Precise GPS *time transfer to a moving vehicle*

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BIOGRAPHY

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Bernard Thomas is an engineer of the Direction des Constructions Navales (DCN) Brest, France, a division of the Délégation Générale de l'Armement (DGA) of the French Department of Defence. Since 1991 he has-worked on the Loran-C and GPS radio-navigation systems, especially on navigation and time applications.

ABSTRACT

GPS time transfers normally employ the common-view method and take place between pairs of stationary receivers at precisely-known locations. This paper focuses on techniques for time transfer to a GPS navigation receiver on a moving ship. a land vehicle or aircraft The accuracy requirement is 20 ns (la) and. preferabiy, the system should work anywhere on earth.

Single point precise orbit and clock positioning emerges as a the best way of achieving extremely high timing accuracy when computation is performed post-mission Its key advantage is its global coverage without re reference stations **or communica**tions 'Links. DGPS time transfer using a calibrated time standard at the reference station is a viable alternative. It may be employed in real time, although its performance may also benefit from post-mission processing using precise orbit data. Both these techniques will be presented in detail and their performance evaluated.

The context of this study is the measurernest on a moving ship! a land vehicle or aircraft of the arrival times of Loran-C pulses The arrival times are required in order to calibrate the Additional Secondary Factors (ASFs) caused by the propagation of the signal over land paths. In this application all processing may be carried out pest-mission. ---

Our experiments show that both timing methods can meet the 20 ns accuracy requirement. The paper compares the two with one another and with more conventional timing techniques. including time transfer via a common-view satellite and geodetic positioning. The specifications of the GPS receivers required to implement the methods are set out The techniques presented are, of course, also applicable to GPS time transfers between stationary locations.

INTRODUCTION

A GPS signal propagates through the earth's atmosphere on its way from the satellite to the user. The signal's propagation in the atmosphere is slower than in a vacuum and its arrival is delayed in consequence. We must take this delay into account when calculacin< the distance from the satellite to the user.

Presented at ION-95, September 12 - 15, 1995, Palm Springs, CA

Loran-C (Long RAnge Navigation) is the world's moat widely-used terrestrial aid to navigation. Its mode of operation nay be considered comparable to that of GPS in that transmitters at known locations radiate signals and a receiver calculates its distances from them by timing their arrivals and from 'knowledge of their speed of propagation. Loran-C signals suffer propagation delays when they cross land masses which are analogous to the delays of GPS signals passing through the atmosphere. However, unlike GPS atmospheric delays which change constantly, the land-mass delays of Loran-C are virtually constant. We can measure and record these 'Additional Secondary Factors (ASAFs)' and so incorporate them into the range measurements .made by receivers [1,2].

We determine ASF values by measuring on a survey ship, a !and vehicle or aircraft the arrival times of Loran-C signals at 'known locations These poaitiona must be 'known with 1σ accuracies of approximately 7 m and the time measurements made.with an accuracy of better than 20 ns. GPS is a candidate to provide both the position and time references This paper focuses on ways of obtaining precise time with GPS on a moving vehicle Our objective is a low-cost technique which may be employed as part of a fully automatic unatteoded, measuring unit to be installed on a ship and left to record Loran-C information throughout a voyage. The recorded dat will be processed at the end of the voyage to revea! the ASF values. The equipmect may be used anywhere throughout the sea area3 of North-WWestern Europe.

This an unusual and very demanding application of GPS for time measurement. Without being GPS timing experts, we sat down and evaluated the follow&g standard GPS timing techniques: 'common-view', 'Enhanced GPS' and 'geodetic positioning' to see whether any of them could fulfil our requirements

STANDARD GPS TIMING TECHNIQUES

In the 'common-view method', two very accurate and stable clocks are used as the time references for two GPS receivers and compared against the clock of a pre-selected GPS satellite which is visible to both receivers [3,4,5]. Conventionally the time measurements are averaged over a period of 13 minutes. The two receivers are stationary, in precisely-hown locaticcs. Corrections are applied to account for the differences between the distances travelled by the signals from the satellite to the locations of the two receivers.

This time transfer method is unsuitable for our purpose: our receiver will be in an unknown location, and moving, and we do not have a relatively-expensive atomic standard as part of the mobile equipment to use in the averaging process.

'Enhanced GPS' was the second technique evaluated. mOST of the effects of Selective Availability (SA) may be averaged out by using a stable reference clock for instance a rubidium standard [6]. The rubidium clock is stable in the short term and the effects of SA are minimised by adjusting it to match GPS *via* a control loop of very long time constant. The performance of this technique is not as good as that of :he common-view method. Besides, it requires a rubidium standard as part of the mobile equipment which is costly and would need several hours of SA averaging time before use.

Geodetic positioning used *for* precise time transfer can provide very high accuracy [7]. The method employs GPS carrier phase measurements .It is, of course necessary to solve for the phase ambiguities on the fly in our application. This is very demanding to do when the mobile is a considerable distance from the reference station It is made even more difficult if the receiver experiences cycle slips because of short periods of signal blockage We judged this otherwise very accurate method inadequately robust fcr unattended use on a vessel.

Having found none of these standard GPS timing techniques suitable for our application, we identified two less conventional options: Precise Single Point (PSP)' and 'DGPS' time transfer PSP is a new technique for timing applications it employs precise orbit ***and clock values*** peat-mission. DGPS time transfer is essentially the same as conventional DGPS. However, the reference station is equipped with an accurate clock and generates range corrections instead of the usual pseudorage corrections We will now describe and demonstrate these two options in further detail.

PRECISE SINGLE POINT TME TRANSFER

Stand-alone GPS has a timing accuracy of only some 300 ns. This is limited mainly by the component of SA which dithers the satellites clocks and, to a lesser extent by the ccmponent which introduces errors in the ephemeris values they broadcast The principie of PSP is simply to replace the broadcast clock and orbit parameters with so-called precise orbit and clock' values. The European Space Agency (ESX), inter alia, calculate such values post-mission, using data from the stations of the International GPS Service (IGS).

PSP has been used for positioning [8,9], achieving an accuracy comparable to that of DGPS. However, not only are the three position coordinates, latitude, !ongitude and height, determined in :he GPS solution, jutahothe :eceiver's clock offset; 4 unknowns and at least 4 satellites are needed to do this. *Our* assumption was that the timing accuracy obtainable should be comparable to the position accuracy. Specifically a lo 3D position accuracy of 7 m, for example, would correspond to a 1σ timing accuracy of 10 ns (applying the 'TDOP is half the PDOP' rule of thumb and assuming that 1 .m is the distance travelled by signals in 3 ns).

Essentially PSP may be thought of as wide-area, post-prcceased, DGPS. It has the great advantage of complete globai coverage while not requiring the mer to provide any reference stations In additicn, not only does it give precise time values, but alzo the precise position values which we also need.

However, there are complications! We must ask: what time does PSP provide? It appears that time values derived using the ESX PSP data use a time scale, :e-computed independently each day which is referenced to GPS time (including the inatantacecus effects of SX) at the epoch of the start of that day.

Our objective in making Loran-C time-of-arrival measurements is to compare the arrival times of Loran-C signals with their transmission times. These are known very precise!y with respect to a timescale generated in France: the so-called 'UTC (Brest)' The solution to the problem of the time scale is therefcre straightforward we simply observe the difference between PSP time and UTC (Brest) by means of a GPS receiver located at the Brest Loran-C control centre. Because this means we are now employing a single GPS time reference station, we have chosen to regard PSP as a tixe *transfer* technique.

This method of time measurement is very attractive since it requires neither reference stations, nor rubidium standards, but simply the logging of pseudorange measurements at the mobile and at Brest .

Computing PSP solutions

The 'precise orbit' files from ESA give the zateilite pcziticn every 15 minutes using the earth-fixed In- Reference Frame (ITRF). The consistency *of* this system with the Worid Geodetic System (WGS) 1984 is believed to be within approximately 1 m. We have used a 9th-order Lagrange polynomial to interpolate the satellite coordinates to any epoch transformed the coordinates from ITRF to WGS84, and ccr:ected the pseudcrsngta for the phase-versus-mass-centre offset. The latter adjustment is required because the precise orbit coordinates calculated are those for the satrellites mass centre, while the pseudoranges are measured with respect to itz antenna phase centre. The difference is 85.4 cm for 3lcck I satellites and 95.2 cm for Block II sateilites; this offset must be added to the observed pseudorange [8]. Finally the sateilite coordinates were corrected for the Sagnac effect i.e. the rotation of the earth-tied reference frame during the travel time of the signal from the sateilite to the receiver.

The ESA clock data, in contrast to standard 15-minute precise ephemeris data, contains precize clock values at 1 minute incervalz. For PSP use, this shorter interval is essential, given the relatively rapid SA dithering of the satellites clocks We used a 5th-order Lagrange polynomial to interpolate the clock values to any epoch and ccrrected the observed pseudoranges for the satellite clock offsets. The clock values from ESA come already corrected for the periodic relativistic effects caused by the slightly eccentric orbits of the satellites

For theq results presented in this paper we have simpiy ignored the existence of the ionosphere. We are currently tlcse to the low point of the 11 year solar cycle and so the solar activity causes relatively little ionospheric delay. We believe that in the future, as zcia: activity increases again, it would be valuable if the IGS ccmputicg centres published additional parameters which single-frequency GPS users could employ for calculating ionospheric delays.

We estimated tropospheric delays by xeanz of Black's mode! [10], assuming a surface temperature of 15 °C and a pressure of 980.0 mbar.

DGPS TIME TRANSFER

Standard DGPS pseudcracge corrections improve the accuracy of positions ove: that of non-differential GPS, but not the accuracy of timing. This is because the reference station does not have a precise clock. 'DGPS time transfer' employs a reference station equipped with an accurate clock - normally an atomic standard. Thus it is able to generate true range corrections and not simply pseudo-range corrections. The mobile adds these range corrections to its measured ranges, and then calculates its position and alzo its receiver clock offset. This clock offset is with respect to the clock at the reference station and, as with PSP, the timing accuracy should be commensurate with the position accuracy. This xethod may also be used over longer base lines and also when there are fewer than 4 satellites in common view, provided that the position of the mobile is then provided by other means. DGPS time transfer may be carried out in real-time, which is essentially what happens when using the RTCM SC-104 type 9 message [11]. Alternatively, it can be computed post-mission; in that case a further improvement in accuracy may be achieved by replacing the broadcast parameters with precise orbital data. We favour the latter sciuticn because it involves no real-time **data links.**

DGPS time transfer is not unlike the common-view method, but it involves no averaging and also it may be used if the receiver's position is unknown (as long as there are 4 or more satellites in common view). If both receivers' positions are fixed it has the advantage that the measurement is made against all possible satellites, rather than just a single satellite. This increases the accuracy of the measurement and gives greater redundancy than does the common-view method. The disadvantage of post-mission DGPS time transfer over the common-view method is that pseudorange records must be stored, but this is acceptable in our application.

RECEIVER HARDWARE REQUIREMENTS

A GPS receiver has two internal clocks: a so-called 'hardware clock' and 'software clock'. The hardware clock is the externally accessible, physical, clock which provides, for instance, 1 PPS output and higher-frequency outputs. It is the internal clock against which input strobes are used to time-tag external events or it may be a higher frequency external clock fed into the receiver. The software clock is the internal clock against which the receiver measures the arrivals of the satellite signals and so calculates pseudorange values. If the GPS receive: is used in a precise timing application, it is essential that the hardware clock be accurately synchronized to the software clock, or that, if not, the discrepancy between them is recorded. Not all GPS receivers fulfil this essential requirement.

Further, the **signal** delay from GPS antenna, through the antenna cable and the front-end of the receiver to the point at which time measurements are made, must **have** been calibrated and must remain constant. These epecialised timing requirements mean that the GPS receiver to be used must be chcaen with care if good timing performance, as well as accurate position measurements, are to be obtained. And both- timing and position measurement functions must work well when the receiver is in motion.

PSP VERSUS DGPS TIME TRANSFER

DGPS time transfer has the **advantage** compared to PSP that it **may** be implemented in real-time, but for our application this is of no great benefit. The two cechniquea are expected to give comparable timing accuracies, and both methods output an accurate position as well as accurate time. DGPS time transfer suffer from baseline limitations, and several **reference** stations would be required to ***cover ail*** of North-West Europe. If we are to use the DGPS time transfer technique to get both time and position information on the mobile, we will need to install several DGPS reference stations because **of** the large operating **area.**

An **advantage** of DGPS time transfer is that, to the extent that the ionospheric and tropospheric delays experienced **at the** *reference* station are the same as those at the mobile, their effects will cancel out; this will generally be the case for separations of up to several hundred kilometres. Moreover DGPS does not need precise clock values. PSP, on the other hand, otters global coverage.

From a theoretical point of view both methods appeared feasible for our application. To establish whether that would be the case in practice we se: up an experiment to demonstrate and evaluate the performance of the two techniques. We also wished to confirm that the specific GPS receiver model we planned to use, a NovAtel GPSCard 3951R Narrow Correlator receiver, was suitable for precise time transfers. We hew from previous experiences that *this* receiver had a satisfactory navigational performance [12,13,14].

RESULTS AND ANALYSES

Measurements and computations

The measurements **were** conducted at Direction des Constructions Navales (DCN) at Brest, France, the location of the UTC (Brest) time standard. UTC (Brest) is a time scale realized by a system based on a minimum of two HP 5071 high performance ceaium beam tubes. It is used for Loran-C synchronisation. Cur measurement setup compared the 1 PPS's hardware clock signal from the NovAtel receiver with that of the UTC (Brest) standard, using an HP 5345 time interval counter with a resolution of 3 ns. We could **have** employed the option provided by the NovAtel receiver to time-tag incoming pulses. However, this function has a resolution of only 49 ns approximately. For the same reason it will not be used in the final XSF measurement system.

The antenna of the GPS receiver was mounted without a choke ring above **a** metal roof which gave noticeable multipath reflections of the satellite signals but is probably more typical of a mobile installation. A 45 m antenna cable with two connectors was used, attenuating the satellite signal by some 4-6 dB and resulting in a poor signal-to-noise ratio (SNR).

We allowed the NovAtel receiver's hardware and software clocks to drift freely and recorded the timing of the hardware clock (1 PPS) against UTC (Brest) once per second. We also stored the pseudoranges measured and the difference between the receiver's

Position	Latitude	Longitude	Height
Mean(m)	0.85	-0.23	1.85
RMS (m)	2.51	1.55	4.77

Tabie 1: *PSP* position solutions *for a 17-hour-long session compared against the position of the antenna at Brest which was recorded in WGS84.*

hardware and software clocks. The measurements took place 5 and 6 April 1995 and SA was in operation.

At the subsequent data-processing stage we calculated the receiver's software clock error and used it, together with the recorded differences between the hardware and software clocks, to compute the hardware clock errors. We then tested both the PSP and DGPS time transfer techniques, using the same raw **data.** We adopted a cat-off elevation mask of 10" and a maximum GDOP of 5.

As reference stations for the DGPS time transfer measurement3 we selected the two IGS reference stations at Ny-Ålesund (79" north and 12° east) on the Arctic island of Svalbard and Herstmonceux (51° north 0° east) in the United Kingdom. Ny-Ålesund is 3477 km, and Herstmonceux 451 km, from Brest (48" north and 5° west). A3 reference clocks Ny Ålesund employs a Hydrogen Maser time standard and Herstmonceux only a Rubidium standard.

Results

The results to be presented should be compared with our accuracy requirements of 7 m in position and 20 ns in time.

The PSP pcaition solutions for a 17 hour-long data set are **shown in** Table 1. The results are slightly poorer than had been achieved using similar measurements by Lachapelle [8]; this is very much to be expected in view of the relative!y-high multipath environment and the low SNR as described above.

The timing_performance from the same data is displayed in Figure 1. The time jump at GPS time 345600 occurs at mid-night and is due to the change of daily time reference by ESA (see Section 'Precise aingie point time transfer' above). When this step is removed (by calculating the **mean** offsets of the data sets from the two days), the time data has a 1σ variation of 11.6 ns. We also calculated PSP solutions using the known, fixed, position: this reduced the lo variation to 4.2 ns. The mean difference between the time solutions with unknown and fixed positions was 3.3 ns.

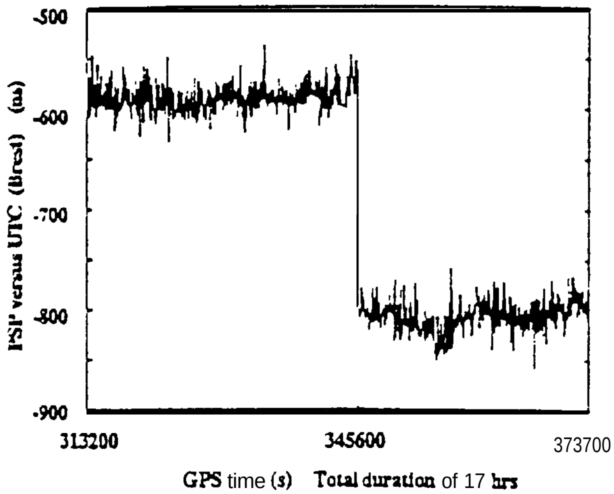

Figure 1: PSP time versus *UTC* (Brest) when *the antenna* position is *assumed to be unknown. The shift* at *GPS* time *345600 is* because *of the daily change of reference time of the ESA clock data.*

Position	Latitude	Longitude	Height
Mean (m)	0.03	-0.04	-1.36
RMS (mj	*3.58*	2.24	7.31

Table 2: Brest *positions determined using the DGPS time transfer* tednique, employing *precise orbit data, from Herstmonceux. The results from* a *17-*hour-long session *compared* against *the position of the antenna at* Brest *which was recorded in WGS84.*

DG?S time transfer using Herstmonceux as the referenc: station gave the position results shown in Tabie 2. The mean offset is a little less than that of the PSP solutions in latitude and longitude (and better than one would normally expect from DGPS over a 45i km distance) and the height componecta are similar. The RMS variations of the DGPS solution arc slightly greater than those from PSP.

The accuracy achieved using DGPS time transfer from Herstmonceux is a little difficult to establish because the reference clock there drifts relatively quickly. We, therefore, did the calculation as a two-step process: at every epoch we first calibrated the Herstmonceux clock by computing a PSP solution there, assuming its tied position; then we calculated the results of the DGPS time transfer from Herstmonceux to Breat, assuming that the position of the receiver in Brest was unknown but using precise orbit data. The result was *3* 1σ variation of 15.8 ns **when** compared with UTC (Brest). This is a very satisfactory performance, bearing in mind that allowance must be made for the errors in the PSP time

Time	Precise orbits	Broadcast Orbits
1σ (ns)	3.7	4.1

Table 3: DGPS *time* transfer from *Ny-Ålesund* to *Brest. Because of the* exceptional 3477 *km separation of* the two stations, relatively-few common-view *satellites were* available and so *the known locations* of the stations were employed.

calibration of the Heratmonceux clock to which no smoothing was applied.

Finally, we also went one step further, and closed the Herstmonceux-Brest loop, to check that we had no residual offset values: first we calculated PSP solutions for Herstmonceux assuming that its position was unknown; then we did a DGPS time transfer to Brest, with the position of Herstmonceux fixed and Brest unknown and using precise orbit data; and finally we compared this result with the PSP solutions for Brest assuming its position unknown. We got a mean offset of 0.024 ns for the 17 hours long session. This tiny residual vale shows conclusively that the residual offsets over a period of 17 hours are negligible.

Finally, we set out to evaluate the performance of DGPS time transfer over longer base lines. We also wished to check the difference in performance if we used broadcast orbit data rather than precise orbit data. For this experiment we used data from Ny-Ålesund, comparing its very accurate Hydrogen Maser clock against UTC (Brest). We employed the known positions of the two stations since they were so far apart that they could only see the required common-view satellites (four or more, above 10° elevation, with a GDOP$\leq$5) for about 50% of the time. There were hour-long gaps with fewer than four common-view satellites.

The standard deviations obtained with both precise orbits and broadcast. orbits are shown in Table 3. The 1σ variation using broadcast orbit data was 4.1 ns. When the precise orbit data was employed this fell to 3.7 ns. These results are so good that the 2 ns resolution of the time interval counter used becomes a significant factor! The mean difference between the precise orbit solutions and the broadcast orbit solutions is 0.4 ns. And the improvement between them due to using precise orbit data is less than 1 ns; this suggests that SA was having little effect on the satellites' broadcast orbit data during our measurements. (It has been reported that the principal component of SA recently has been clock dither and that the orbital component has been relatively weak.) Figure 2 shows the time transfer results when using the poorer, broadcast, orbit data.

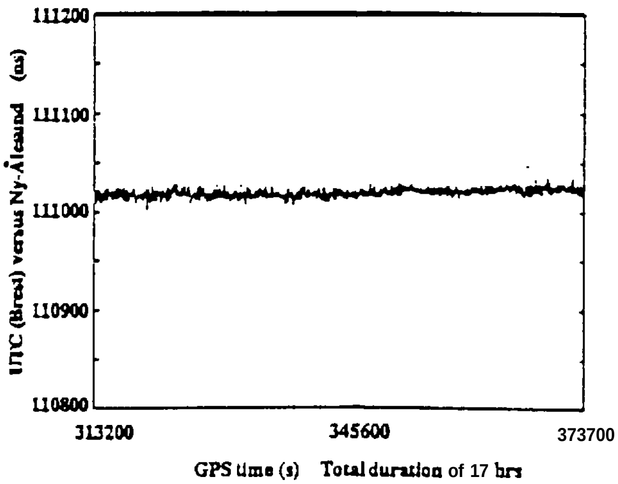

Figure 2: *DGPS time transfer from Ny-Ålesund to Brest using broadcast orbit data. The positions of both stations are assumed to be fixed. The 1σ variation* is *only 4.1 ns.*

Summary of the results

We have demonstrated that both the PSP and DGPS time transfer methods satisfy the requirements set out in the introduction to this paper (7 m in position and 20ns in time, 1σ), with some margin in hand. Thus we consider both methods to be excellent candidates for our application.

We have ignored the existence of ionospheric delays in our PSP solutions, and got away with this because of the favourable conditions at the current point in the solar cycle. We will certainly develop a satisfactory way of estimating the ionospheric delays if we conduct further PSP time transfers in the future. DGPS time transfer is much less affected by atmospheric delays.

The NovAtel receiver we used performed very satisfactory. We still have left to assess its long-term timing stability.

Our next objective is to demonstrate time transfer, using these techniques, on a ship. We chose, to conduct the experiment in two stages, employing a stationary receiver for the first because it makes the measurements much simpler. However, there are strong reasons for arguing that the results are also valid for time transfer to a moving vehicle: we have demonstrated that we can achieve timing accuracies commensurate with the positioning accuracies of our GPS receiver. The navigation performance of the receiver when in motion is known to be similar to its static performance [12,13]. In addition, the long term position performance of PSP [8,9] and of DGPS are well known and satisfactory which indicates that the results are reproducible. In addition, apart from being at a fixed location, our stationary measurements were conducted under very realistic conditions, with no antenna choke ring, a poor multipath receiving environment and low SNR.

This paper focuses principally on the stability of time transfers, rather than on absolute accuracy. Achieving absolute timing is a matter of calibrating offieta and thereafter ensuring that receiver delays do not change significantly with time and temperature - by more than some 5 ns in our application. GPS receivers especially designed for time transfer necessarily fulfil this requirement.

CONCLUSIONS

The objective of this investigation was to identify low-coat time transfer techniques suitable for eventual use on a moving ship, a land vehicle or aircraft. The demanding accuracy requirement set was 20 ns, and the technique had to be capable of being implemented in an automatic, unattended, measuring system, and, preferably, offering global coverage. This is a very unusual timing application of GPS.

Two possible techniques have been identified and evaluated: the use of precise orbit and clock values to calculate the accurate time and position post-mission, and DGPS time transfer with an accurate clock at the DGPS reference station.

The results reported here demonstrate that both techniques offer time stability of the order of 10 ns (lo!. A NovAtel GPS receiver was used for the measurements, and its position was assumed to be unknown and was calculated together with the precise time as will be the case in the eventual application. Even better results were achieved when the receiver's position was assumed to be known and fixed. It is anticipated that both techniques are suitable for our application.

Precise orbit and clock solutions give global coverage, and may be used for precise time transfer berween GPS receivers at opposite sides of the world, stationary or mobile, in known or unknown locations.

ACKNOWLEDGEMENTS

The authors would like to thank: the Orbit and Attitude Division of the European Space Agency at the European Space Operations Centre, Darmstadt, Germany, for generously providing us with precise clock values; personnel of DCN Brest, France, for providing the facilities and giving helpful assistance during the measurements; and Pat Fenton and Bryan Townsend of NovAtel Communications Ltd., Calgary, Canada, for providing the GPS receiver used for the measurements.

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