	6.428
2/22/96	17:17:05	4	0.9	45 24 0.29	- 75 55 9.0596	39.158	8.613	-1.156	-5.851
2/22/96	17:17:10	4	0.6	45 24 0.227	- 75 55 9.0415	40.72	6.667	-0.763	-4.289
2/22/96	17:17:15	4	0.5	45 24 0.2071	- 75 55 9.0339	41.032	6.053	-0.596	-3.977
2/22/96	17:17:20	4	0.3	45 24 0.17	- 75 55 9.0193	42.019	4.907	-0.28	-2.989

Table 2 - Sample of some information output to the position file from *GPSPace.*

Using the position file, additional statistics were computed on the epoch positioning results. For the static data, the differences in latitude (dlat), longitude (dlong), and height (dhgt), with respect to the true coordinates at each epoch, were used for statistical analysis and the RMS of the differences for each component were calculated.

Time averaging was also performed using the static data to help determine the impact of occupation times for receivers. Averaging was performed over time periods of 2, 5, 15, 30 and 60 minutes.

For the kinematic data the radius of the circle was computed for each epoch of GPS positioning. Subsequently, the RMS of the differences between the computed and known radius of the circle was calculated.

DATA ANALYSIS

Static results are presented first followed by the kinematic results. For analysis purposes, receivers have been grouped into three classes based on their price range:

- low-cost single frequency / cost $5000 or less (Rx#-L)
- high-cost single frequency / cost between $5000 and $20,000 (Rx#-H)
- geodetic dual frequency / cost $20,000 or more (Rx#-G)

The geodetic receivers are those that measure both frequencies and were used twice in the analysis, first using L1 data only and then L1 and L2 combined data. Results from L1 only processing are included with those of high-cost single frequency receivers.

Static Analysis

After analyzing static data from both stations, no significant difference in results were noticed. Therefore for clarity, only data collected from station 943017 are presented.

Broadcast Versus Precise Orbit and Clock Results

Figure 3 shows the improvements when processing with precise orbits and clocks when compared to broadcast. The results are for a typical high-cost single frequency hand-held GPS receiver. The left side of the figure shows the single epoch positions computed using the broadcast ephemeris and clocks. From the plots it can be seen that the epoch estimates of position differences vary within ±75 metres in latitude; ±60 metres in longitude; and ±150 metres in height from the truth.

Once the precise orbits and clocks are applied, significant improvements are noted. The right side of the figure shows the results of processing with precise orbits and clocks. Single epoch position differences are now within ±1.5 metres in latitude; ±1 metre in longitude; and ±6 metres in height when compared to the truth. These results will vary slightly depending on the characteristics of the receiver. Nevertheless, they are typical of what one can expect when using a single frequency receiver and replacing broadcast orbits and clocks with precise orbits and clock data. Note that no correction was applied for ionospheric effects.

Positions Computed Using Broadcast Ephemeris and Clocks

Positions Computed Using Precise Ephemeris and Clocks

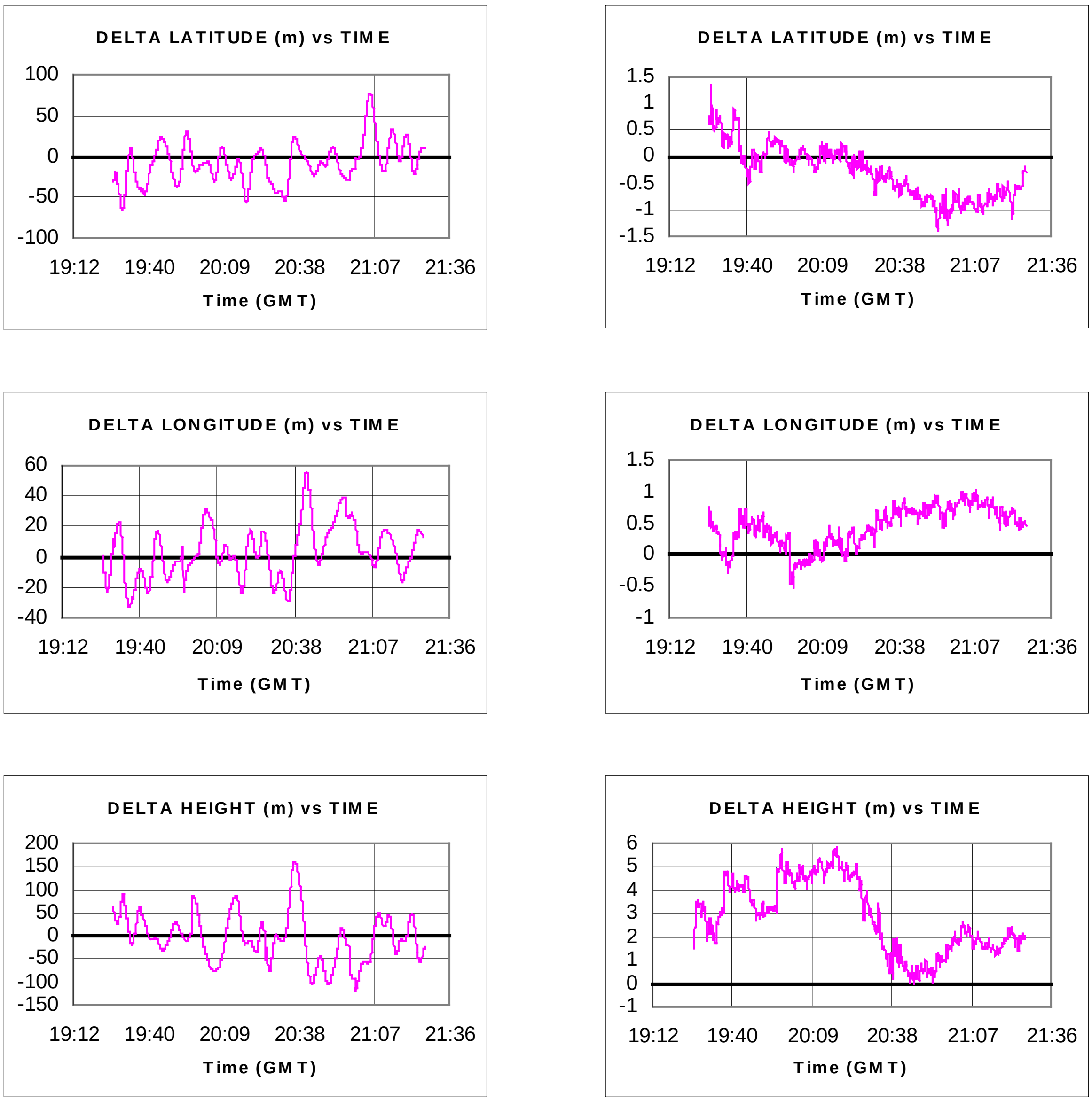
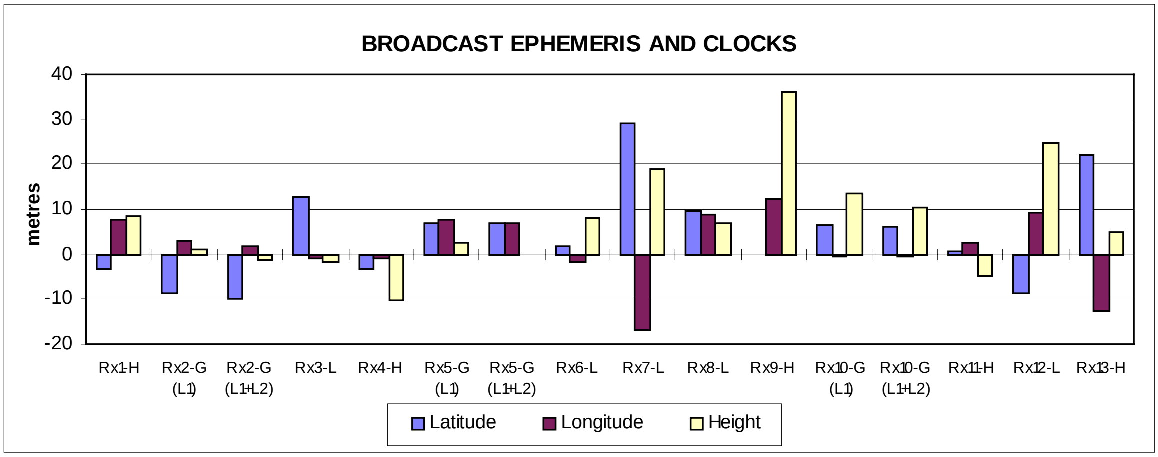


Figure 3 - Positions computed using broadcast information compared with positions computed using the precise CACS products from data of a single frequency hand held receiver.

(Note the vertical scale difference)

Figure 4 indicates the accuracy of the average position obtained from a 2-hour observing session processed using either broadcast or precise orbits. It shows the differences in latitude, longitude and height between the session average and the true position of the station for all receivers tested. After two hours of data collection, the point positioning accuracy is at about the ten-metre level in all three dimensions when processed using the broadcast ephemeris and clocks. This is commensurate with the errors in the broadcast satellite positions. When precise orbits and clocks are used, the average point positioning accuracy is approximately half a metre in latitude and longitude and three metres in height. A height bias is evident for all single frequency results. Results from dual frequency receivers do not show this bias.



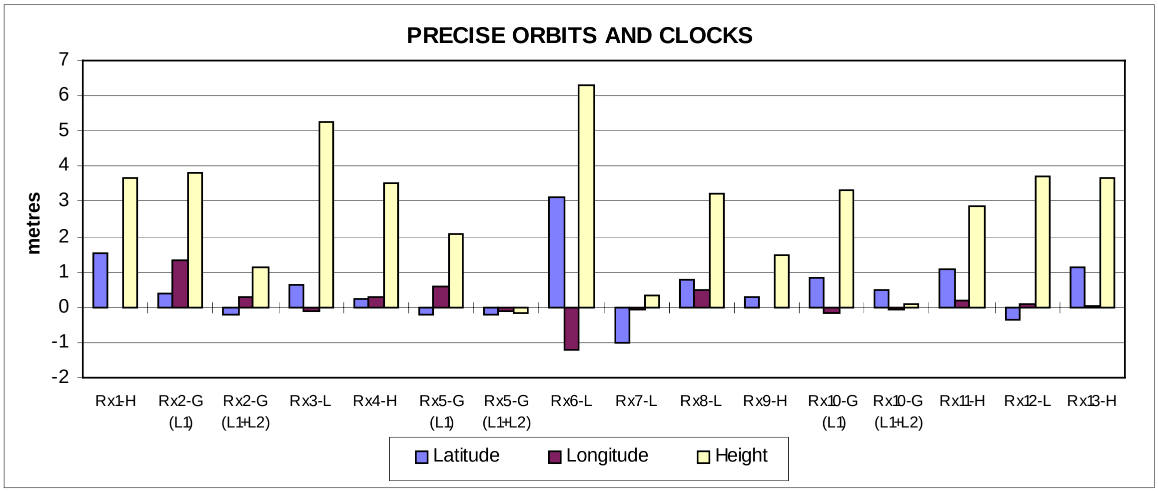


Figure 4 - Difference between the session average and the true position of the station when processed using broadcast information versus precise orbits and clocks.

Impact of Receiver Class on Positioning Accuracy

Figure 5 shows the impact of receiver class on single epoch positional accuracy when using broadcast ephemeris and clocks. All receivers tested have RMS values anywhere between 20-40 metres in latitude and longitude and between 40-70 metres in height. No significant improvement in accuracy can be seen between low and high-cost receivers when only broadcast information is used.

Similarly, figure 6 shows the impact of receiver type on single epoch positional accuracy when using precise orbits and clocks. This figure shows significant differences from one receiver class to another.

Positioning with L1 low-cost receivers showed two different levels of results. The first three receivers in this class have a low price tag and do not provide carrier smoothing of the code which results in a lower pseudo-range measurement precision. The positional accuracies achieved were at the 5-10 metre level in the horizontal components and at the 15-25 metre level in the height component. On the other hand, the last two receivers, which were included in the L1 low-cost receiver class because they cost under $5,000, use carrier smoothed code and yielded higher precision pseudo-ranges comparable to those of high-cost type receivers. The accuracies obtained with these were at the 1-2 metre level for the horizontal coordinates and better than 5 metres in height.

Positioning with L1 high-cost receivers consistently showed accuracies of 2 metres or better in the horizontal components and 2-5 metres in height. All these receivers use carrier smoothed code yielding higher precision pseudo-ranges. The differences in the accuracy achieved from the different receivers may be caused by varying antenna types, internal signal processing algorithms and inter-channel delays or could also be related to the different observing conditions.

For all results of L1 only processing, the resolution of the height component remains significantly weaker. This is explained by the fact that the ionospheric biases affect mainly the height component and for this analysis, no ionospheric correction has been applied. The resolution of the latitude is also consistently weaker than the longitude, although at a much lesser level than for height. It is also attributed to both the fact that no ionospheric model has been applied, and to the weaker satellite constellation geometry in the north-south direction.

Positioning with geodetic type receivers using dual frequency data showed accuracies of 0.6 metre or better horizontally and 1-2 metres in height. Although ionospheric biases are mostly removed by using both L1 and L2 frequencies the RMS of the vertical component is still slightly higher. This is attributed to the impact of satellite geometry which becomes important at this accuracy level.

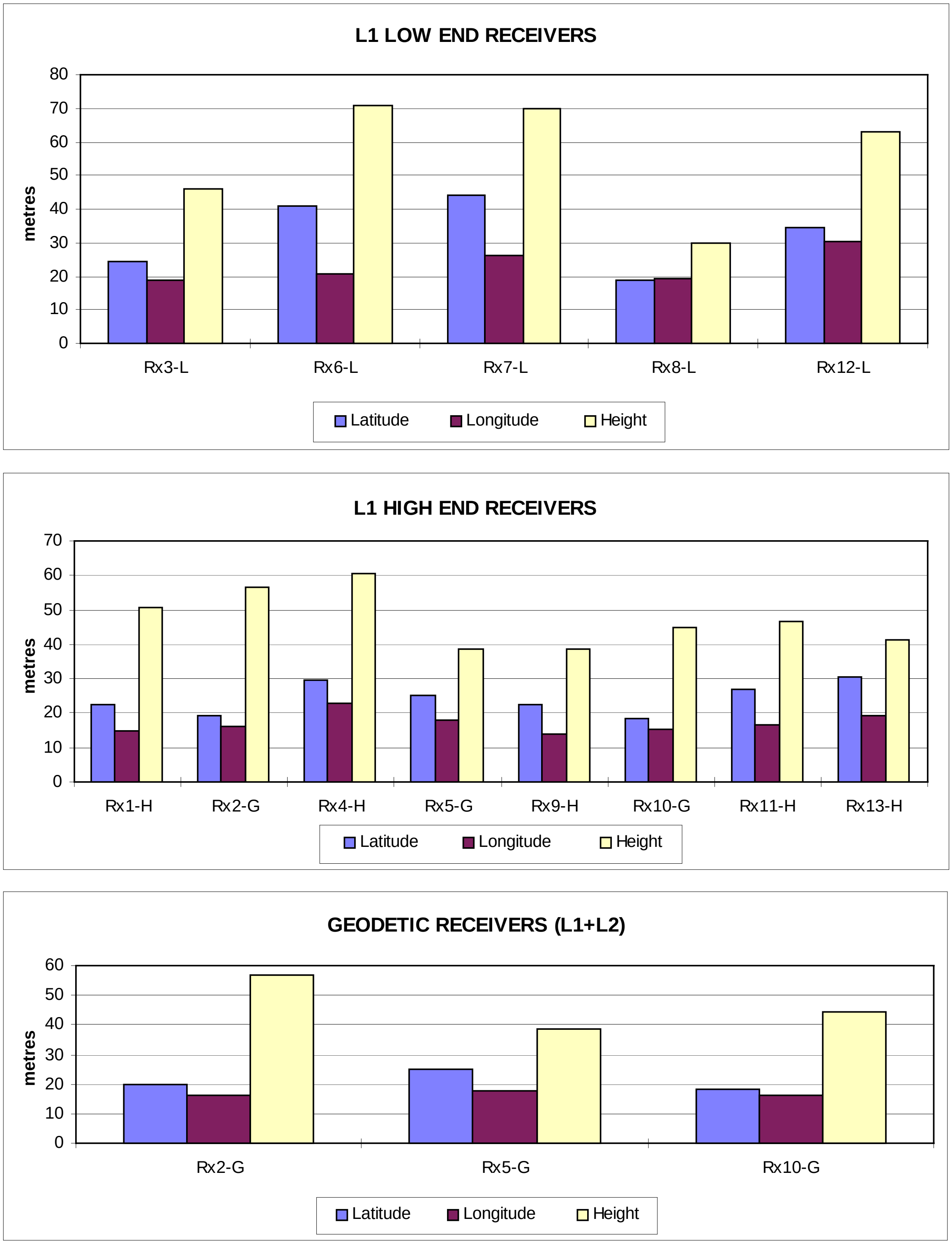


Figure 5 - RMS of the single epoch determinations about the known position using broadcast orbits and clocks
(Note the vertical scale changes)

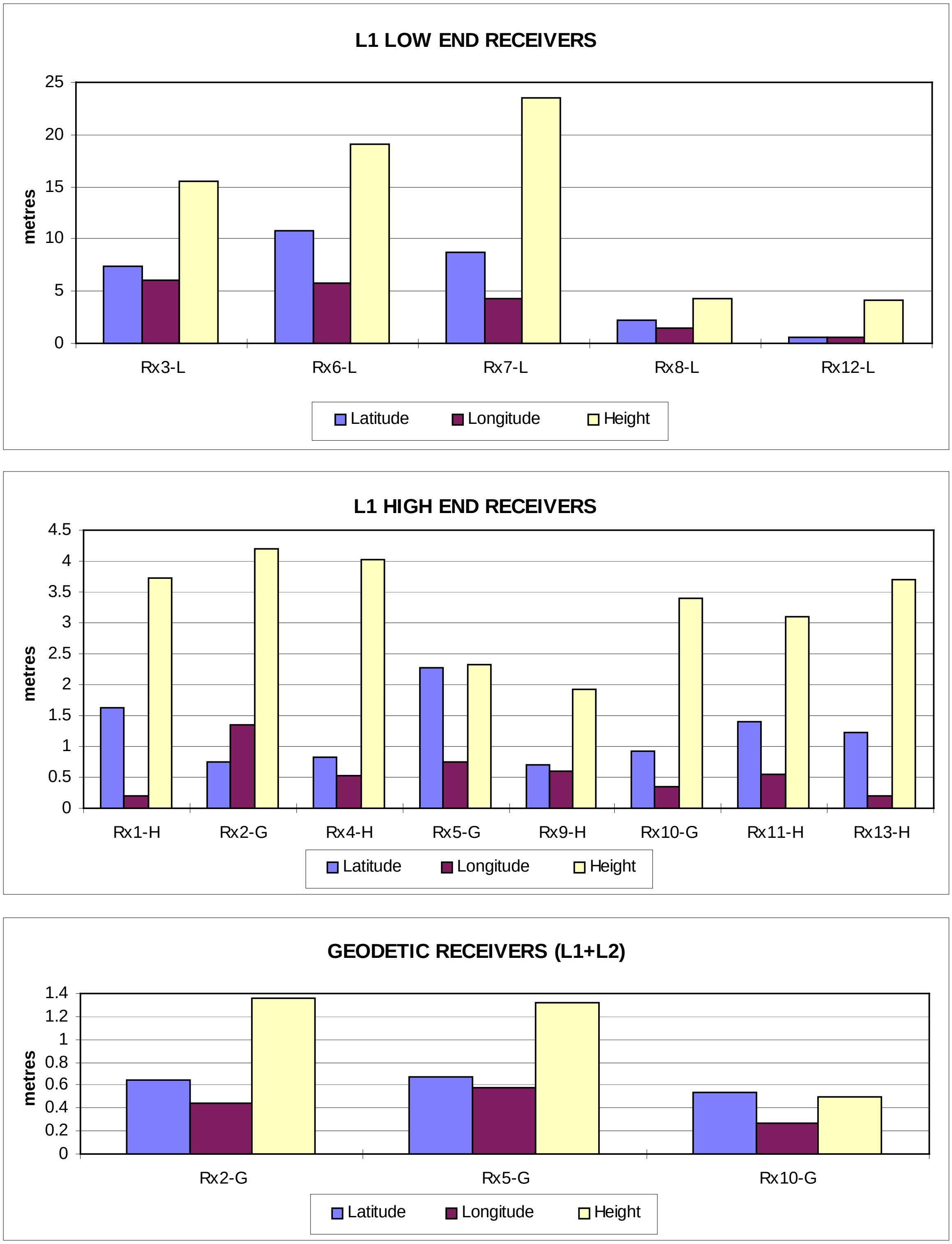


Figure 6 - RMS of the single epoch determinations about the known position using precise orbits and clocks.
(Note the vertical scale changes)

Impact of Position Averaging over Time

The following three figures show the effects of position averaging over time when operating in static mode. Average positions were computed for segments of 2, 5, 15, 30 and 60 minutes using the epoch by epoch estimates (5-second intervals) over the full two-hour tracking session. Thereafter, differences between the period averages and the true position were obtained and their RMS computed. Only the results from using the CACS precise orbits and clocks were analyzed in an attempt to determine optimal observation periods depending on receiver type.

Figure 7 shows the latitude, longitude and height RMS for single epoch positions and for positions averaged over time periods of 2, 5, 15, 30 and 60 minutes for L1 low-cost receivers. As expected, longer averaging periods yield better results. The improvement is very significant when going from single epoch to the 2-minute averaging period with an improvement of the results by a factor of 2 to 5. This is especially noticeable on the low cost receivers, without carrier smoothing of the code, where even a short averaging period permits a drastic reduction of the noise due to poorer measurement precision. As the averaging period increases from 2 to 60 minutes there is additional improvement in accuracy by a factor 1.5 to 2.

Figure 8 shows the latitude, longitude and height RMS for single epoch positions and for positions averaged over time periods of 2, 5, 15, 30 and 60 minutes for L1 high-cost receivers. In this case, there is little improvement as the averaging period increases. This means that approximately the same level of accuracy is attained from a single epoch as for averaging for two hours. This type of result is expected from receivers that offer high precision pseudo-ranges.

Figure 9 shows the latitude, longitude and height RMS for single epoch positions and for positions averaged over time periods of 2, 5, 15, 30 and 60 minutes for geodetic receivers. Again, there is little improvement in accuracy when averaging over time.

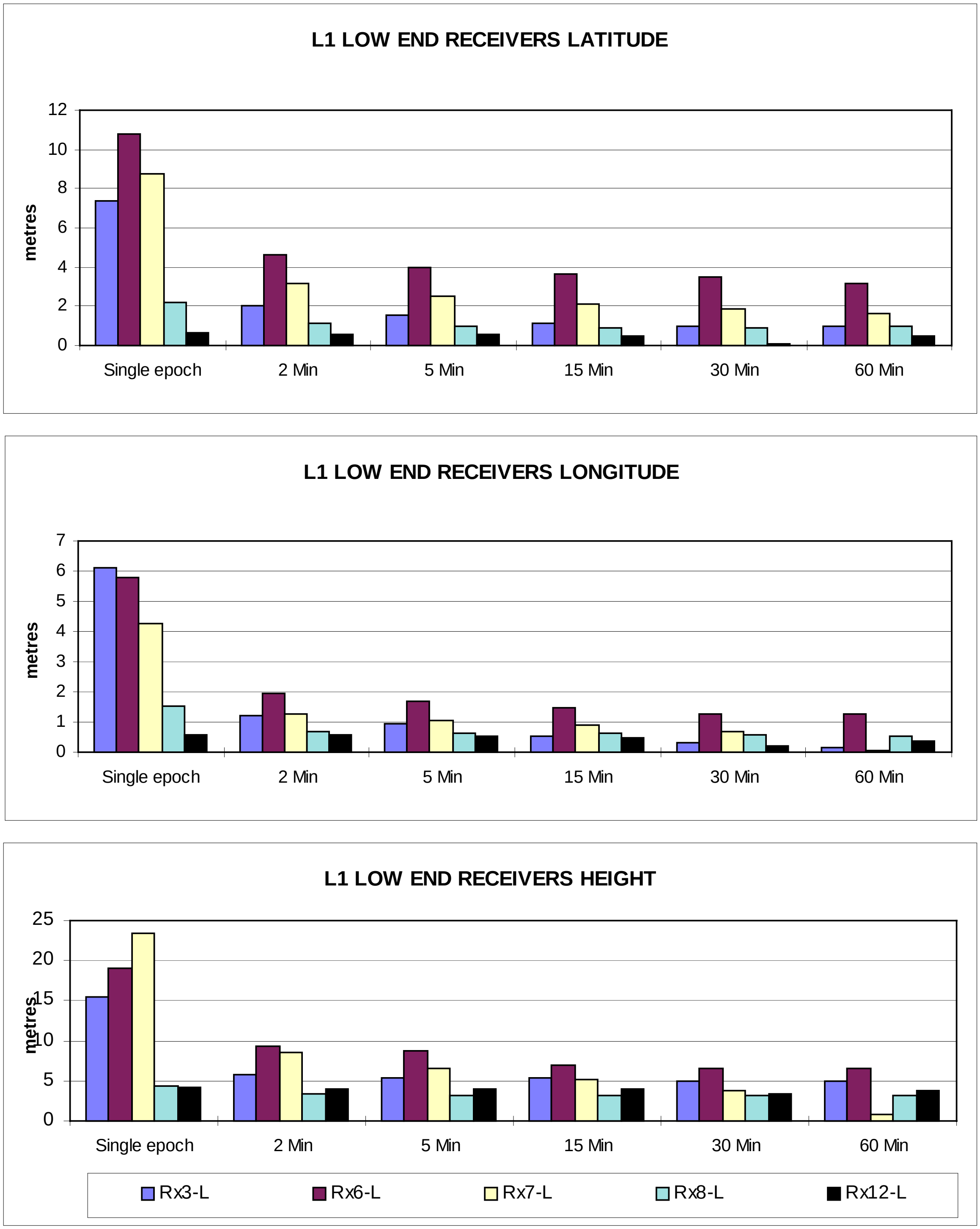


Figure 7 - RMS values of L1 low-cost receivers when processed using precise orbits and clocks and averaged over time.

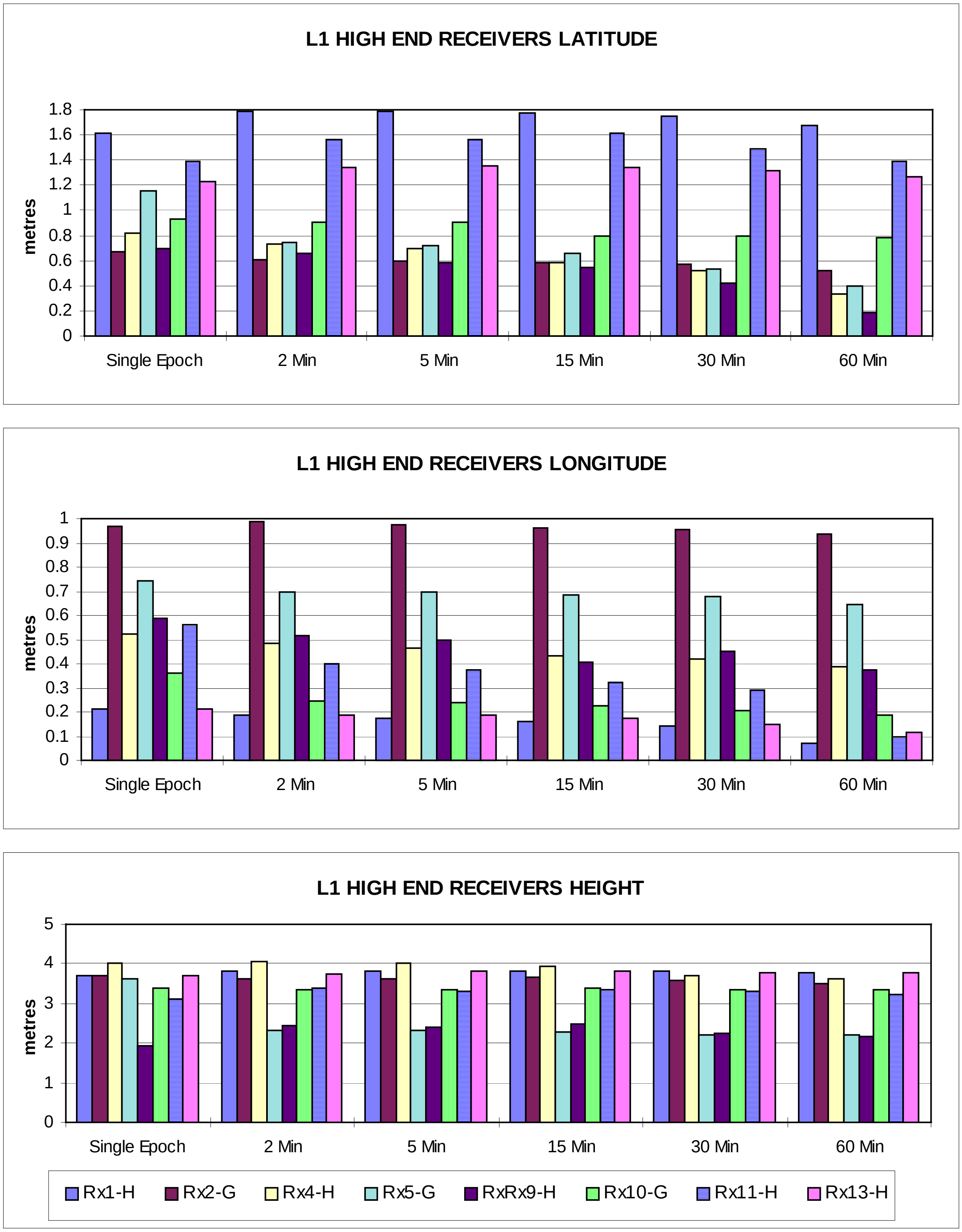


Figure 8 - RMS values of L1 high-cost receivers when processed using precise orbits and clocks and averaged over time.

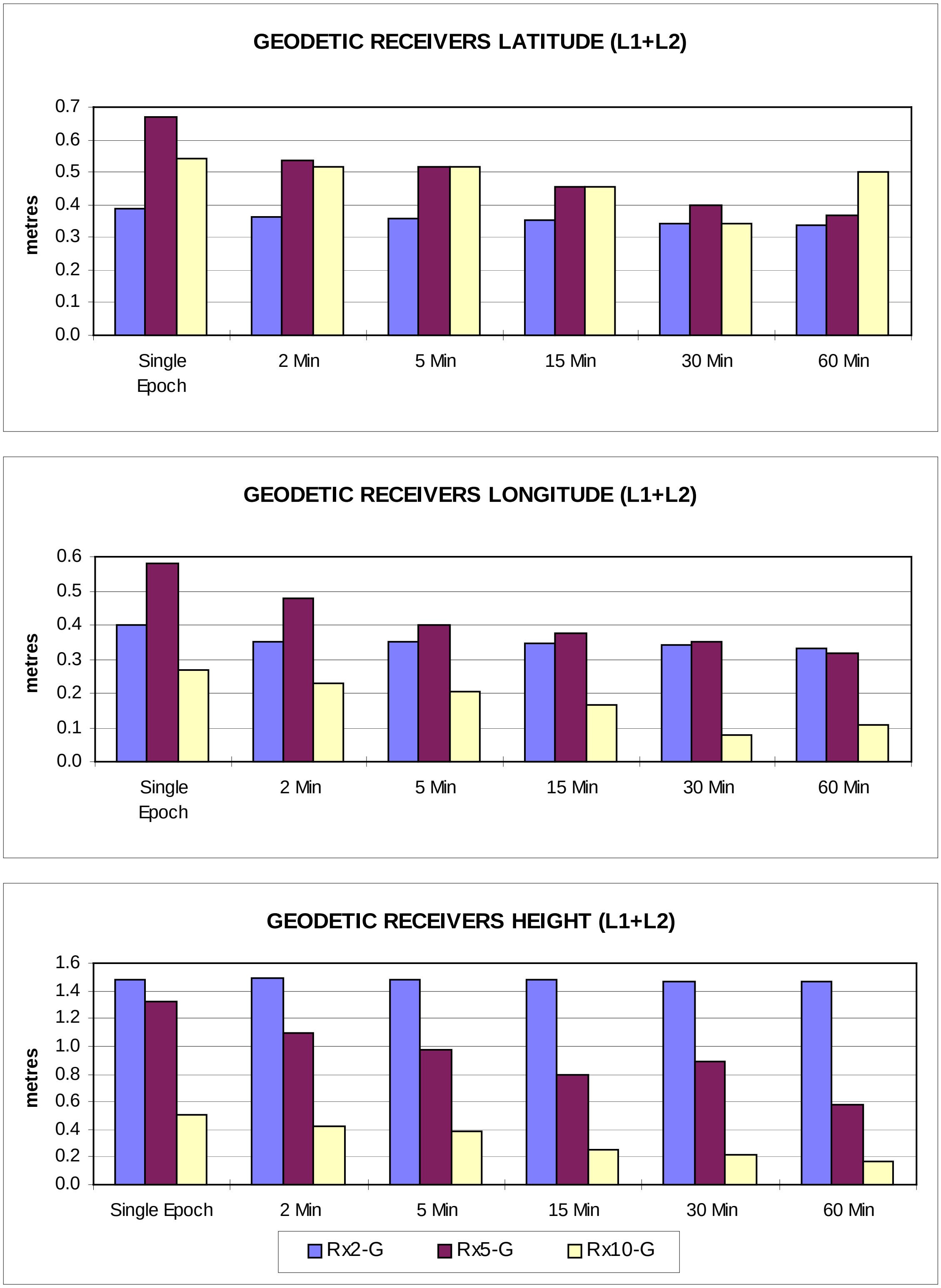
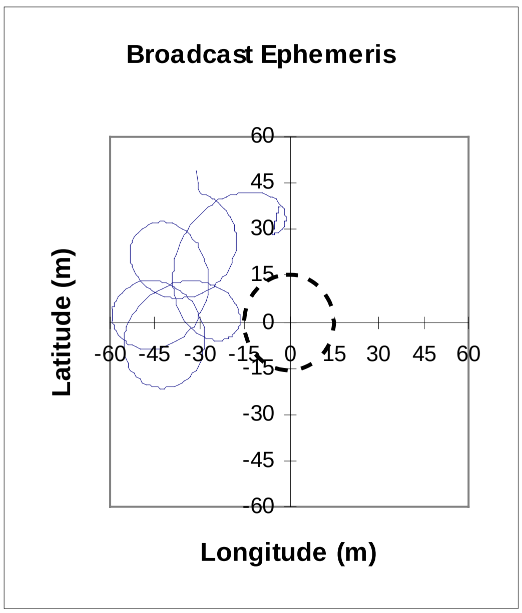


Figure 9 - RMS values of geodetic receivers when processed using precise orbits and clocks and averaged over time.

Kinematic Analysis

The analysis of the accuracy of positioning when operating in kinematic mode is based on the differences between the circle radius computed for every observed epoch as the antenna is circled around a fixed point and the known value of this radius.

Figure 10 compares the footprint of a circle with a radius of fifteen metres determined from GPS positions computed using the broadcast ephemerides versus precise orbits and clocks. This particular data set was collected using a high-cost single frequency receiver. When processed using the broadcast ephemerides, the circular path of the antenna is distinguishable but each revolution deviates from the true path by as much as sixty metres over a ten minute period. This spiral effect is caused by selective availability. When the data is processed using precise orbits and clocks, the computed positions are in close agreement with the true footprint of the circle. These plots clearly illustrate the effect of replacing the broadcast information with the precise orbits and clocks.



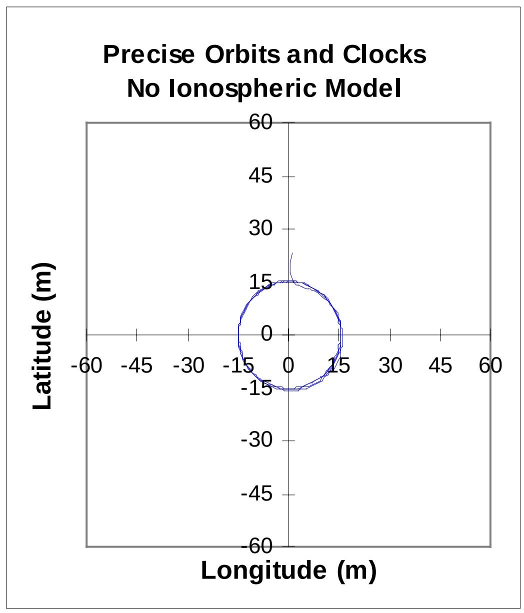
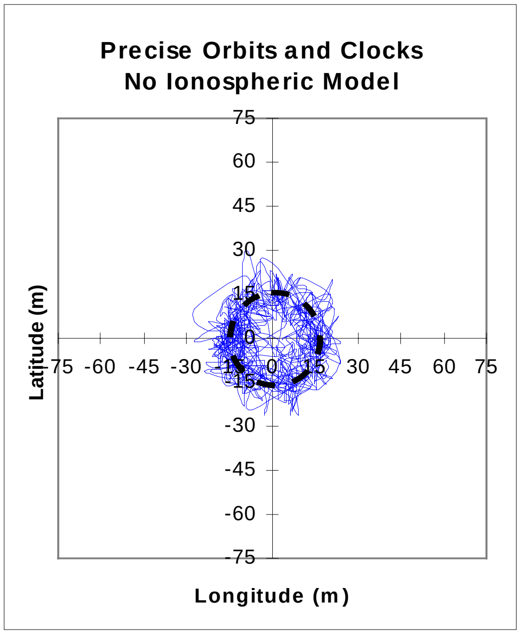
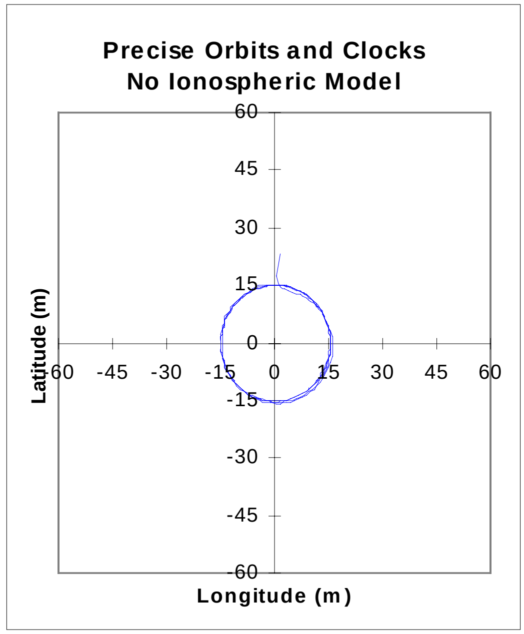


Figure 10 - Horizontal position plots of a high-cost single frequency receiver (Rx13-H) when processed with broadcast ephemerides versus precise orbits and clocks.

As seen in the previous section, receiver characteristics also have an important impact on achievable accuracy. Figure 11 shows the horizontal position plots of two receivers tested using precise orbits and clocks. The plot on the left is from a low-cost five channel single frequency receiver with no carrier smoothing of the code. The plot on the right is from a high-cost twelve channel single frequency receiver. Obvious differences in the accuracy of positioning are attributed mainly to pseudo-range precision and antenna multipath rejection capabilities.



Rx6-L



Rx13-H

Figure 11 - Comparison of kinematic data collected with a single frequency low-cost receiver versus a single frequency high-cost receiver.

Figure 12 shows the horizontal positioning accuracy of each receiver tested in kinematic mode. The RMS value represents the level of agreement between the computed radius of the circle (from GPS positions estimated every second over 5 revolutions - about 600 samples) and the known radius of the circle. The receivers have once again been grouped into three classes: L1 low-cost receivers; L1 high-cost receivers; and geodetic receivers. Results are comparable to those obtained from single epoch static positioning. Accuracies at the one to two metre level are reached with most single frequency receivers except for the low-cost receivers with low precision pseudo-ranges (i.e. where pseudo-ranges are not carrier smoothed). Only dual frequency geodetic receivers consistently gave accuracies in the sub-metre range.

Two additional observations were made when analyzing the results: First, the multipath rejection capability of the antenna becomes very important when observing in a kinematic mode or deriving positions from a very short observation period as there is no possibility of smoothing out multipath effects. This is illustrated in figure 13 which shows the horizontal position plot of the L1 high-cost receiver (Rx1-H) with the highest RMS value in its class. The observed radius of the circle is in close agreement with the true radius except in the lower right corner of the figure. This sudden shift in position occurs as the antenna passes within five metres of a metal covered trailer. Because the constellation of satellites tracked remained the same throughout the session, multipath is believed to be the cause for these sudden variations. At this level of precision, the multipath rejection capabilities of the antenna becomes important.

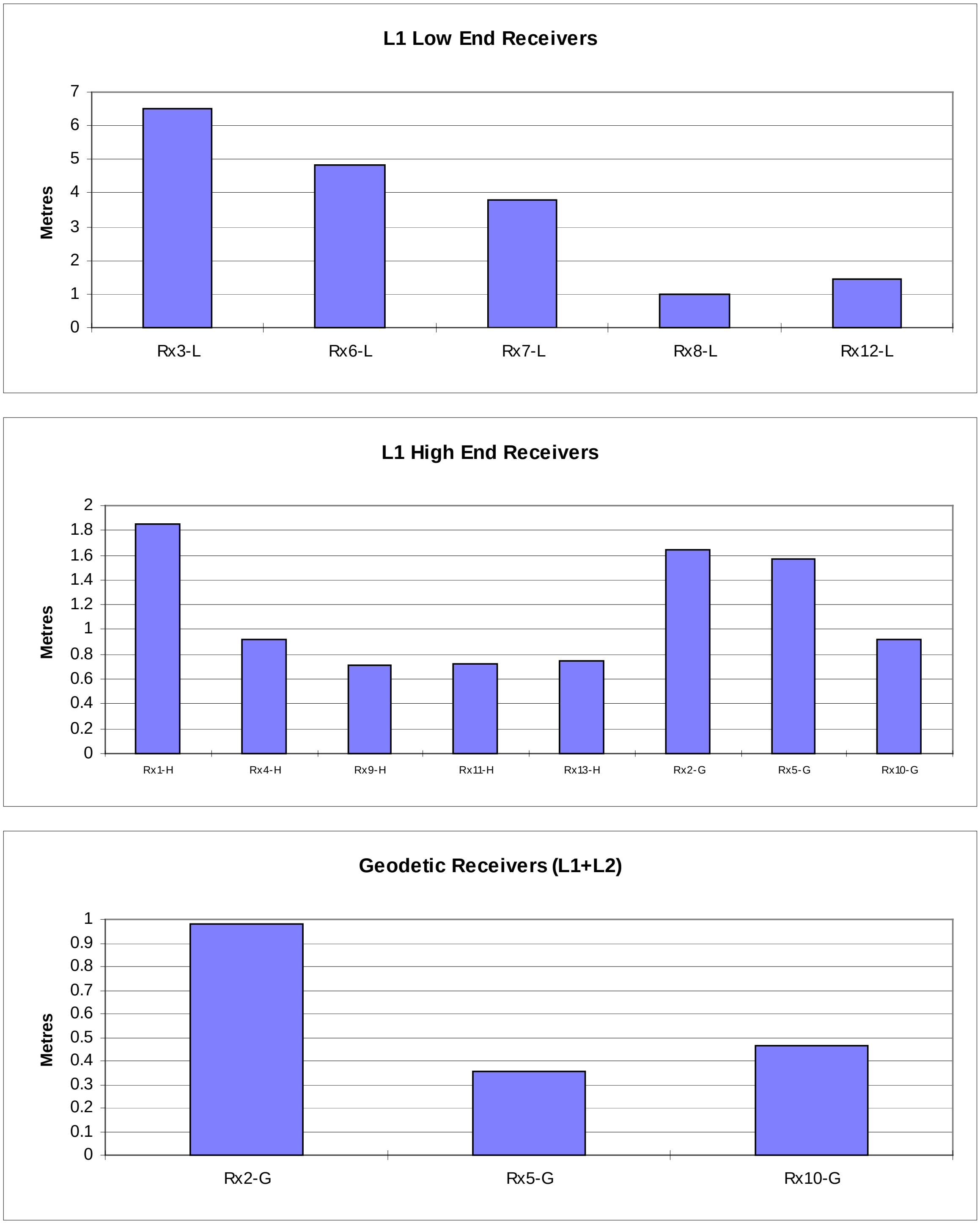


Figure 12 - Kinematic accuracies (RMS of ΔR) of tested receivers broken down by class.

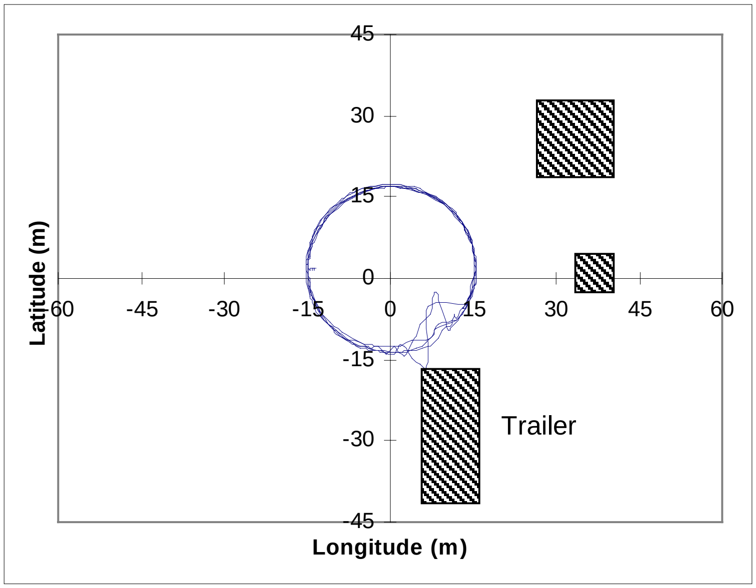


Figure 13 - Effect of multipath on a single frequency high-cost receiver (Rx1-H).

Second, it was also noticed that circles defined by single frequency receivers results were occasionally shifted towards the north. Figure 14 compares the horizontal plots of a geodetic receiver processed using only the L1 frequency versus both frequencies. In this instance, there is approximately a two-metre bias in latitude from the single frequency processing that disappears completely when both frequencies are processed. These graphs suggest that unaccounted for ionospheric delays may systematically affect horizontal positioning, in these cases, at the level of 1 to 3 metres. This behavior was more apparent when observations were taken during mid-day, a period of higher ionospheric activity.

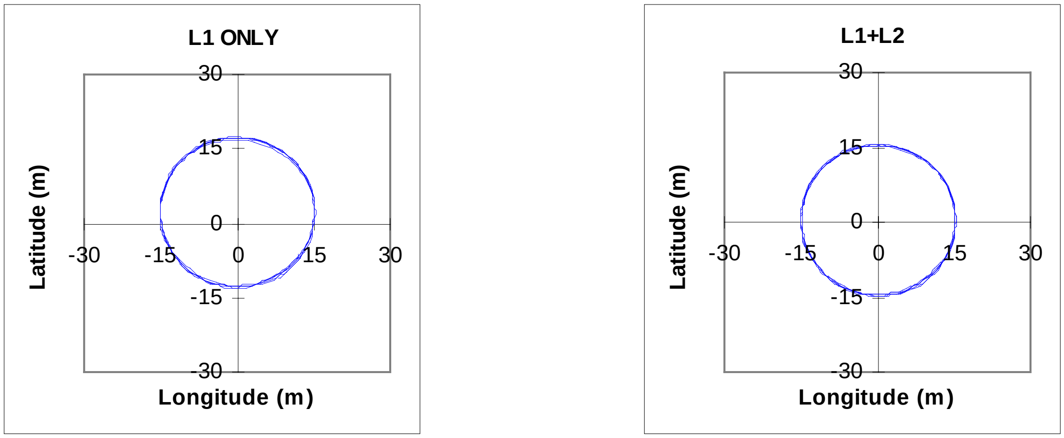


Figure 14 - Comparison of a dual frequency receiver (Rx5-G) processed with L1 frequency and with L1+L2 frequencies.

CONCLUSION

Results of the analysis in static mode show that when only broadcast satellite information is used single-point positioning precision is basically independent of the quality of GPS equipment, i.e. satellite errors dominate the positioning error budget. The accuracy of single-point position using broadcast appears to be limited to the 10-metre level for most receivers even after 2 hours of averaging.

The use of CACS precise orbits and clocks greatly improves the pseudo-range single point positioning for all receivers tested (Table 3). Depending on receiver class, single epoch position accuracies vary from 5-10 metres in horizontal and 15-25 metres in height with L1 low-cost, down to better than 2 metres in horizontal and 2-5 metres in height for L1 high-cost or L1 low-cost receivers with carrier smoothed code, and reach accuracies of 0.6 metres or less in horizontal and 1-2 metres in height for dual frequency geodetic type receivers. The difference between high-cost single frequency and dual frequency receivers was found mainly in the quality of the height component and to a lesser degree in the latitude. This is expected since no ionospheric corrections were applied to the single frequency data. After this analysis was completed, a wide-area single layer ionospheric model has been developed and is generated from the Canadian Active Control System, applying this model to the observations is expected to remove most of the ionospheric bias.

Receiver Class	Horizontal Accuracy (RMS)	Vertical Accuracy (RMS)
Low-Cost Rx (⇔ $5,000) no carrier smoothed pseudo-range	5-10 m	15-25 m
Low-Cost Rx (⇔ $5,000) with carrier smoothed pseudo-range	1-2 m	2-5 m
High-Cost Rx ($5,000 - $20,000)	<2 m	2-5 m
Geodetic Rx (> $20,000)	< 0.6 m	1-2 m

Table 3 - Positional accuracy by class when using precise orbits and clocks.

Position averaging over time in static mode presents some advantages mainly for users of L1 low-cost receivers with low quality pseudo-ranges for which an improvement of the results by a factor of 2 to 5 was obtained with as little as a 2-minute averaging period. L1 high-cost and geodetic receivers offer single epoch accuracies comparable to what is obtained after averaging over time.

Analysis of data collected in kinematic mode confirmed the results obtained in static mode. Accuracies at the one to two metre level are reached with most single frequency receivers except for the low-cost receivers with low precision pseudo-ranges (code not carrier smoothed). These showed results at the 4-7 metre level. Only dual frequency geodetic receivers consistently gave accuracies in the sub-metre range.

The analysis of the antenna trajectory along the footprint of the circle for high-cost single frequency and geodetic receivers confirmed that degradation of accuracy resulting from multipath may result from a combination of site conditions and satellite geometry. This is a reminder of the requirement for multipath resistant antenna designs for reliable and accurate positioning. Comparison of single with dual frequency horizontal positioning of the circle footprint has also illustrated the latitude bias that may results from not applying ionospheric corrections to single frequency data. These biases are expected to disappear when the CACS single layer ionospheric model is applied in the processing of the data and require additional processing and analysis.

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