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GPS FOR MARINE NAVIGATION AND HYDROGRAPHY

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Abstract

Current marine navigation and shipborne surveying accuracy requirements are reviewed. The technical characteristics of GPS are summarized and its single point positioning performance is given and compared with the above requirements. A detailed description and analysis of the three types of observables possible with GPS, namely code, carrier and Doppler frequency measurements, are presented. The following error sources are discussed: cycle slips, Selective Availability, ionospheric and tropospheric effects and multipath. A description of the various receiver measuring techniques currently available, namely C/A code L1, L2 squaring, L2 codeless, P codeless and P code, is given, together with advantages and disadvantages for marine positioning. The single and double differenced observables used in differential GPS (DGPS) mode are analysed in terms of real time versus post-mission suitability. The latest techniques for quasi-instantaneous ambiguity resolution such as wide and extra wide-laning are discussed in terms of receiver requirements and operational procedures. An attempt is made at providing DGPS kinematic accuracy estimates for various cases with and without Selective Availability. Trends and prospects are forecast in the following five areas: system enhancements, user equipment, observable types and modelling, marine applications and GPS-related services.

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INTRODUCTION

The navigation and positioning accuracy requirements encountered in marine applications are diverse and range from several nautical miles (nm) to sub-metre. Typical navigation and marine surveying accuracy requirements are listed in Tables 1 and 2. The marine navigation requirements given in Table 1 for the harbour phase are extracted from the U.S. Federal Radionavigation Plan (DoT/DoD, 1990). These are the most stringent of the three sets of requirements given in the Plan for three corresponding phases of marine navigation, namely the ocean, coastal and harbour phases. Selected marine surveying accuracy requirements are given in Table 2. When the source is not given, the requirements are proposed by the authors.

Table 1

Marine Navigation Requirements - Harbour Phase[1]

Requirements	**Measures of Minimum Performance Criteria to Meet Requirements**					
	Predictable Accuracy (2 drms)	**Coverage**	**Availability**	**Reliability**	**Fix interval**	**Fix Dimension**
Safety of Navigation – Large Ships & Tows	8-20 m	Harbour & harbour approaches	99.7%	**	6-10 sec.	Two
Safety of Navigation – Smaller Ships	***	Harbours & harbour approaches	99.7%	**	***	Two
Resource Exploration	1-5 m	Harbours & harbour approaches	99%	**	1 sec.	Two
Fishing, Recreational and Other Small Vessels	***	Harbours & harbour approaches	99.7%	**	***	Two

[1] U.S. FRP1990 (DoT/DoD, 1990)

** Dependent upon mission time.

*** Varies from one harbour to another.

The single point positioning performances of GPS are summarized in Table 3. A comparison of Table 1 with Table 3 reveals that the single point accuracy of the SPS (Standard Positioning Service) cannot generally meet the harbour phase requirements, whether Selective Availability (SA) is on or not. DGPS (Differential GPS) is required in most cases. DGPS accuracy performances, which are summarized in Table 5, will be discussed later on in the paper. Civilian tests conducted in the early 80's confirmed the potential of DGPS for many of the above marine applications.

Table 2

Marine Surveying Accuracy Requirements[1]

Activity	Accuracy (2drms)	Remarks
General bathymetric survey[2]	≥400m	Scale ≥1:200 000
Charting - Large scale[3]	5m	Preferably real-time
Navigational aids in constricted waterways	3m	Real-time
Navigational aids (≤10 nm offshore)	≥20 m	
Territorial Boundary (12 nm)[4]	10 m	
Sea-floor Mapping EEZ (200 nm)[5]	50(CEP)	
3-D Seismic	10 m	
Pipelines	2-20 m	
Oil & Gas	25-50 m	
Site surveys, recovery & reentry	10-20 m	
Construction	2 m	
Dredging	2-10 m	
Future 3-D Seismic[6]	25 cm	Controversial
Heave component and shipborne tidal monitoring	10 cm	Height component
Offshore structure monitoring (static)	cm-level	

1 Relative to Shore Station(s)
2 PATHAK et al. (1990)
3 After CASEY et al. (1987)
4 After BLANKENBERG (1983)
5 After WOLFF (1988)
6 After U.S. NRC (1983)

A typical example of how the high performance of GPS has driven requirements is the 10 cm vertical accuracy proposed for shipborne tidal monitoring. DGPS is reaching this capability and will permit the direct estimation of the tide at the ship, without any strict need for an array of shore-based stations, provided that heave motion can be estimated and separated from tidal effects. All the requirements listed in Table 2 can only be met with DGPS. The cost effectiveness of DGPS for most applications is clearly superior to that of conventional methods. For instance, a study of Canadian charting methods lead to the conclusion that DGPS would result in a productivity gain of over 40% (KIELLAND and CASEY, 1990). Not shown in Table 2 is the very high probability of error detection required for all applications in order to achieve a satisfactory level of quality assurance.

GPS CHARACTERISTICS AND PERFORMANCES

The major technical characteristics and single point positioning performances of GPS are summarized in Table 3. The development of GPS was initiated in the early 70's by the U.S. Department of Defense and the system is expected to be declared fully operational in 1993 when 21 operational (Block II) satellites are functioning in their assigned orbits (DoT/DoD, 1990). The three (active) spare satellites will ensure that the operational constellation will not drop below 21 satellites. The relatively high carrier frequencies selected for the system mean that signal reception is line-of-sight and nearly independent of atmospheric conditions, except those related to ionospheric scintillation. The C/A modulates the L1 carrier and is used for the Standard Positioning System (SPS) which is available for worldwide civilian use on an unrestricted basis. The relatively high accuracy of the C/A code was deemed incompatible with the national security requirements of the U.S. and SA was implemented in April 1990. In August of the same year, SA was turned off, presumably due to Operation Desert Shield. One can speculate that it could be turned on again at any time. The more accurate P code modulates both L1 and L2 and will normally be restricted to military users. P code civilian receivers are, however, available commercially for those periods during which the P code might be available, i.e. when Anti-Spoofing (A-S) is turned off. The current plan is to turn A-S on when the system is declared fully operational in 1993. The estimated instantaneous SPS and L1/L2 P code accuracies achievable with GPS in single point mode both with SA on and off are given in Table 3. These estimates are valid for marine applications using either parallel channel, multiplexing or fast sequencing receivers. The use of the P code yields marginal advantages in instantaneous single point mode, except under highly disturbed ionospheric conditions. Civilian P code receivers are also affected by SA. DGPS performances will be discussed in a subsequent section.

The single point positioning accuracies given in Table 3 are for the instantaneous positioning case. When observations span a significant period of time, namely a few hours, the accuracy improves substantially. This was investigated by MALYS et al. (1990) using dual frequency receivers. Accuracies of 1.5 m and 75 cm (rms in each one of the three components) were obtained using broadcast (with SA off) and DMA/NSWC precise orbits respectively. The establishment of shore control station in a local datum is therefore possible with GPS without any direct tie to the local datum provided the relationship between the local datum and WGS84 is known.

The geometry of the 21+3 satellite constellation will ensure nearly even coverage in most parts of the world except in higher latitudes (>60°) where a slight degradation of accuracy in height will occur. This is due to the 55° inclination selected for the orbits. Typical GPS ground tracks are shown in Figure 1 (SANTERRE, 1990). The typical PDOP (Position Dilution Of Precision), over a 24-hour period, is shown in Figure 2 for an ideal 24-satellite constellation and a masking angle of 5° for a location off the coast of Newfoundland. This is an optimal case since the actual constellation may frequently drop below 24 satellites and the masking angle will have to be increased when accuracies better than 5 m are required. In reality, short outages (<30 minutes) are likely to occur for high accuracy 3-D users. The VDOP (Vertical Dilution Of Precision) corresponding to the case illustrated in Figure 2 is slightly lower than 2 as compared to a variation between 1.5 and 2.5 at the North Pole, where the elevation angle of GPS satellites can still reach over 45° due to their relatively high altitude above the Earth. This is why the VDOP degradation is minimal. In early 1991, six Block I and ten Block II satellites resulted in some 10 to 20 hours of 3-D coverage in most parts of the world.

Table 3

GPS Technical Characteristics and Single Point Positioning Performances

Satellite Constellation	Satellites	21 satellites + 3 active spares Satellites broadcast signals autonomously		
	Orbital Characteristics	6 planes, 4 satellites per plane 55 deg inclination, 12-hour period, 20,231 km altitude		
Signal structure	Frequencies	Dual L-band (1575.42 MHz, 1227.6 MHz)		
	Digital Signal	Spread spectrum PRN, C/A code @ 1.023 MHz, P code @ 10.23 MHz Continuous navigation message @ 50 Hz		
	Other	Code Division Multiple Access signal separation		
Coverage		Worldwide		
Instantaneous Accuracy			Selective Availability	
			On	Off
(SPS,C/A code, 95% [PDOP≤3.0]	Position	Horiz:	100 m	20 to 30 m
		Vert:	156 m	30 to 45 m
	Velocity		0.45 m s^{-1}	0.3 m s^{-1}
	Time		300 ns	40 ns
(L1/L2 P code,95% [PDOP≤3.0]	Position	Horiz:	100 m	15 to 25 m
		Vert:	156 m	20 to 30 m
	Velocity		0.45 m s^{-1}	0.1 m s^{-1}
(Anti-Spoofing Off, Civilian receiver)	Time		300 ns	30 ns

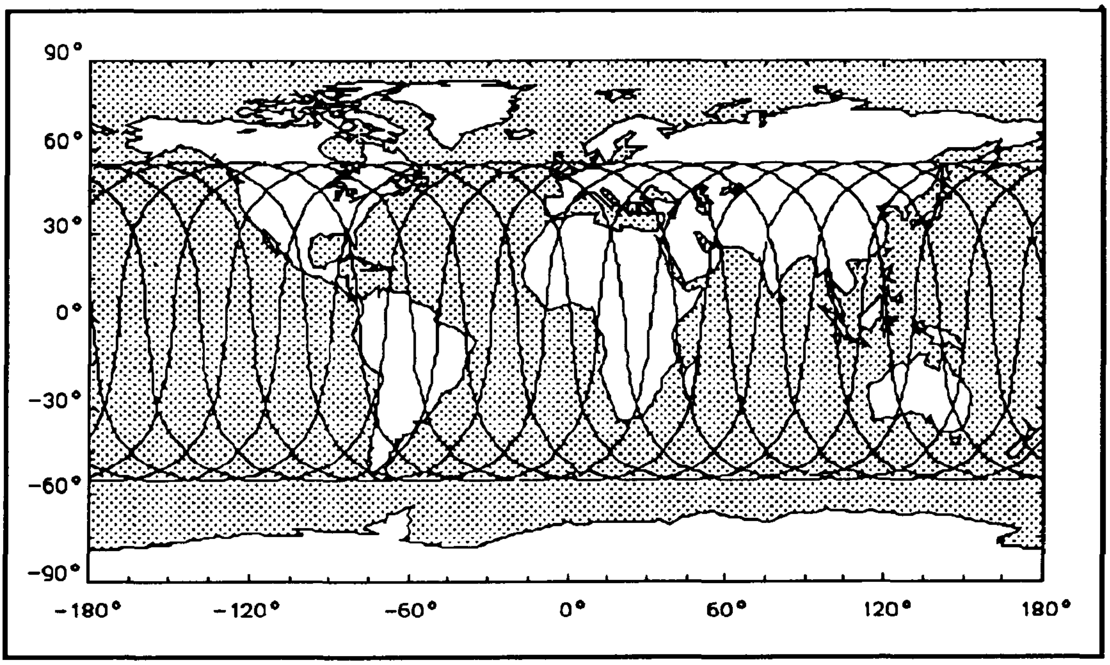

FIG. 1.- Typical Ground Track Coverage of GPS Satellites.

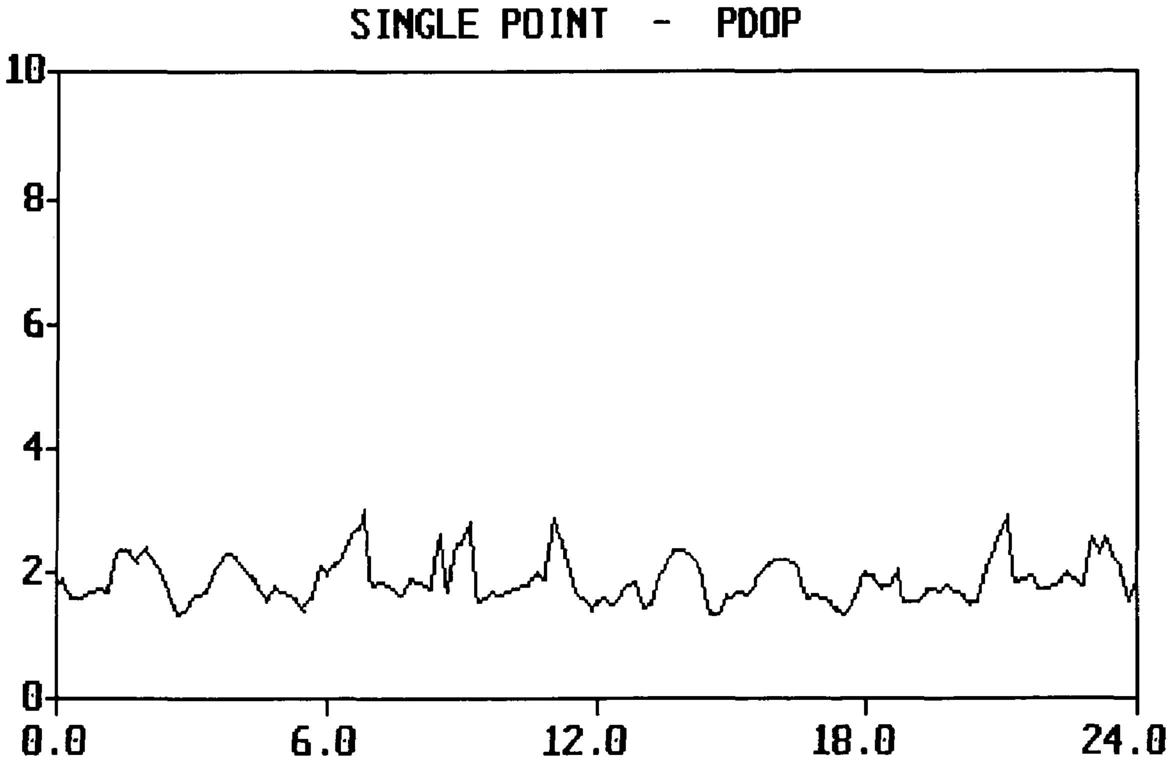

FIG. 2.- PDOP for a Location Off the Coast of Newfoundland Based on 24-Satellite Constellation. The Masking Angle is 5°.

GPS OBSERVABLES AND ERROR SOURCES

Bi-phase modulation of the carriers using pseudo-random noise (PRN) codes, together with the availability of precisely synchronized atomic time and frequency standards onboard the satellites, make precise instantaneous ranging possible. Phase locked tracking of the carriers provides range rate measurements with a yet higher level of accuracy. The observation of the Doppler frequency provides a measure of the instantaneous phase rate $\dot{\Phi}$, where the dot denotes differentiation with respect to time. The instantaneous pseudorange, carrier phase and Doppler frequency observables can be written as:

$$p=\varrho+d\varrho_n+d\varrho_{SA}+c(dt-dT)+d_{ion}+d_{trop}+\varepsilon(p_{rx})+\varepsilon(p_{mult})$$

$$\Phi=\varrho+d\varrho_n+d\varrho_{SA}+c(dt-dT)+\lambda N-d_{ion}+d_{trop}+\varepsilon(\Phi_{rx})+\varepsilon(\Phi_{mult})$$

$$\dot{\Phi}=\dot{\varrho}+d\dot{\varrho}+c(d\dot{t}-d\dot{T})-\dot{d}_{ion}+\dot{d}_{trop}+\varepsilon(\dot{\Phi})$$

where p, Φ and $\dot{\Phi}$ are the observations, ϱ = **|** **r** - **R|** , **r** being the computed position vector of the satellite using the ephemerides and **R**, the unknown position vector of the receiver. The $d\varrho_n$ term represents the nominal broadcast orbital error and $d\varrho_{SA}$, the additional error due to SA; the magnitude of $d\varrho_n$ is 5 to 25 m. The magnitude of $d\varrho_{sa}$ will be discussed in a subsequent section. The dt and dT terms represent the satellite and receiver clock errors, and d_{ion} and d_{trop}, the ionospheric and tropospheric delays. The carrier phase measurement contains an unknown ambiguity, N, which can constrain its use. N for a given receiver-satellite pair remains unchanged from initial acquisition until phase lock is lost. λ is the wavelength, e.g., 19 cm at L1 and 24 cm at L2. The magnitude of the receiver noise terms $\varepsilon(p_{rx})$ and $\varepsilon(\Phi_{rx})$ are 1 to 3 m (C/A code) and 3 to 10 mm respectively, depending of the tracking bandwidths and of the signal-to-noise ratio which, in turn, is mainly a function of the satellite elevation. The corresponding P code noise is 5 to 50 cm. The terms $\varepsilon(p_{mult})$ and $\varepsilon(\Phi_{mult})$ represent multipath errors. Carrier multipath is of the order of some cm but excessive multipath results in a loss of phase lock and a weakened solution through the presence of a new ambiguity term. The instantaneous phase rate observable, $\dot{\Phi}$, which is usually made on the code tracking loop, is not affected by cycle slips or carrier phase ambiguities and is typically used for velocity aiding and carrier phase cycle slip detection and correction. All of the above error sources contribute to limit the single point instantaneous accuracy achievable with GPS to several tens of metres as shown in Table 3.

Loss of Phase Lock and Cycle Slip Detection and Recovery

The initial carrier phase ambiguity resolution is discussed in a subsequent section. Once a satellite is acquired, it is essential that losses of phase lock be minimized for the highly accurate carrier observable to be useful in a kinematic environment. The dynamics typically encountered on a survey launch are harsh and may result in losses of phase lock and/or cycle slips as frequently as every 15 to 30 minutes (LACHAPELLE et al., 1988). The first problem is to detect the occurrence of a cycle slip. With single frequency C/A code receivers which output the Doppler frequency $\dot{\Phi}$, the phase velocity trend method is often used (e.g. , CANNON, 1990). The carrier phase Φ_k phase at t_k is predicted using Φ_{k-1} and the phase rates at k and k-1:

$$\hat{\Phi}_k = \Phi_{k-1} + \frac{\dot{\Phi}_k + \dot{\Phi}_{k-1}}{2} \Delta t$$

The phase acceleration is assumed constant over Δt. If $| \hat{\Phi}_k - \Phi_k | <$ preset threshold, it is assumed that no cycle slip has occurred. The method is usually valid within 1 cycle if $\Delta t \leq 1$ s and provided the loss of phase lock does not last for more than one second. The advantage of a high raw data output rate is evident in this case. If the instantaneous Doppler frequency is not available, the phase rate estimated over the interval (Φ_{k-1}, Φ_k) is used to predict the phase change over (k, k+1). The same inequality as above is then used to detect the occurrence of a cycle slip. The accuracy of this method is a function of the platform's dynamics and the data output rate. For an output rate of one second, the detection threshold is typically of the order of one to five cycles. The above phase velocity trend method is used in conjunction with a least-squares estimator to deal with redundant satellite observations. The higher the level of redundancy, the more effective the method to recover cycle slips. The use of rubidium or a superior ovenized quartz oscillator is advantageous in this case.

If dual frequency carrier phase measurements are available from a P code receiver, another method of cycle slip detection, originally proposed by GOAD (1985), consists of forming the following difference over the interval (k, k+1) where k and k+1 are successive measurement epochs:

$$\delta\Phi_{k,k+1} = \delta\Phi(L1) - \delta\Phi(L2) = \delta d_{ion}(L2 - \delta d_{ion}(L1)$$

Over a short interval (one second), $\delta\Phi_{k,k+1}$ will be well below one cycle because L1 and L2 are relatively close to each other and the dispersive effect of the ionosphere will be well below one cycle over such a short interval. If $\delta\Phi k,k+1>1$ cycle, a cycle slip has occurred on one of the two carriers. The method works well in kinematic mode and is accurate to within one cycle.

The above cycle slip detection methods are based on the assumption that the duration of a loss of phase lock will be short, namely a few seconds at most. If satellite re-acquisition takes more than several seconds, the problem becomes that of an initial carrier phase ambiguity resolution. If a codeless technique is used to measure the carrier phase on L2, the above method is not effective due to the strong correlation between the two carrier measurement tracking loops.

Selective Availability

The $d\varrho_{SA}$ term in the pseudorange and carrier phase observation equation is caused by the injection of two types of error in the broadcast ephemerides, namely the orbit or ε-type SA, and the satellite clock dithering, or δ-type SA. The latter adversely affects the velocity accuracy as seen in Table 3. The dithering is implemented through the injection of errors in the a_1 satellite clock term:

$$\Delta t_{sv} = a_0 + a_1(t - t_{oc}) + a_2(t - t_{oc})^2$$

Δt_{sv} and dt in the above observation equations are related through the following equation:

$$dt = \Delta t_{sv} + \varepsilon_t \text{ (residual errors)}$$

The ε-type can be implemented on Block I and II satellites while the δ-type can be implemented on Block II satellites only. The level of SA observed by different authors vary widely. KREMER et al. (1990) reported effects at the 100 m level with a correlation time of three minutes using data observed during the SA test in Fall 1989; this level is compatible with that predicted earlier (KALAFUS et al., 1986). SA was turned on "operationally" in Spring 1990; TOLMAN et al. (1990) reported typical "operational" SA values of several tens of metres with 10-minute periods, and attributed mostly to the δ-type, as shown in Figure 3. The level of "operational" SA observed in April 1990, appears lower than that observed during the Fall 1989 test period. During Summer 1990 however, prior to SA being turned off, SA levels well in excess of 100 m were observed on several satellites. The effect of SA can be reduced by DGPS as it will be discussed in a subsequent section. Post-mission precise orbits available in post-mission are not affected by SA.

Ionospheric Errors

The ionosphere affects GPS signals in two ways, namely (i) group delay and carrier phase advance, and (ii) scintillation. The term d_{ion} in the pseudorange and carrier phase equation represents the group delay or carrier phase advance. These can be practically eliminated if dual frequency measurements are available because the ionosphere is dispersive in the RF part of the spectrum, i.e., the effect is different on each frequency. This is one of the several advantages of dual frequency measurements. In this case, the group delay and carrier phase advance are:

$$\Delta\varrho_{ion}(L_1)=\{\varrho(L_1)-\varrho(L_2)\}/\{f^2(L_2)/[f^2(L_2)-f^2(L_1)]\}$$

$$\Delta\Phi_{ion}(L_1)=\{f^2(L_2)/[f^2(L_2)-f^2(L_1)]\}/\{\Phi(L_1)-[f(L_1)/(L_2)]\Phi(L_2)\}-\{N(L_1)-[f(L_1)/f(L_2)]N(L_2)\}$$

where $\Delta\varrho_{ion}(L_1)$ and $\Delta\Phi_{ion}(L_1)$ are the ionospheric corrections to the L1 pseudorange and carrier phase measurements, respectively. The total ionospheric carrier phase advance $\Delta\Phi_{ion}(L_1)$ at a specific epoch cannot be determined due to the ambiguities $N(L_1)$ and $N(L_2)$, the differential carrier phase advance between L1 and L2 being

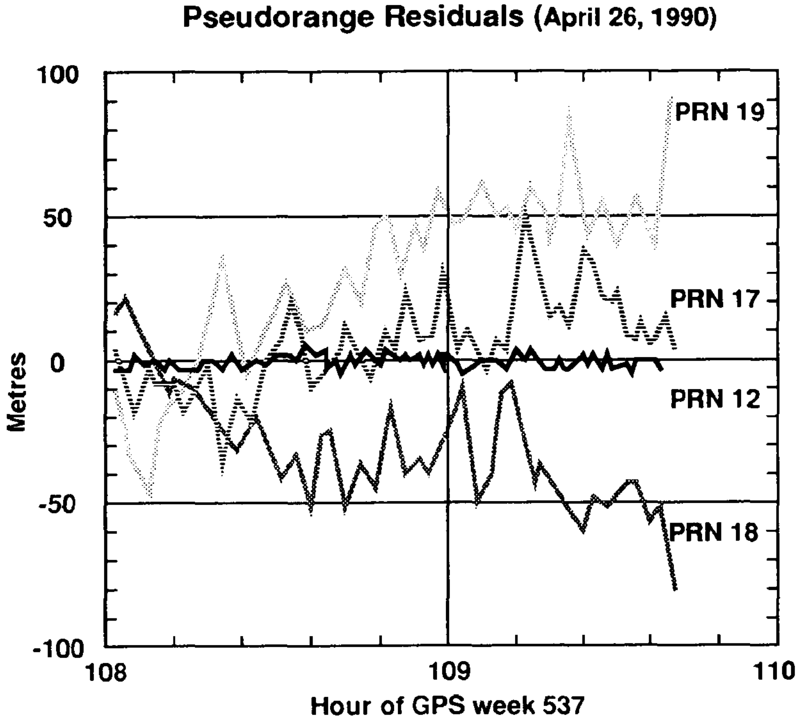

FIG. 3.- "Operational" Type SA Effects Observed in April 1990 (After TOLMAN et al., 1990).

generally larger than one wavelength. However, if both L1 and L2 carriers are tracked without any cycle slips over an interval (t_1, t_2), the differential ionospheric delay $\delta\Delta\Phi_{ion}(L_1)$ over (t_1, t_2) can be determined because the ambiguities remain unchanged over (t_1,t_2) and vanish in the differentiation between the two epochs. This is why the L2 carrier squaring technique cannot be used to determine the absolute ionospheric delay. The use of a P codeless technique (MEEHAN et al., 1987) can however be used effectively.

The group delay (or carrier phase advance) is a function of several parameters. It exhibits a diurnal variation by a factor of three with a maximum at 1400 local time, a seasonal variation with a maximum at Spring equinox and a geographic maximum within 20° from the geomagnetic equator. Its correlation time is approximately three hours while its correlation distance is typically 1,000 km at mid-latitude. Variations due to the solar cycle can reach a factor of three. The current solar cycle (No. 22) reached a maximum during 1990. The magnitude of this cycle is compared to previous cycles in Figure 4. (KUNCHES & HIRMAN, 1990). The group delay can reach 50 m at the zenith in extreme cases; the corresponding effect near the horizon is 150 m. An 8-coefficient model is broadcast as part of the navigation message using averaged data observed previously (KLOBUCHAR, 1986). This model is deemed accurate to 50% at mid-latitudes. In high latitudes, the absolute group delay is generally smaller than in lower latitude. However, its short term variability is three times higher and the above model is less accurate (BISHOP & KLOBUCHAR, 1990). The opposite signs of the group delay and carrier phase advance may be used to average out the effect of the ionosphere with single frequency measurements (GOAD, 1990), although the accuracy is limited by C/A code noise.

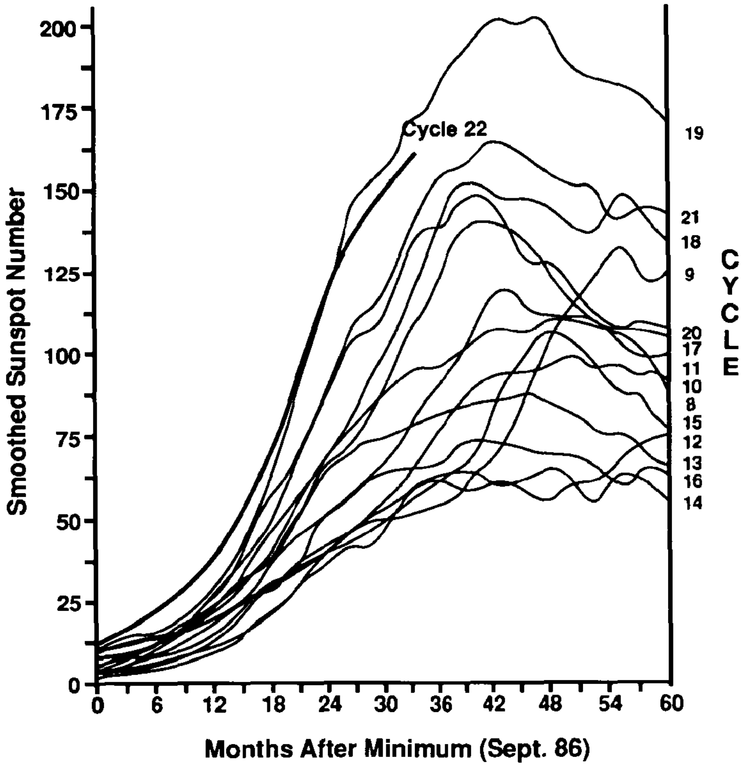

FIG. 4.- Amplitudes of Current and Previous Solar Cycles (After KUNCHES et al., 1990).

Ionospheric scintillation, which consists in a rapid fluctuation of the Total Electron Content, is unpredictable, correlated with the solar cycle in magnitude and is particularly severe in high latitudes. Scintillation results in a variation of amplitude and Doppler shift of the incoming signals. Under severe conditions, these can result in losses of phase lock due to a lower signal to noise ratio (SNR) and/or a sudden Doppler shift outside the tracking bandwidths of the receiver. Steep electron density gradients are known to exist in the auroral zone. An alignment with the line of forces of the earth's magnetic field occurs and the effect on GPS signals is maximum when the rays to the satellites are parallel to the line of forces, a situation which occurs in Canada's Arctic for instance, where much hydrographic work remains to be done. The use of current L2 squaring receivers has generally resulted in lower performance due to receiver implementation and lower signal strengths. During periods of intense solar activity, as in the past two years, geomagnetic activity forecasts can be effectively used to avoid observing during intense ionospheric scintillation periods. Now that the current solar cycle maximum has passed, scintillation will generally decrease to reach a minimum around 1995-1996.

Tropospheric Errors

The effect of tropospheric refractivity d_{trop} is a function of pressure, and dry and wet temperatures. The effect, which increases exponentially as the satellite elevation decreases, is shown in Figure 5 for selected station elevations above sea level. The effect, which is maximum for a station at sea level, is usually split into a dry and a wet component. The dry component accounts for some 80 to 90% of the total effect and can be estimated with an accuracy of 1% at the zenith. The wet component accounts for the remainder and can be estimated with an accuracy of 10 to 20% at the zenith. This is due to the unpredictable nature of water vapour which is mostly concentrated within the first 10 to 12 km of troposphere. The above accuracies decrease as the satellite elevation decreases. The use of satellites with elevation angles below 10° will therefore result in a lower position accuracy. A lower SNR at low elevation will further degrade the code and carrier measuring accuracy. These are the major reasons why satellites with elevation angles greater than 15° are used for precise static positioning. However, this is a heavy penalty to pay in a shipborne environment where redundant measurements on all-in-view satellites provide valuable quality control information. The use of a weighting function related to the satellite elevation is sometimes used to account for the lower accuracy of observations made on satellites at low elevations.

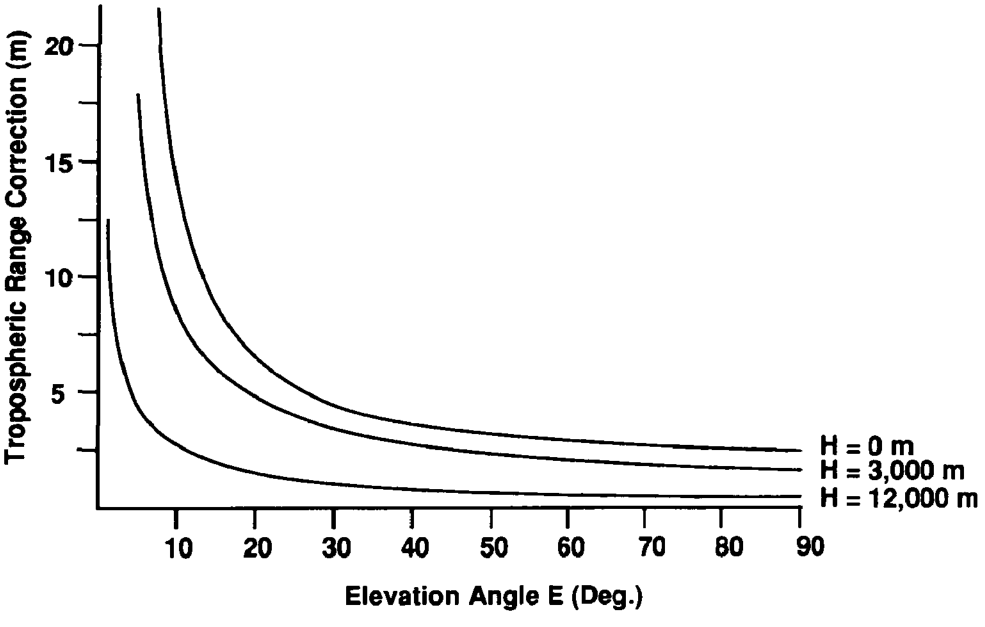

FIG. 5.- Tropospheric Delay at RF Frequencies.

Vertical profiles of refractivity are usually estimated from surface measurements and standard models of the atmosphere such as the U.S. Standard Atmosphere. These models are based on a spherically symmetric and horizontally uniform troposphere. A mapping function is used to estimate the effect along the slant range to the satellite. As the troposphere is non-dispersive in the RF part of the spectrum, models developed for the lower frequency Transit system are applicable to GPS. The best known models are HOPFIELD's and BLACK's (BLACK and EISNER, 1984). An alternative to using surface measurements to estimate the wet component is the use of water vapour radiometers (ROCKEN et al., 1991) which measure water vapour accurately in specific directions using RF frequencies of several GHz. The use of such instruments at the differential monitor stations would assist in improving the accuracy of the height component for high accuracy applications where the tidal effect is required. The correlation distance of the wet component is relatively short, typically 20 km or less, especially for marine applications, and the use of DGPS over longer distances will only marginally reduce its effect.

Multipath

Multipath affects both code and carrier measurements. The effect of carrier phase multipath does not exceed several centimetres but may, however, cause frequent cycle slips. Code multipath is limited to a maximum of one chip length of the PRN code, i.e., 293 m with the C/A and 29.3 m with the P code. The P code is therefore less affected by multipath than the C/A code. In static mode, multipath is non-gaussian and difficult to remove or reduce using filtering techniques, unless observations take place over more than one day (EVANS & HERMANN, 1989). An example of static C/A code multipath in a highly reflective environment is shown in Figure 6. Amplitudes of 20 m and periods of up to several minutes were observed. In a static case, e.g., at the monitor station, the location and characteristics of the antenna, together with the use of a RF absorbent ground plane, will reduce multipath substantially (LACHAPELLE et al., 1990). In kinematic mode, multipath is more random as shown in Figure 7. The degree of randomness will depend on the dynamics of the platform. Even in cases where multipath can be considered random, it will result in additional measurement noise of several metres (LACHAPELLE, 1990, ALLISON et al., 1990). In such cases, it becomes difficult to fully exploit the advantages of low C/A or P code measuring noise. Multipath is the most important error source when using code measurements to resolve the initial carrier phase ambiguities.

USER EQUIPMENT

The five GPS receiver measuring techniques currently used are listed in Table 4 together with their major characteristics. Receivers may combine one or several measuring techniques. The largest class of GPS receivers is that based on the C/A code L1 measuring technique. This class will satisfy most marine navigation requirements in single point mode both for the ocean and the coastal phases. Most of the requirements given in Tables 1 and 2 can also be met with this class of receivers in DGPS mode. In order to meet requirements at the sub-metre level, the use of some of the other measuring techniques is usually needed.

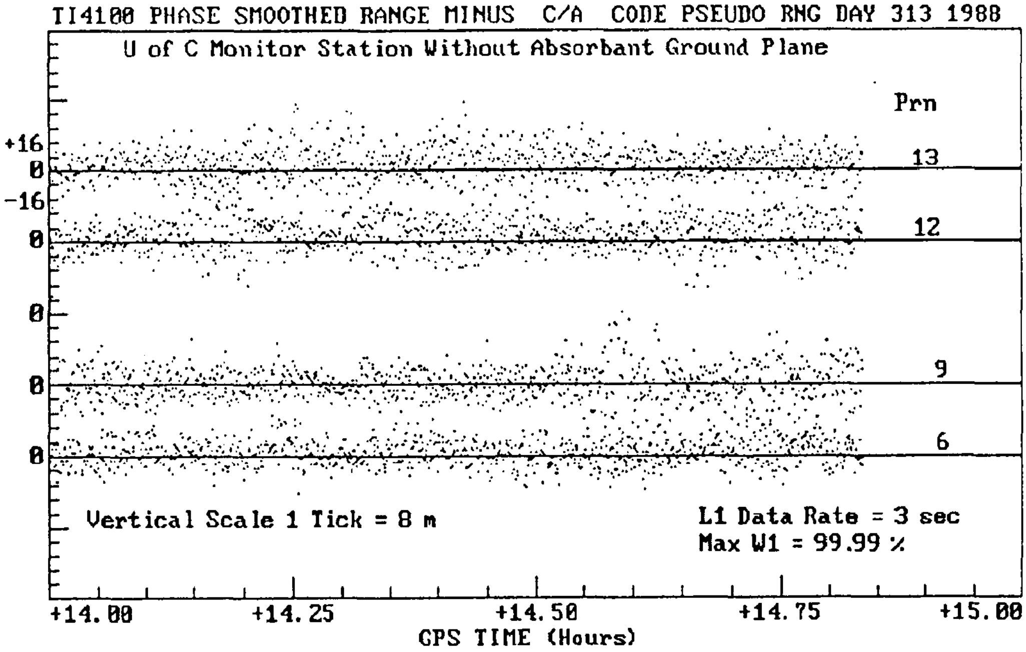

FIG. 6.- Static C/A Code Multipath: A ≤ 20m, T ≤ 3 minutes, non-gaussian.

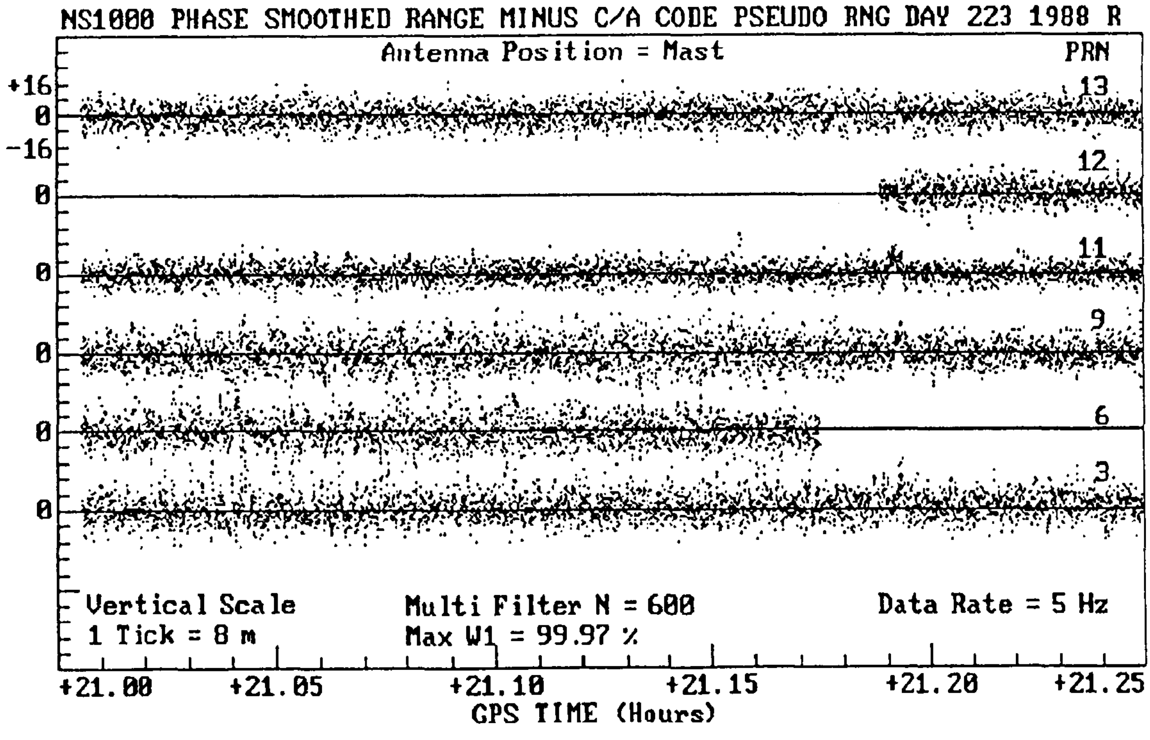

FIG. 7.- Kinematic C/A Code Multipath: A ≤ 20 m, Quasi-Random.

Table 4

GPS Receiver Measuring Techniques

No.	Class	Characteristics
1	C/A code L1	Code only or code and carrier phase
2	L2 squaring	Carrier phase on L2 through squaring (1/2 original λ, i.e., 12 cm) No P code required
3	L2 codeless	Carrier phase on L2 through L1/L2 correlation (original λ, i.e., 24 cm)
4	P codeless	P(L1) and P(L2) correlation provides absolute ionospheric group delay without acess to P code
5	P code	Code and carrier on L1 and L2 P code required

The most sophisticated class of receivers is obviously that based on the P code. Accurate pseudorange and full phase cycle measurements can be obtained on both carriers independently. Civilian P code receivers are becoming increasingly available. The major disadvantage is the Anti-Spoofing policy to take effect when GPS is declared operational in 1993. Since all civilian P code receivers must first acquire the C/A code however, the C/A code measuring techniques is implicit in these receivers. Several manufacturers now offer full or partial P code receivers. Of the two codeless techniques (Nos. 2 and 3) used to measure the carrier phase on L2, the second one is preferable since it recovers the full cycle and is therefore more effective for initial ambiguity resolution. Both codeless techniques may however be sensitive to platform dynamics, depending on various factors. The P codeless measuring technique is currently a unique feature of the Rogue receiver (MEEHAN et al., 1987). The ionospheric group delay can be measured without explicit access to the P code, an important advantage to eliminate the effect of the ionosphere. In the process, the full carrier phase cycle on L2 is also measured.

For any class of receiver or measuring technique used, several characteristics are of major importance for precise marine positioning. These are as follows:

(i) Availability of at least eight parallel channels to ensure continuous code and carrier phase tracking of all-in-view satellites above an elevation of 5°. Dedicated channels will result in a phase sensitivity gain of at least 5dB as compared to sequential or multiplexed channels. Tracking all-in-view satellites will increase measurement redundancy which is important for quality control, cycle slip detection and initial ambiguity resolution.

(ii) Availability of the Doppler frequency for the detection of cycle slips.

(iii) A minimum code, carrier and Doppler frequency data rate of 2 Hz for an effective detection of cycle slips and heave motion averaging.

(iv) Access to L2 carrier phase measurements for ambiguity resolution using widelaning (see next section). Short of the full P code measuring technique, the L2 codeless technique should be used over the L2 squaring technique to recover the full cycle. The P codeless technique is an advantageous option, especially for shore-based monitor stations, to monitor and reduce the effect of the ionosphere.

(v) An antenna with an appropriate response pattern down to 20° below its horizon will improve signal tracking of satellites with low elevation under survey launch-type roll and pitch motion. Such an antenna will, however, be relatively sensitive to multipath, a problem difficult to deal with onboard small survey vessels with the current antenna technology. The response pattern of the antenna at the monitor station should have different characteristics to further reduce systematic multipath effects. The use of a RF absorbent ground plane is recommended in this case.

(vi) Best receiver measuring accuracy performance available with current technology. This is discussed in more detail below.

Receiver measuring errors consist mostly of thermal noise intercepted by the antenna or produced by the internal components of the receiver. Their magnitude depends on parameters such as tracking bandwidth, carrier-to-noise density ratio, and code and carrier tracking parameters (MARTIN, 1980). Since signal strength is strongly correlated with satellite elevation, measuring accuracy will vary significantly from zenith to horizon. The accuracy of carrier phase measurements, although affected by the tracking bandwidth, is generally better than 1 cm. Major improvements have been made in receiver design through the 80's and manufacturers now claim an accuracy of the order of 1 m for C/A code and 10 cm for P code measurements.

Given that a minimum accuracy of 10 cm is required to solve the carrier phase ambiguity instantaneously, the possibilities with the new P code-based receiver technology look indeed promising, provided that multipath and tropospheric effects can be kept in check.

DIFFERENTIAL GPS

Differential GPS involves the use of at least one monitor station located at a known point where the same satellites as those from the ship are simultaneously observed, as shown in Figure 8. The data from both the monitor and the ship are used to form differenced observations which eliminate or reduce some of the errors discussed previously. As a result, the position accuracy of the ship with respect to that of the monitor station increases substantially. If high accuracy is required in real time, measurements obtained at the monitor must be transmitted to the ship. This involves the use of a RF data link. The type, density and frequency of the measurements transmitted from the monitor to the ship is a function of the accuracy required and of the effect of SA.

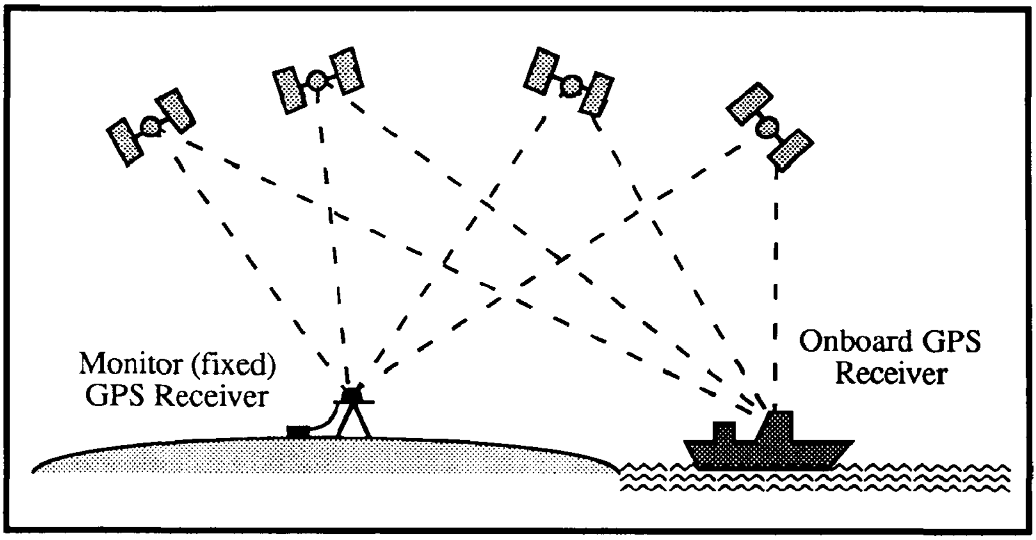

FIG. 8.- Concept of Differential GPS Positioning.

Differenced Observables

For kinematic applications, the two most widely used differencing modes are (i) the pseudorange single difference between receivers and (ii) the pseudorange and carrier phase double difference between receivers and satellites. The pseudorange single difference between receiver is:

$$\Delta p = \Delta \rho + \Delta d\rho - c\Delta dT + \Delta d_{ion} + \Delta d_{trop} + \Delta \varepsilon(p)$$

where Δp is the difference between the two pseudoranges observed at the two receivers to the same satellite. The common satellite clock error dt cancels out. The differential receiver clock parameter ΔdT is still present and has to be carefully modelled, especially under SA (SHARPE, 1989). The term Δdp is reduced substantially from $d\varrho$ since the baseline is relatively short as compared to the distance to the satellite. The relationship between an error dr in the satellite position and the resulting error db in the baseline is (WELLS et al., 1986)

$$db = (b\ dr)/r$$

where b is the baseline length and r, the distance to the satellite, is 20,000 km on average. An error dr of 20 m, which is the nominal broadcast error, results in an error of 1 ppm in the baseline, e.g., 10 cm for a baseline of 100 km. If SA is on and dr is 100 m, db is 5 ppm or 50 cm for a 100 km baseline. The term Δd_{ion} vanishes if dual frequency measurements are used to correct for the effect of the ionosphere. Otherwise, the effect is reduced substantially for distances of up to 1,000 km under normal ionospheric conditions as discussed previously. The differential error $\Delta\varepsilon(p)$, due to the receiver noise and multipath is not reduced by differentiation, but is increased due to the amplification of $\Delta\varepsilon(p_{rx})$ by a factor of $\sqrt{2}$, because the $\varepsilon(p_{rx})$'s are uncorrelated between receivers.

The above pseudorange single difference is used in one form or another for real-time DGPS. Time averaged differential range and range rate corrections are transmitted in real time from one or several monitors to the ship at an interval required to maintain a specified level of accuracy. If SA is off, the interval may be several minutes, thereby decreasing the data link requirements. However, if SA is on, the differential corrections must be transmitted more frequently to maintain a specified level of accuracy. Figure 9 shows accuracy degradation versus update rate under SA (KALAFUS et al., 1986). Under SA, a maximum data transmission rate of 50 bps is sufficient to maintain an accuracy of a few metres using the above method.

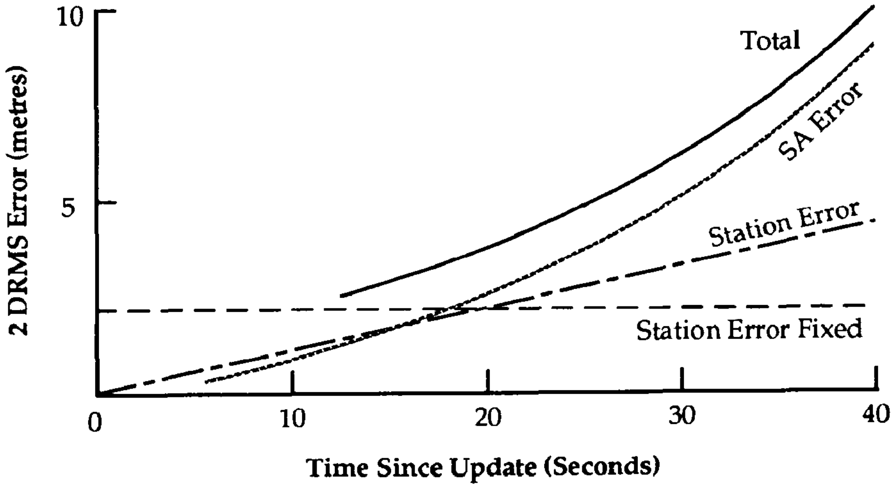

FIG. 9.- Effect of Update Rate on Accuracy in DGPS Mode with SA On.

Real-time C/A code single differences can yield, in the absence of large multipath effects, a rms accuracy of 7 to 10 m when a good geometry is available, e.g., PDOP ≤ 3. In order to improve accuracy without increasing the data transmission burden, code and carrier phase can be combined using the phase smoothed pseudorange method (HATCH, 1982). An rms accuracy of 2 to 3 metres can be obtained in survey launch mode with this method (LACHAPELLE et al., 1988).

The pseudorange and carrier phase double differences between receivers and satellites have the form:

$$\nabla\Delta p = \nabla\Delta\varrho + \nabla\Delta d_{ion} + \nabla\Delta d_{trop} + \nabla\Delta\varepsilon(p)$$
$$\nabla\Delta\Phi = \nabla\Delta\varrho + \lambda\nabla\Delta N - \nabla\Delta d_{ion} + \nabla\Delta d_{trop} + \nabla\Delta e(p)$$

where the differential receiver clock term dT has now cancelled out. The second equation is used extensively in land kinematic mode where initial carrier phase ambiguity resolution can be accomplished using various methods involving either access to the monitor station by the remote receiver or observation at a known point for a brief period of time in static mode. Accuracies at the cm-level can then be achieved provided that cycle slips are detected and effectively recovered (CANNON et al., 1990). The method is easier to use in post-processing mode since real-time use involves the transmission of the raw data to the moving platform at every epoch.

Ambiguity Resolution

Initial ambiguity resolution may be successfully accomplished for kinematic applications when the separation between the monitor and the moving platform can be kept relatively small, namely less than 10 to 20 km, using dual frequency measurements. Widelaning carrier phase observations are formed by differencing between L1 and L2 observations using either a P code dual frequency receiver or a C/A code dual frequency receiver with codeless extraction of L2 (WÜBBENA, 1989; GEIER et al., 1990):

$$\phi_\Delta = \phi_1 - \phi_2$$

with

$$f_\Delta = f_1 - f_2;\ \lambda = c/f_\Delta = 86.25\ cm$$

The wavelength is increased by a factor of 4.5 from 19 cm (L1) to some 86 cm. The ambiguities are easier to estimate in view of this large lanewidth. The use of a C/A code dual frequency receiver with L2 by squaring is not as effective because the above lanewidth is reduced from 86 to 43 cm due to the halving of the L2 carrier wavelength in the squaring process. If a P code receiver is used, the extra widelaning technique can be used to further accelerate convergence to the correct ambiguities (SEEBER et al., 1989; ABIDIN, 1990). Ambiguity resolution is accomplished through the use of code measurements and the redundancy and geometry of the satellites. Simulations made by GEIER et al., (1990) have resulted in convergence periods of four to 15 minutes using dual frequency measurements and the following satellite constellations: full GPS, GPS plus GLONASS, and GPS plus a geostationary satellite. Initial results obtained by SEEBER and WÜBBENA, (1989) with the extra widelaning technique in shipborne mode indicate that an accuracy at the sub-decimetre level is attainable. It is emphasized that the above techniques are limited by the assumption of a highly correlated ionosphere between the monitor and the ship, effective cycle slip detection and recovery throughout the mission, relatively short separation between monitor and ship, and effective control of multipath effects as previously discussed. An ideal marine application is perhaps river dredging where the dynamics of the vessel are relatively low. The U.S. Army Corps of Engineers is considering implementation of these techniques for many of its dredging projects (DeLOACH, 1991).

If the above techniques are to be used in real-time, a powerful data link is required to transmit the raw data from the monitor to the moving platform. Several ground- and satellite-based RF data link technologies, ranging from upper MF to UHF are capable of satisfying the 1000 to 2000 bps requirement (LANIGAN et al., 1990). The most flexible group is the upper MF group in the range 1.6 to 3.0 MHz. Line of sight is not required and a range of over 400 km over sea water can be obtained. These advantages are however offset by a high capital acquisition cost.

Modelling

Several methods and software packages are available for the combination and processing of DGPS code, carrier and Doppler frequency data. One of the earliest method proposed for the combination of code and carrier measurement was the phase smoothed pseudorange recursive filter of HATCH (1982), which was successfully tested in the marine environment (LACHAPELLE et al., 1988). This method, which is especially well suited for real-time applications, was subsequently refined by the addition of a series of second stage parallel Kalman filters to effectively deal with the effect of SA on the local clock and the combination of the redundant measurements from all satellites (SHARPE, 1989).

In recent years, various KALMAN filter approaches have been proposed and developed for the combination of GPS observables. Two general approaches prevail, namely the general integrated filter where the estimated values are obtained from a linear combination of the noisy measurements, and the reference trajectory approach where the precise carrier phase measurements provide a deterministic but noisy trajectory (HWANG & BROWN, 1990). In the latter case, the filter operates only on the measurement noise, without applying any constraint on the trajectory. The former case, which implies a certain degree of constraint on the trajectory, can be split into various sub-cases coinciding with reasonable assumptions concerning the dynamics of the vehicle, i.e., constant velocity or constant acceleration (SCHWARZ et al., 1989). All of these filters can be applied to single point and/or single or double differenced data. Under benign dynamics, differences between the position estimates obtained using combination methods should not be statistically different if the methods have been implemented correctly. For instance, see (CANNON et al., 1990) for a comparison between the performance of a "constant velocity" KALMAN filter and a straight least-squares approach.

DGPS Accuracy Performances

The accuracy of DGPS is a function of the separation between the monitor and remote stations, the effect of SA, the receiver characteristics and measuring techniques used, the tropospheric and ionospheric conditions, and the observables and algorithms adopted. An attempt has been made by the authors to estimate the achievable accuracy for two DGPS operating modes, namely separations of 50 and 500 km between the monitor and remote receivers, respectively. The results are presented in Table 5. These estimates are based on our current knowledge of the effect of SA and are therefore subject to revision as a better understanding of the effect of SA, especially for large monitor-remote separation, is gained. The effect of

SA was estimated using the "operational" SA characteristics obtained by TOLMAN et al., (1990) and showed in Figure 3. Other assumptions are:

(i) Use of receivers which can track all-in-view satellites
(ii) Use of one monitor station and broadcast ephemerides
(iii) Average multipath conditions
(iv) Average 30-N ship's dynamics
(v) Average ionospheric and tropospheric conditions
(vi) PDOP ≤ 3

The "carrier phase only" case is that when the initial ambiguities are resolved. Since pseudoranges are sometimes used in this process, the case is not truly that of carrier phase only. This case, which is still more potential than operational, requires P code or C/A code L1 with full cycle extraction of the L2 carrier phase. The other cases apply to C/A code L1 receivers.

Two procedures not further discussed herein are available to further increase DGPS performance, namely the use of several monitor stations around the area of operation and the use of post-mission orbits. These two procedures mostly aim at reducing the effect of SA.

A comparison of the accuracy estimates of Table 5 with the marine surveying accuracy requirements of Table 2 reveals that DGPS can or has the potential to meet all requirements.

TRENDS AND PROSPECTS

The following emerging trends will increase the cost-effectiveness and range of applications of GPS throughout the 90's.

The major system enhancements likely to take place through the 90's are as follows: (i) The Block IIR satellites, to be launched from 1995 onwards, will have an inter-satellite tracking capability. This will decrease the satellite clock error term and increase broadcast orbit accuracy (in the absence of SA); (ii) Interoperability between GPS and GLONASS, the USSR equivalent to GPS, would result in better coverage, improved geometry and higher redundancy. One of several advantages would be a more effective resolution of the initial carrier phase ambiguities (GEIER et al., 1990). Integrated GPS/GLONASS receivers have already been built by several manufacturers (EASTWOOD, 1990); (iii) INMARSAT's proposed geostationary overlay of satellites will be usable with standard GPS receivers and will have advantages similar to an interoperable GPS/GLONASS system, with the additional advantage of a built-in integrity monitoring system (KINAL & SINGH, 1990). The combined constellation resulting from the augmentation of GPS with the three proposed INMARSAT satellites is shown in Figure 10.

Table 5

GPS Kinematic Differential Positioning Performances[1]

(SPS, C/A code, 95%) [PDOP≤3.0]	**Separation Monitor to Remote**	**Selective Availability**		
			On	**Off**
Code only	50 km	Horiz:	4 to 9 m	4 to 8 m
		Vert:	5 to 11 m	5 to 10 m
	500 km	Horiz:	6 to 11 m	5 to 8 m
		Vert:	7 to 12 m	6 to 10 m
Code and carrier[2]	50 km	Horiz:	1 to 3 m	1 to 2 m
		Vert:	1 to 4 m	1 to 3 m
	500 km	Horiz:	3 to 9 m	2 to 4 m
		Vert:	4 to 10 m	3 to 5 m
Carrier only[3]	50 km	Horiz:	0.1 to 0.8 m	0.05 to 0.1 m
		Vert:	0.2 to 1 m	0.06 to 0.12 m
	500 km	Horiz:	2 to 6 m	0.5 to 3 m
		Vert:	2 to 7 m	0.7 to 4 m
(P Code[4], 95%) [PDOP≤3.0]	**Separation Monitor to Remote**	**Selective Availability**		
Code only	50 km	Horiz:	1 to 3 m	1 to 2 m
		Vert:	1 to 3 m	1 to 2 m
	500 km	Horiz:	3 to 6 m	2 to 4 m
		Vert:	3 to 7 m	2 to 5 m
Code and carrier[2]	50 km	Horiz:	0.5 to 2 m	0.5 to 1.5 m
		Vert:	0.5 to 2 m	0.5 to 1.5 m
	500 km	Horiz	2 to 4 m	1 to 3 m
		Vert:	2 to 5 m	1 to 4 m

1 One Monitor Station Only

2 No precise knowledge of initial separation vector between monitor station and moving platform

3 Assuming that the initial ambiguities can be determined and that losses of phase lock can be recovered effectively - These levels of accuracy should be assumed as potential at this time

4 Assuming that Anti-Spoofing is off.

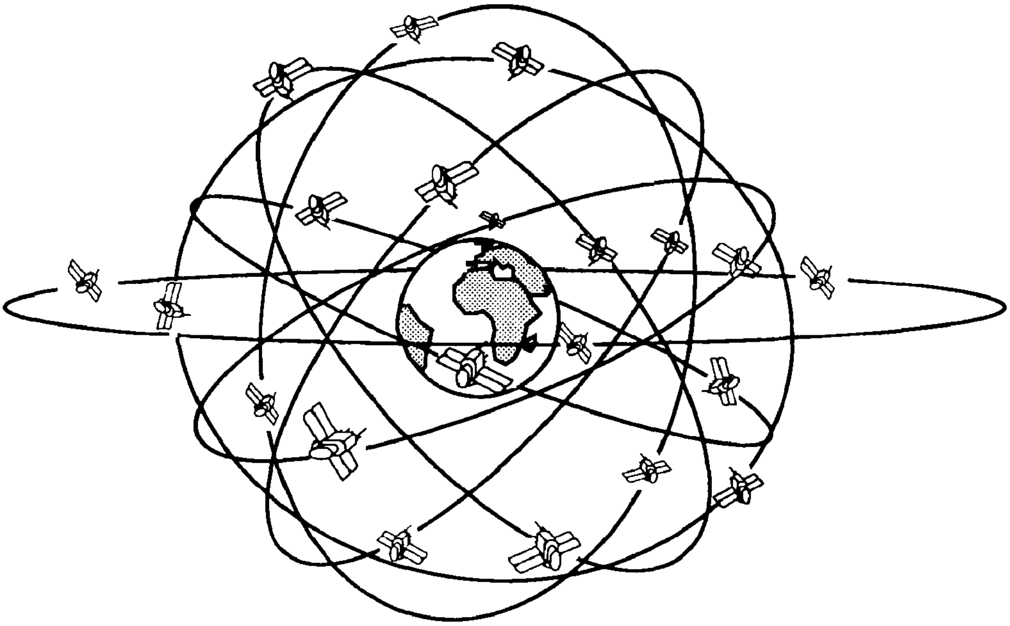

FIG. 10.- GPS Augmented with INMARSAT's Geostationary Overlay.

User equipment has gone through a major transformation during the last five years in terms of versatility, performance, portability and cost. This is well illustrated by the various types of measuring techniques now available, as shown in Table 4. Further significant enhancements are emerging. Parallel channel receivers which can yield "geodetic" type accuracy are now becoming available at some 10% of the cost of the "benchmark" receivers in the market (KEEGAN, 1990). Multi-antenna receivers which can measure azimuth and attitude components within a few degrees in kinematic mode are becoming available commercially, e.g., Ashtech's 3DF receiver. The miniaturization of GPS equipment will continue with the increasing use of MIMIC (Monolithic Microwave Integrated Circuit) and VHSIC (Very High Speed Integrated Circuit) technologies. It is estimated that the use of these technologies will result in a manufacturing cost of some $500 for a basic receiver by the mid 90's (KRAKIWSKY et al., 1990).

The accuracy and versatility of the new code and codeless technologies is resulting in an abundance of observables. Modelling and processing methods to combine these measurements for optimal results will be refined further. Instantaneous carrier phase ambiguity resolution methods are likely to substantially improve over the next few years (ABIDIN, 1990; HATCH, 1990) as procedures to control the effect of multipath are refined. Advanced statistical quality control methods for the detection of non-random biases (SALZMANN & TEUNISSEN, 1990; LU & LACHAPELLE, 1990) will further assist with the above task while contributing to an enhanced quality assurance process.

Marine applications will continue to rapidly expand as GPS is declared fully operational in 1993. The ever decreasing cost of user equipment will result in a rapidly growing marine user community. Multi-antenna receivers may begin to replace conventional shipborne gyrocompasses by the end of the decade. Their use in hydrographic surveying will provide valuable attitude measurements for the precise reduction of hydrographic data. Floating platforms equipped with high performance receivers will be used as tidal stations. GPS will increasingly be used in remote areas (JACKSON, 1990) and for the verification and calibration of navigational aids such as Loran-C (LACHAPELLE & TOWNSEND, 1991). Vessel traffic systems based on the combination of GPS and satellite-based communications (GIBBONS, 1991) will increase safety at sea while contributing to more effective environmental protection.

GPS-related services will expand. Several national government agencies are already offering or developing Civil GPS Services. Numerous information bulletins and technical magazines are partially or totally dedicated to GPS. Regional differential services are already in place in many parts of the world and the establishment of satellite-based continental or global differential services is taking place (SLACK, 1990).

From the above, it is obvious that the long term prospects for GPS and its successors are indeed promising. The superior performance of GPS will not only result in better charting and increased safety of navigation, but also in new areas of application ranging for physical oceanography to environmental protection.

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