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# Evaluation of GPS-Aided Artillery Positioning and Orientation Methods

G. Lachapelle * M.E. Cannon * J. Bird **


## ABSTRACT

The artillery survey requirements ratified by Canada through NATO (STANAG 2373) call for a positioning accuracy of 10 m (PE) in fixation (horizontal) and altitude (height), and an orientation (heading) accuracy of 0.3 mil (1 arcmin) to 0.6 mil (PE), depending on the type of guns used. These accuracy levels are to be achieved in a maximum observation time of 20 minutes. The positioning requirement is currently met by Canadian Forces artillery personnel by using conventional survey methods which are labour intensive and requires the availability of known survey points in the area. The heading requirement is met effectively using gyrotheodolites.

A cost-effective alternative to the above methods is proposed herein. It consists of GPS in stand-alone mode, complemented by automated survey methods where required. Using emerging low cost, portable, and robust GPS user equipment, the artillery positioning and heading requirement can be met in minutes. The heading requirement is met using a twin-antenna GPS system. In situations where severe signal masking due to concealment requirements may preclude the use of GPS, the transfer of position and heading from nearby points where GPS signal reception is possible can be carried out using conventional survey methods, which can also be used as backup in the unlikely event of GPS failure. Due to the high level of automation of GPS and of modern survey equipment, it is anticipated that the survey training requirements will be reduced substantially.

## RÉSUMÉ

Les besoins d'arpentage d'artillerie ratifiés par le Canada dans le cadre de l'OTAN (STANAG 2373) exigent une précision de positionnement de 10 m (PE) en localisation respective (horizontale) et altitude (hauteur), et une précision d'orientation (direction) de 0,3 mil (1 arcmin) à 0,6 mil (PE), selon la catégorie de canon utilisée. Il faut obtenir ces niveaux de précision dans un temps maximum d'observation de 20 minutes. Les artilleurs des forces canadiennes remplissent actuellement ces exigences de positionnement en utilisant des méthodes d'arpentage conventionnelles qui emploient beaucoup de personnes et nécessitent la présence de points connus d'arpentage dans la région.


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*Department of Geomatics Engineering, The University of Calgary

** Defence Research Establishment Ottawa, Department of National Defence

## INTRODUCTION

Field artillery is used nowadays for indirect fire. Indirect fire can be subdivided into observed and predicted fire. In the case of predicted fire, the fire is delivered without adjustment so that all known corrections are applied beforehand; since there is no requirement of target visibility, it is an effective means of engagement but the prediction accuracy is critical to achieve maximum surprise. Artillery survey is a critical component in this case. Artillery surveyors provide the essential survey information, such as location and orientation, to firing batteries and target acquisition devices in order to place these equipments and devices on a common reference system. This allows targets to be accurately located and the batteries to engage quickly, accurately and with surprise. An historical review of artillery survey methods is provided by Sebert (1996).

In order to effectively engage targets by predicted fire, the relative positions of guns and targets must be accurately known (i.e., fixation) and a common orientation (i.e., heading) must also be available to the firing equipment in a timely manner. DND requirements have been ratified by Canada through the North Atlantic Treaty Organization (NATO STANAG 2373, 1989). **Table 1** presents these requirements which are subdivided into orientation, fixation, altitude (i.e., height) and time. Fixation requirements refer to the horizontal components, i.e. 10 m in fixation means 10 m in eastings and 10 m in northings. The probability level associated with the requirements is the Probable Error (PE), which refers to a 50% probability (i.e., 0.6745 $\sigma$ where $\sigma$ is the standard deviation). A 10 m PE in height corresponds to a standard deviation of 15 m, while 10 m PE in northings and eastings correspond to a DRMS (2D horizontal) error of 21 m. Likewise, a 0.3 mil PE in orientation corresponds to a standard deviation of approximately 0.4 mil. A 95% probability level is obtained by multiplying the above standard deviations by a factor of 2.

The current methods used by the Canadian Armed Forces for the determination of fixation and orientation, rely on the measurement of distances, angles, altitude and directions. Distance are measured mostly by Tellurometer, which has a range of ² 50 km, taping, traversing, and other well-known survey methods. Angular line-of-sight measurements are made with 0.1 mil theodolites. The altitude above sea level can be determined either by levelling from survey markers, by barometry or by direct reading from topographic maps. High altitude points are optimal from a survey point of view but undesirable from a safety and tactical point of view. Target illumination is required for night operation which is prohibitive in many situations. Most of these methods, except for orientation

**Table 1.**
**Specified Survey Data Requirements (NATO STANAG 2373, 1989).**

| Equipment | Orientation (PE) (mils†) | Fixation (PE) (metres) | Altitude (PE) (metres) | Time to achieve (min) |
|---|---|---|---|---|
| 105MM HOW | 0.6 | 10 | 10 | 20 |
| 155MM HOW | 0.3 | 10 | 10 | 20 |
| AN/TPQ 36 | 0.4 | 6 | 10 | 20 |
| AN/TPQ 37 | 0.4 | 6 | 3 | 20 |
| Sound Ranging(external) | 0.3 | 10 | 10 | 20 |

† 1 mil = 3.375 arcmins ≈ 1 mrad

determination using gyrotheodolites, are relative in the sense that they transfer the position and orientation for known survey markers to a point in the proximity of the gun battery. The Gun Alignment and Control System (GACS) can be initialized and used to transfer the survey coordinates to each gun in the battery using a laser transceiver. The methods assume that such survey markers, with known coordinates in a well defined coordinate system, are available in the theater of operation, an assumption which often goes unfulfilled, as evidenced by the numerous peace keeping missions to which the Armed Forces have participated during the past decades. Horizontal positions are generally represented as rectangular coordinates which refer to a grid system designated on a large or medium scale military map. The accuracy of the existing survey markers is specified as 2 m in each of the three coordinate components and 0.6 mil in orientation to account for error propagation during transfer procedures.

Since 1993, Canadian Forces artillery survey personnel use gyrotheodolites to establish the orientation. The azimuth is an astronomical azimuth which refers to the instantaneous axis of rotation (pole). The difference between this type of azimuth and a geodetic azimuth in the geocentric WGS84 system is the difference between the instantenous and average pole which is negligible (< 0.02 mil), and the Laplace correction rarely exceed 0.1 mil. The Laplace correction is usually neglected because of the difficulty in estimating the local deflection component in the prime vertical. The gyrotheodolite used by the Canadian Forces is the Leica GG3 North Finding Survey Station which comprises a SKK3-1 gyro and a T16SK-1 theodolite. The SSK3-1 is built to MIL-STD-810C specifications while the T16SK-1 theodolite is built to U.S. MIL-T-52114 specifications. The orientation accuracy meets the most stringent accuracy sought herein, namely 0.3 mil ($1\sigma$). This level of accuracy is obtained well within 20 minutes, including set-up time. A gyrotheodolite is a very effective instrument for the purpose sought herein as it is a rugged, reliable and self-contained instrument which does not require external precise survey information and does not rely on any electromagnetic signals which could be jammed. The only disadvantages are a relatively high cost (≈ $100k) and a limited latitude range (typically ± 70°).

The above conventional survey methods, with the exception of orientation determination with a gyrotheodolite, are slow, labour intensive, demanding in terms of qualified personnel and weather dependent, They may result in the loss of the element of surprise, require intervisibility between points, require the occupation of points difficult or impossible to access and require the availability of points with known coordinates in the relevant coordinate system. Full operation of the Global Positioning System (GPS) and the availability of low cost PPS user equipment has however resulted in the need to assess if and how GPS could be used to replace or augment the artillery survey methods currently used in order to improve cost effectiveness. The following sections analyse the conditions under which GPS could be used to meet the requirements stated in **Table 1**.

## GPS

System characteristics and its error sources are described in detail in the literature (e.g., Wells et al 1986, NATO 1991, Parkinson & Spilker 1996). The most relevant characteristics for artillery positioning are summarized in **Table 2**. The 1575.42 MHz $L_1$ carrier is bi-phase modulated by a narrow-band 1.023 MHz pseudo-random (PRN) C/A-code which is accessible to all civilian users. The $L_1$ and $L_2$ (1,227.42 MHz) are bi-phase modulated by a wide-band 10.23 MHz pseudo-random P-code which is accessible to authorized, i.e., PPS, users. The C/A-code on $L_1$ is also used by current PPS P-code receivers to access the P-code through the use of the Hand Over Word (HOW) broadcast as part of the navigation message. The advantages of the P-code, relative to the C/A-code, are higher resistance to

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Ils remplissent efficacement ces exigences de direction en utilisant des gyrothéodolites..

Une alternative économique à ces méthodes est proposée dans cet article. Elle consiste à utiliser le GPS en mode autonome, auquel on ajoute au besoin des méthodes informatiques d'arpentage. À l'aide d'un matériel nouveau économique, portatif et robuste de SPP, on peut remplir en quelques minutes les exigences de positionnement et de direction de l'artillerie. On peut satisfaire ces exigences de direction au moyen d'un système de GPS à antenne double. Dans les situations où les signaux sont masqués à cause de besoins de camouflage et où l'on ne peut pas utiliser le GPS, on peut transférer le positionnement et la direction de points voisins où l'on peut recevoir les signaux du GPS, à l'aide de méthodes conventionnelles d'arpentage, que l'on peut également utiliser en cas de panne du GPS. Étant donné le niveau élevé d'automation du matériel de GPS et du matériel moderne d'arpentage, on pense que les besoins de formation en arpentage seront considérablement réduits.

**Table 2.**
**Relevant GPS Characteristics For Artillery Survey.**

- 21 satellites + 3 active spares, for a total of 24
- Fully operational since 1995
- 24-hour, all-weather availability
- Line-of-sight (Upper UHF)
- Carriers: $L_1$ = 1575.42 MHz and $L_2$ = 1227.6 MHz
- PRN 1.023 MHz C/A (L1) and 10.23 MHz P (L1 & L2) codes
- Global Earth Centered Earth Fixed (ECEF) reference grid (WGS84)
- No known survey points on the ground required
- Precise Positioning Service (PPS) available to NATO countries
- Stand-alone PPS accuracy can meet artillery positioning requirement
- Two-antenna receiver system can meet orientation requirement
- Portable, easy to use, low cost and reliable user equipment
- Limited training required

non-intentional and intentional interference, the improvement in interference rejection being 10 dB, less vulnerability to multipath, accuracy, and faster accuracy recovery upon signal reacquisition.

The first advantage is very significant for military users. The second and third third advantages, namely less vulnerability to multipath and higher accuracy, are less significant with the availability of high performance Narrow Correlator™ C/A-code technology (e..g., Van Dierendonck 1994). However, C/A code is only available on $L_1$ which means that the effect of the ionosphere, which can affect positions by up to 10 to 20 m, cannot be estimated as is possible with the use of the P code which is available on both $L_1$ and $L_2$. The Standard Positioning Service (SPS), which is C/A code-based, is affected by Selective Availability. The highest level of accuracy in stand-alone mode (i.e., single point) is therefore obtained with the Precise Positioning Service (PPS) using dual-frequency user equipment. A high level of accuracy with C/A code user equipment can be obtained in differential mode, which requires the availability of a reference station and the transmission of differential corrections over a radio link, an operational mode which should be avoided if at all possible for field military operations.

The line-of-sight characteristic means that solid obstructions will block signals while foliage will attenuate signals rapidly, an important limitation for artillery survey where batteries are often concealed under foliage. This aspect will be discussed again later.

PPS receivers are fitted with a Security Module to remove the effect of Selective Availability. A Security Module is also used to recover the Y code (P-code when Anti-Spoofing is on. The vulnerability of the encrypted P-code to spoofing (false or deliberately misleading signals) is considered low and anticipated to remain so. The situation is different with jamming due to the low power of either the C/A or P-code which makes them vulnerable to line-of-sight jamming. It is been reported however that technical and tactical options exist to to minimize this type of interference (NAPA/NRC 1995). The NAPA/NRC study also recommends that, in case of conflicts, U.S. Forces jam $L_1$ locally to deny the GPS signal to adversaries without adversely impacting the $L_2$ P-code signal. In doing so, current PPS P-code receivers would also be jammed since C/A-code acquisition is required to subsequently acquire the P-code. In order to overcome this problem, the study recommends the development of direct P($L_2$) acquisition receivers.

A related recommended military enhancement for Block IIF satellites, to be launched in the 2010's, is the use of a yet wider-band code, namely 100 to 200 MHz, at a frequency higher than the current $L_2$, namely at 2 to 3 GHz, to increase anti-jam capability by 10 dB and to increase immunity to ionospheric scintillation, a concern in many areas of the world, including Northern Canada (NRC 1995). Another possibility to increase resistance to jamming is the use of nulling/directive antenna systems which have the potential to increase anti-jam capability by another 25 to 35 dB using newly developed effective and economical techniques based on low-cost correlator Application Specific Integrated Circuits (ASIC's) and signal processing at baseband (NRC 1995).

## Current Accuracy Performance

The currently specified and derived stand-alone instantaneous GPS positioning accuracies are given in **Table 3**. An understanding of these accuracies requires a discussion of GPS DOP's (Dilution of Precision's) and UERE's (User Equivalent Range Error's). The DOP is a figure of merit which is a function of the spatial geometry of the satellites observed. A smaller DOP translates into a better geometry and, consequently, to a better accuracy. The three types of DOP used in this paper are the PDOP (Position Dilution of Precision), the HDOP (Horizontal Dilution of Precision) and the VDOP (Vertical Dilution of Precision). The PDOP for a 21-satellite constellation typically varies from 1.5 to 8 with a median of 2.7 (Parkinson et al 1995). The corresponding HDOP is often assumed to be 2.0 when the best four satellites are used, although it has been shown that the value will be $^2$ 1.5, 95% of the time, if an all-in-view receiver with a masking angle of 5° is used (NAPA/NRC 1995). The corresponding VDOP is typically of the order of 2.1 to 2.4. For artillery survey where the guns are often concealed in valleys partly under foliage, a masking angle assumption of 5° is likely to be too optimistic. The consequence of this on the DOP will be discussed later.

The PPS UERE at the one sigma level consists of the quadratic root sum square of the individual contributing errors. The position accuracy is obtained by multiplying the DOP required by the UERE. The MRSE, DRMS and altitude errors are therefore:

$$\text{MRSE} = \text{PDOP} \times \text{UERE}$$
$$\text{DRMS} = \text{HDOP} \times \text{UERE}$$
$$\text{Altitude Error} = \text{VDOP} \times \text{UERE}$$

**Table 3.**
**Currently Specified and Derived GPS Instantaneous Stand-Alone Positioning Accuracies ( NRC 1995))***

| | 50th[2] Percentile | | DRMS (65 - 68%) | | 2DRMS (95%) | |
|---|---|---|---|---|---|---|
| | PPS | SPS | PPS | SPS | PPS | SPS |
| POSITION | | | | | | |
| • Horizontal | 8 m | 40 m | 10.5 m | 50 m | 21 m | **100 m** |
| • Vertical | 9 m | 47 m | 14 m | 70 m | 28 m | 140 m |
| • Spherical | **16 m**[1] | 76 m | 18 m | 86 m | 36 m | 172 m |
| VELOCITY | | | | | | |
| • Any axis | $0.07\ m\ s^{-1}$ | | $\mathbf{0.1\ m\ s^{-1}}$ | | $0.2\ m\ s^{-1}$ | |
| TIME | | | | | | |
| • GPS | 17 ns | 95 ns | 26 ns | 140 ns | 52 ns | 280 ns |
| • UTC | 68 ns | 115 ns | **100 ns** | 170 ns | 200 ns | 340 ns |

* SPS accuracies are given for the case when SA is on
1 Formal accuracies are in bold
2 50th Percentile is equivalent to P.E. (1D), CEP (2D), or SEP (3D)

For the case of a dual-frequency encrypted P-code receiver, the specified UERE is of the order of 6.5 m (NATO 1991). The PDOP, HDOP and VDOP implied by an UERE value of 6.5 m to obtain the DRMS accuracies given in **Table 3** are 2.8, 1.6, and 2.2, respectively. The HDOP is optimistic for the case of a 4-channel receiver. A lower PPS UERE value of 4.1 m was recently estimated by NAPA/NRC (1995). The contribution (1 $\sigma$ level) of each of the error sources, namely the tropospheric, clock and ephemeris, receiver noise and multipath errors was 0.7 m, 3.6 m, 0.6 m, and 1.8 m, respectively. If one assumes that a $L_1/L_2$ 4-channel PPS receiver is used with an HDOP of 2.0 and an UERE of 4.1 m, a 2DRMS error of 16.4 m, as compared to 21 m specified in **Table 3**, is obtained. If the UERE is recalculated for a $L_1$ receiver user an error contribution of 7 m for the ionosphere, a value of 8.1 m is obtained, which translates into a DRMS accuracy of 16.2 m and a vertical acccuracy (1$\sigma$) of 17.8 m. This means that a $L_1$ PPS receiver can meet the artillery horizontal positioning requirement under good geometry but not the vertical one. The two values of 6.5 and 4.1 m for the PPS UERE are specified values. Field experiments have shown that a UERE of the order of 2.5 m is often obtained (Parkinson et al 1995). A lower UERE value is important as a higher DOP can be tolerated to obtain a specified positioning accuracy threshold as shall be seen in the next section.

### Potential PPS Enhancements

Two potential PPS enhancements may occur in future, namely receiver enhancements and reduction of satellite clock and ephemeris errors. NRC (1995) analysed the impact of emerging PPS receiver technologies on stand-alone GPS accuracies. The enhancements would consist of all-in-view tracking, which would reduce the HDOP from 2.0 to 1.5, lower noise, better multipath rejection capability and the use of a better tropospheric model. The combined effect would reduce the UERE from 4.1 m to 3.7 m.

The major effect remaining effect contributing to the UERE would be the satellite clock and ephemeris error component, at 3.6 m. Several methods have been proposed to reduce the satellite clock and ephemeris error (e.g., NRC 1995). Under the WAGE (Wide Area GPS Enhancement) programme initiated in 1995, several PPS enhancements are being considered, namely the generation of correction tables in subframe 4 of the navigation message broadcast (WAGE 1), the incorporation of Defense Mapping Agency (DMA) monitor stations into the Control Segment Kalman Filter (WAGE 2) and the reduction of the Master Control Station navigation upload structure to reduce system latencies (WAGE 3) (Moeglein et al 1996). Testing of the WAGE 1 concept in early 1995 resulted in an UERE of 2.0 m (Shank et al 1995). If all three phase of WAGE were implemented, the UERE would decrease from the 3.7 m value discussed above to at least 1.4 m. Such a low UERE would allow yet poorer DOPs to meet the artillery survey requirements.

The minimal DOP's required to meet the artillery fixation accuracies listed in **Table 1** for various UERE values are summarized in **Table 4**. As the UERE decreases, much high DOPs can be tolerated, an important advantage for operation in concealed areas which nearly always result in signal masking. The DOPs given in **Table 4** are for instantaneous positioning. The artillery survey time requirement is 20 minutes. Accumulation of

**Table 4.**
**GPS PPS UERE and DOP Required to Meet Artillery Survey Accuracies in Instantaneous Stand-Alone Mode[1].**

| | DOPs Required | | |
|---|---|---|---|
| **UERE Assumed** | **PDOP** | **HDOP** | **VDOP** |
| 6 m (current specification) | 4.3 | 3.5 | 2.5 |
| 2.5 m (currently measured)[2] | 10.4 | 8.4 | 6.1 |
| 1.4 m (satellite & clock corr improvements)[3] | 18.6 | 15.0 | 11.0 |

1 An all-in-view dual-frequency PPS receiver is assumed
2 After Parkinson (1995)
3 (After NRC 1995)

GPS measurements over such a period means that the best instantaneous DOPs during the 20-minute period could be somewhat still higher than the values given in **Table 4**.

### The Foliage Problem

Artillery pieces are likely to be concealed under foliage in which case line-of-sight signal reception will not be possible from many or most satellites. The conditions encountered during artillery applications will typically range from desert to heavy foliage conditions.

Foliage will cause reflection and multipath, in addition to diffraction and absorption which, in turns, result in attenuation. A single tree leaf is sufficiently thin to allow some signal to go through and reach the antenna underneath. Numerous thick leaves however may result in sufficient attenuation to prevent the receiver from acquiring or maintaining lock on the signal. The size of the tree trunk and branches will become increasingly significant as the satellite elevation decreases. At a certain elevation, they may block the signals completely, depending on the type and density of trees. The parameters affecting attenuation under foliage are listed in **Table 5**.

Foliage attenuation varies approximately as the square root of frequency. It also varies widely as a function of the type of tree, namely from less than 1 dB $m^{-1}$ to over 4 dB $m^{-1}$ at $L_1$ (Spilker 1996). In practice, the EM field becomes incalculable under foliage conditions due to the interaction between the parameters listed in **Table 2**. An empirical approach, as the one used by Lachapelle & Henriksen (1995) and Cameron (1995) becomes effective, at least in a comparative sense, to assess foliage effects. The disadvantage of these approaches is that the results obtained provides only an indication of what might occur in other foliage situations and using other receiver types.

If one assumes that a receiver can suffer a loss of up to 15 dB, which appears to be the case for many receivers, between a few to tens of metres of foliage would be sufficient to preclude signal reception. GPS can therefore operate under relatively thin foliage conditions, as shown by Lachapelle & Henriksen (1995) and Cameron (1995). The latter reference shows that the type of camouflage net used to conceal artillery pieces does not result in a significant level of signal attenuation. If relative motion is occuring between the leaves and the receiver, i.e., the kinematic case, the receiver signal re-acquisition capability becomes a critical factor and the use of an all-in-view receiver has intrinsic advantages.

**Table 5.**
**Parameters Affecting Signal Availability Under Foliage.**

- thickness of trunk and branches
- thickness of leaves
- density and humidity of leaves
- type of foliage (e.g., type of tree)
- thickness of foliage
- season in the case of deciduous trees
- number of tracking channels
- receiver mechanization and SNR
- receiver code accuracy
- receiver re-acquisition time
  (due to relative motion between leaves and receivers)
- multipath
- antenna sensitivity {f(elevation)}

As foliage and tree density increases, artillery survey with GPS under foliage will become increasingly difficult. Satellites will be lost, resulting in poorer DOPs. As shown earlier, improvements in the space and ground control segments and user equipment will result in an improved UERE and in less stringent DOP requirements. Regardless, there will be situations where the surrounding foliage and other signal masking sources are sufficiently dense to preclude GPS from meeting the accuracy requirements. The use of GPS offset, with positions transferred to the artillery pieces through conventional survey methods, would become an attractive alternative under such conditions.

### Heading Determination

If the relative tridimensional coordinates of two neighboring points are precisely known, the coordinate differences can be transformed into an azimuth or orientation (e.g., Lu et al 1994). In the case of GPS, differential carrier phase measurements made in static mode or on a rigid moving platform can be used to obtain highly precise relative coordinates, provided that the carrier phase integer ambiguities can be resolved. Since the distance between the points is usually short, namely $^2$ 100 m, the ambiguities can usually be resolved well within a few minutes using single-frequency measurements. The orientation accuracy is a function of:

- carrier phase noise and multipath (typically 1 - 2 cm for double differenced observations)
- antenna phase centre stability
- satellite geometry
- distance between points (the greater the distance, the higher the accuracy)
- observation time

An important requirement when using GPS for attitude determination is that the carrier phase measurements be relatively free from carrier phase lock interruptions because new ambiguities have to be resolved each time this occurs. This is generally not possible under foliage conditions where losses of phase lock are frequent. As for the case of positioning, the orientation accuracy degrades as the DOP increases.

Two approaches can be used to obtain orientation with GPS. The first one involves the use of a single receiver to consecutively establish the coordinates of two points close to each other. It is assumed that throughout the entire operation, the satellite orbital and clock errors remain constant. These errrors are reduced by conducting the operation over a period of time as short as possible, namely over periods of tens of seconds. Investigations using the Rockwell single-antenna PPS PLGR+GLS system suggest that an accuracy of one to several mils ($1\sigma$) can be obtained in 30 seconds using an inter-antenna distance of 50 m (Ulmer at al 1995. The second approach uses at least two antennas simultaneously. The errors due to satellite orbits and clocks cancel out in the differentiation process. The receivers may be housed in one unit or operated independently. If real-time orientation is required, the receivers must be linked and may be housed in one unit. In order to resolve the ambiguities instantaneously, configurations where at least two of several antennas are relatively close to each other can be designed (e.g., Diefes et al 1994, El-Mowafy & Schwarz 1995). In order to enhance operational flexibility, the antennas can be rigidly mounted relatively close (² 1 m) to each other on the same groundplane or on a rigid horizontal bar.

The relationship between heading accuracy and inter-antenna distance is illustrated in **Figure 1** using two 8-channels C/A code Motorola Oncore sensors in static mode (Sun & Cannon 1995). The accuracy ($1\sigma$) is for one epoch, once the integer ambiguities are resolved. When a baseline of 0.9 m is used, the standard deviation of one measurement is 4.8 mils. Since carrier phase measurements in most SPS and PPS receivers have approximately the same low noise (typically less than a few mm) and since they are equally affected by multipath (< 1/4 $\lambda$ or 5 cm on $L_1$), the accuracy shown in **Figure 1** would be expected to be similar for most systems. The acccuracy can be improved by either or both increasing the inter-antenna distance and averaging the heading solutions over numerous epochs. Since 20 minutes is the maximum time allowable to obtain the heading in the artillery case, an averaging period of some 10 minutes could be considered, leaving the remaining 10 minutes for set-up and azimuth tranfer to the to Gun Battery Fire Control System. The use of such an interval, in addition to increasing the inter-antenna-distance to a few metres, should be sufficient to meet the most stringent heading accuracy requirement soughtfor artillery, namely 0.3 mil ($1\sigma$). If this is not sufficient, the inter-antenna distance could be increased (to a maximum of a few tens of metres) until the accuracy is met for a specified observation interval under a specified satellite geometry. Tests on a mobile platform have shown that an instantaneous accuracy ($1\sigma$) better than 0.9 mil could be achieved using an inter-antenna distance of 12 m and an instantaneous accuracy better than 0.3 mil using a distance of 43 m (e.g., Lachapelle et al 1994, McMillan et al 1994). The latter result indicates that an inter-antenna separation of about 40 m would be sufficent to meet the highest orientation requirement instantaneously. A dual PLGR-GLS system based on the twin-antenna principle described above is now available from Rockwell.

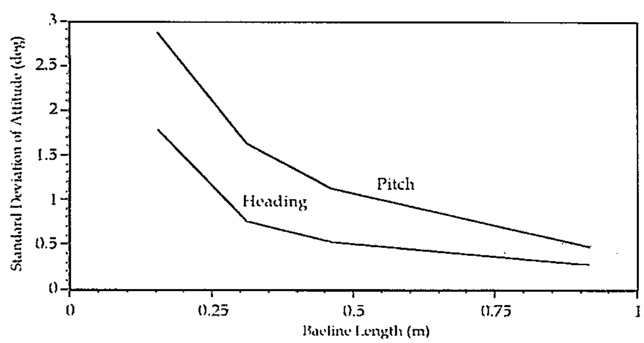


**Figure 1.**
**Relationship Between Inter-Antenna Distance and Heading and Pitch Accuracy**

## Heading Transfer to GPS to Gun Battery Fire Control System

A two-antenna GPS heading system could in principle be mounted directly on the Gun Battery Fire Control System. When this is not possible, two offset points where satellite visibility is sufficient could be observed by the GPS heading system and the heading transferred to the Gun Battery Fire Control System using a theodolite or total station, as shown in **Figure 2**. This operation could be done while the GPS heading is observed and a correction applied at the end of the observation period. The azimuth accuracy ($1\sigma$) of the artillery piece is 0.4 mil for the most stringent applications. The accuracy achievable with the technique illustrated in **Figure 2** is a function of the initial GPS-derived heading and the heading transfer errors. Using a 0.1 mil theodolite and assuming that seven intermediate points are required, the transfer error would be approximately 0.26 mil. An initial accuracy of 0.3 mil for the GPS heading system would result in a final accuracy of 0.4 mil ($1\sigma$) for Gun Battery Fire Control System heading. The transfter method described above is also applicable to position transfer.

## User Equipment

PPS receivers can be sub-divided into several types, namely $L_1$ C/A, $L_1$ P, and $L_1/L_2$ P-code. The $L_1$ types are not suitable candidates for artillery survey in stand-alone mode due to the lower altitude accuracy resulting from the effect of the ionosphere. The $L_1/L_2$ P-code type is the preferred choice for the current

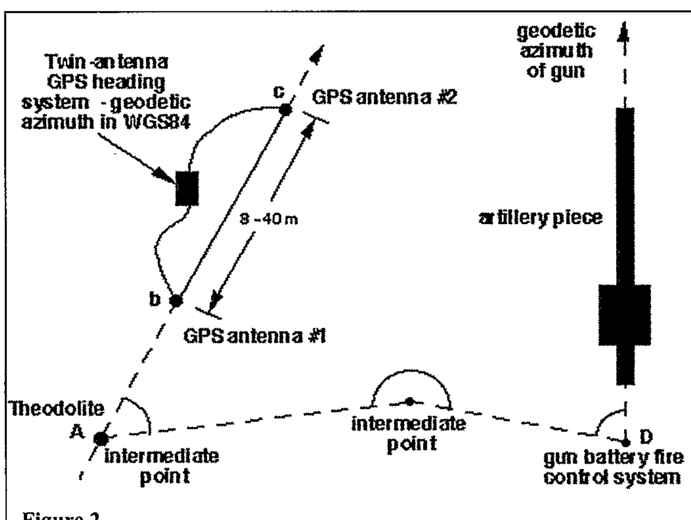


**Figure 2.**
**Orientation Transfer from Twin-Antenna GPS Heading System to Gun Battery Fire Control System with a Theodeolite.**

application. At this time, it includes the military version of the 12-channel dual-frequency Ashtech Z-12 unit, currently available from E-Systems Inc., and a $L_1/L_2$ PLGR to become available from Rockwell prior to the year 2000. The anticipated price of the latter is less than U.S. $3k.

Although the definition of equipment specifications is beyond the scope of this study, comments on selected major characteristics are appropriate at this point. Due to the operating constraints of artillery survey, all-in-view receivers are considered highly desirable in the long term for stand-alone operation. Dual-frequency ($L_1/L_2$) units are required to meet the altitude accuracy requirement. The $L_1$ PLGR as a viable option for stand-alone operation in the long term is not recommended. The forthcoming $L_1/L_2$ PLGR, although it may not have an all-in-view capability, would however meet the ionospheric requirement.

The antenna should have an adequate vertical response pattern, i.e., sensitivity, down to 5° above the horizon. This is critical under foliage conditions where low elevation satellite signals will be attenuated by tree trunks, branches and leaves. The position and orientation data update rate may be important during relocation (mobile) and for operation under adverse conditions. Current equipment can usually provide updates at intervals of every few seconds or better. Carrier phase availability is not a necessity in the short term for stand-alone positioning operation but it has advantages to reduce code noise and multipath effects since carrier phase noise and multipath is typically two orders of magnitude lower than code noise and multipath. Carrier phase measurements are however required for heading determination. External aiding a barometer could become important to improve geometry under severe signal masking conditions. INS aiding, although effective, does not appear to be a viable option in the foreseable future due to comparatively high costs.

Several SPS multi-antenna receiver do not represent a viable option heading determination in the long term due to the susceptibility of the C/A code to jamming. PPS-based systems are however available. The single-antenna $L_1$ Rockwell PLGR+GLS system described by Ulmer et al (1995) is priced at less than U.S. $3k and yields an accuracy ($1\sigma$) of 1.1 to 2.5 mils HDOP< 5.0) within 30 seconds using an inter-antenna distance of 50 m. A PLGR+GLS system consisting of two interconnected receivers is becoming available from Rockwell. The orientation accuracy ($1\sigma$) is expected to be better than 0.5 mil and typically, of the order of 0.2 mil. The two antennas are not rigidly mounted on a single horizontal bar but come with cabling which permits inter-antenna distances of several tens of metres. The cost is expected to be less than U.S. $6k. This system, presumably ruggeddized to the same level as the PLGR, would fully meet the accuracy of 0.3 mil ($1\sigma$) sought herein.

## Combination of GPS and Conventional Methods

It has been shown above that GPS has the capability of meeting the artillery survey requirements for both position and azimuth determination in stand-alone mode. This capability is compromised in areas with dense foliage or steep terrain, as well as in built-up areas, especially for heading determination where phase signals free from multipath are crucial. One technique to transfer positions and orientation to batteries under foliage or in areas with obstructed horizons is to use GPS for positioning and heading determination in relatively unobstructed areas and then to transfer those to the batteries using conventional survey equipment.

The advantages of this combined technique include the ability to utilize the rapid and accurate positioning and azimuth determination abilities of GPS while being able to accurately transfer the positions and headings to the batteries using techniques and equipment already in use. Such a system would be portable and would not require radio transmission. Distance measurement would most likely be short, allowing the use of infrared type EDM's commonly found in total stations. With the advent of electronic total stations capable of surviving the rigorous military environment (Traveller 1995), data collection and processing could be automated, eliminating transcribing errors and improving processing times. Disadvantages of using theodolites, EDMs and total stations include the need to establish additional turning points to bypass obstacles such as trees and the necessity of training surveyors for both GPS and conventional based techniques and increased setup and leveling time in rough terrain.

The transfer of elevation from GPS stations to batteries could readily be accomplished within the accuracy limits using trigonometric leveling with theodolites or total stations. Barometric leveling techniques using digital barometers would also be useful for altitude transfer, consistent results of better than 3 m ($2\ \sigma$) in mountainous terrain and under variable weather conditions being achieved (McLintock et al 1994). In favorable weather conditions and flat terrain, results of better than 1 m are achievable. Current commercial systems feature automated data collection and processing.

Heading can be readily derived independently of GPS using a gyrotheodolite. Their main limitation is their range of operation within a latitude range of about ± 70°. This should not present a problem in northern Canada because the tree line does not extend to these latitudes, in which a GPS-based system would be very effective, both for position and heading determination. Such a system can be purchased for a fraction of the cost of a gyrotheodolite.

The features of a GPS - Conventional solution include:

- rapid and accurate position and azimuth deterimination by GPS in unobstructed areas coupled with accurate position, altitude and orientation transfer using theodolites and EDMs
- Cost effectiveness since the GPS equipment required is low cost and the conventional survey equipment required is already used by Canadian Forces artillery surveyors
- portable equipment using small independent power sources
- no on-site radio transmissions required for either measurement system
- conventional distance measurements will be shorter than required for the conventional-only option, allowing the use of lightweight, inexpensive infrared EDMs or steel tapes
- total stations combine horizontal and vertical angle measurements along with distance measurements, minimizing setup and measurement time

- automatic data storage on total stations eliminates reading and transcribing errors, improving measurement time and reducing blunders. Data processing speed is also improved, because measurements do not have to be entered by hand
- a disadvantage is that additional turning points have to be established to bypass obstacles
- conventional (EDMs, steel tapes, theodolites and gyrotheodolites) can be used as back-up in the event of total GPS failure
- minimal re-training with GPS would be required for existing personnel. However, new personnel would still require reduced training with conventional methods
- altitude transfer could be readily accomplished using digital barometric levelling techniques, which feature automated data collection and processing. Their main advantage is that line-of-sight is not necessary
- differential levelling is an accurate means of altitude transfer, but trigonometric or barometric levelling would be faster and still yield accuracies well within those required. In the case of trigonometric levelling, the same instrument can be used for both orientation, horizontal position and altitude transfer.

## Recommended Options

Given the availability, capability, limitations, cost and overall effectiveness of the GPS technologies reviewed above and their prospects in the medium term, GPS + conventional surveying is recommended as the primary system, with conventional surveying + GPS as back-up. As GPS technology further evolves, the GPS component of the primary system will become more important and conventional will serve more and more as back-up only. The use of conventional methods as a complement to GPS and as back-up does not require any major re-training or expenditures other than maintenance and replacement costs, since most of the equipment required is already in use. The introduction of GPS will further improve effectiveness in the field and will decrease training requirements. Since the cost of GPS equipment is now much lower than that of conventional equipment, long term gains in term of capital expenditures will also be realized.

### GPS + Conventional as the Primary System

GPS is recommended as the major positioning component of the primary system because of the following reasons. Under good operational conditions, i.e., reasonably clear line-of-sight to the satellites, it has the capability to fulfill the positioning accuracy and time requirements worldwide on a common, accurate and consistent survey grid. It can fulfill the above requirements in stand-alone mode (using dual-frequency PPS equipment), without the transmission of any signal from ground-based equipment. Unlike any other system, it does not require any starting point with known coordinates. Its PPS is designed to operate under jamming conditions. The user equipment required is now robust, compact and generally easy to use. The capital cost of user equipment is relatively low, e.g., much lower than conventional survey equipment currently used. The training of personnel is expected to be substantially less complex and less time consuming than that required for conventional methods.

GPS will continue to improve incrementally over the forthcoming years. Performance improvement of the space segment will result in the reduction of the UERE. The development of yet more performing and, possibly lower cost, positioning user equipment will take place. System and user equipment modifications which will make the system even more robust to jamming, thereby improving its reliability during actual military operations, will possibly be implemented.

The disadvantages of GPS at this time are as follows. The system has not been thoroughly and successfully tested under a wide range of military operations, especially for orientation determination, as desirable for complete acceptance by operations personnel. There are still concerns with jamming of $L_1$; this frequency is required at this time by any PPS $L_1$ or $L_1/L_2$ equipment. User equipment and procedures are still evolving rapidly; successful and effective adoption of GPS methods and procurement of equipment will require commensurate planning and flexibility.

Due to artillery concealment needs, GPS will not be able to provide the accuracy required in all cases, especially for orientation determination which depends on precise but ambiguous carrier phase measurements. Under foliage, GPS carrier phase measurements are affected by frequent cycle slips which renders them of limited use. In this situation, GPS will be used to establish points and orientation of lines joining two points in nearby areas where the signals are available. It is recommended that the current GG3 gyro systems continue to be used for orientation determination for an interim period while GPS orientation equipment and methods gain acceptance. The GG3 gyro is robust, accurate, rapid, unaffected by jamming, self-contained, transportable and overall very effective. GPS orientation determination will however be recommended as back-up.

It is also recommended that conventional survey techniques be used for the transfer of the positions and orientation to the gun battery fire control system. Some of the conventional survey equipment and methods required for the position and orientation transfer are relatively simple and already in use.

There are several advantages in using conventional survey methods as complement to GPS. Conventional equipment is robust and easy to maintain. The equipment and methods are mature and do not change appreciably over periods of several years. Canadian Forces already own much of the equipment required and their personnel is fully trained with its use. Conventional survey methods can be used as back-up, as described below.

### Conventional + GPS as Back-up System

It is recommended that the artillery survey methods currently used by Canadian Forces serve as back-up for positioning and that, during an interim period, GPS serves as back-up to the gyro-based primary orientation system recommended above. Given that the conventional equipment is available and adequate to meet the requirements, that the procedures are mature and that the artillery personnel is fully trained in the use of these methods, this selection cannot be matched at this time in terms of cost-effectiveness.

An incremental improvement to the current conventional methods should be considered, namely the introduction of total stations equipped with external and automated dataloggers and software to transfer orientation and tridimensional positions from existing trig stations in one operation to improve effectiveness and decrease training requirements.

As confidence in the capability and availability of GPS increases and user equipment to counteract potential jamming becomes available, the extent to which back-up equipment and methods are necessary should be reviewed to achieve a balance between cost and an acceptable level of preparedness.

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