# RTCM RECOMMENDED STANDARDS FOR DIFFERENTIAL NAVSTAR GPS SERVICE

VERSION 2.1

DEVELOPED BY
RTCM SPECIAL COMMITTEE NO. 104

JANUARY 3, 1994

Radio Technical Commission For Maritime Services
1800 Diagonal Road, Suite 600
Alexandria, Virginia 22314-2840 U.S.A.

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# PREFACE

This recommended standards document has been developed by RTCM SC-104 to replace the document entitled "RTCM Recommended Standards for Differential Navstar GPS Service, Version 2.0" issued on January 1, 1990. Experience has shown that the recommended data format and message structure were generally sound, and that the 25% overhead required for the parity coding guarantees a highly robust channel for the differential GPS corrections.

The results of usage of the RTCM SC-104 standard have been highly successful. While 8-10 meters (95%) was originally targeted for shipboard applications, results have generally been better than 5 meters, often achieving 1-3 meters. These results have been obtained using the C/A code pseudorange measurements, with varying amounts of integrated Doppler smoothing. Real-time kinematic techniques will enable decimeter accuracy for those applications amenable to them.

Governments have taken advantage of the SC-104 standard by prescribing it as the format for publicly supported radiobeacon broadcasts of differential GPS corrections. Scandinavian and North American countries have announced plans to equip their coastal waters with these services. This medium is highly attractive because of its inexpensiveness and accessibility.

The major revisions in Version 2.1 have been the following:

1. Update chapters 1-3, and add a section on GLONASS
2. To allow service providers to define the meaning of the station health field
3. To fix some message types previously designated as tentative, and to add new messages which support real-time kinematic applications.
4. Provide additional guidance material in Chapter 5 and Appendices I-IV.

There is additional work currently in progress to address messages to support differential GLONASS, provide guidance for interfacing between radiobeacon-based data links and GPS receivers, and to provide standards for ground-based radiobeacon differential GPS stations. Documentation on these topics will be released as the work is completed.

## TABLE OF CONTENTS

# 1. INTRODUCTION

## 1.1 SUMMARY

The Global Positioning System (GPS) is a satellite-based positioning system which is currently providing global service nearly 24 hours each day. It is expected to become operational in late 1993. Differential GPS service, which achieves high accuracies by providing corrections to the GPS satellite ranging measurements, is accomplished by broadcasting corrections from a reference station placed at a known location. The RTCM Special Committee 104, (SC-104), Differential GPS Service, has examined the technical and institutional issues, and has formulated recommendations in the following areas:

(1) Data Message and Format - The message elements that make up the corrections, the status messages, the station parameters, and ancillary data are defined in some detail. They are structured into a data format similar to that of the GPS satellite signals, but a variable-length format is employed.

(2) User Interface - A standard interface is defined which enables a receiver to be used in concert with a variety of different data links. For example, using the standard, a receiver can be used with a satellite link or a radiobeacon data link.

A number of different messages have been defined in the Data Message and Format area, with different levels of finality. Some message types have been "fixed", i.e., they will not be subject to change. If, for some reason that emerges in the future, they prove inadequate, new messages will be defined to accommodate the new situations; however, the message structure is considered fixed for Version 2. Some message types are considered tentative, and may be fixed (in their current or altered form) at some future time, if field experience with them justifies it. Still other message types have been reserved for specific use, but their content has not been defined or proposed. The other types are available for future definition, and can be used by service providers who want to provide specially tailored messages.

There are two institutional issues that have not yet been resolved: (1) Who assigns the station identification numbers? and (2) Who assigns message types for special-purpose service providers? Up to the time of this publication, each service provider has been free to assign station identification numbers at will, and confusion has been avoided because the data links have been distinct, and have not interfered with each other. It may prove necessary at some future time to coordinate this assignment process, in which case RTCM could act as the coordinating body.

The Committee has attempted to accommodate the widest possible user community, including not only marine users, but land-based and airborne users as well. Both radiolocation and radionavigation applications are supported. Provision is made for ultra-high accuracy static and kinematic techniques that enable decimeter relative positioning. A standard data link interface is defined which will enable a receiver to utilize different data links to receive corrections.

It is expected that the RTCM SC-104 format will support the most stringent and unique applications of this high-accuracy positioning technique.

## 1.2 BACKGROUND - NAVIGATION AND POSITIONING SERVICES

### 1.2.1 General

Navigation and positioning systems are used extensively in governmental and commercial activities for a variety of purposes. Radio signals have been used for decades to provide homing references and lines of position. International agreements governing use of the radio frequency spectrum include provisions for such usage, with allocations set aside for radionavigation and radiolocation services. In considering applications of radionavigation and radiolocation as used in this document it is important that the terms be understood in the sense of the definitions contained in the Radio Regulations of the International Telecommunication Union (ITU). Article 1 of the Radio Regulations contains the following definitions:

- Radiodetermination: The determination of the position, velocity and/or other characteristics of an object, or the obtaining of information relating to these parameters, by means of the propagation properties of radio waves.
- Radionavigation: Radiodetermination used for the purposes of navigation, including obstruction warning.
- Radiolocation: Radiodetermination used for purposes other than those of radionavigation.

In the United States the Federal government has long been a provider of navigation services to the general public, especially supporting air and maritime commerce. The responsibility for civil navigation is now vested in the U.S. Department of Transportation (DOT). In addition, the Department of Defense (DoD) provides navigation services to military users. Some DoD systems are used by the civilian community. The Federal Radionavigation Plan of the U.S. government is issued periodically by the DOT and DoD to reflect the policies for the implementation and operation of radionavigation systems used by both the military and civil sectors.

### 1.2.2 Current Radionavigation Systems

There are a number of radionavigation systems currently in operation which find extensive usage in the civil sector. Each has particular features which make it attractive for certain users. When the Global Positioning System (GPS) becomes operational, some of the current systems may be terminated, since the services they provide will also be provided by GPS.

### A. LORAN-C

LORAN-C was originally developed to provide military users with a radionavigation capability having much greater coverage and accuracy than its predecessor, LORAN-A. It was subsequently selected as the federally provided radionavigation system for civil marine use in the U.S. coastal areas. It has also been installed in a number of other areas around the world. New stations have been recently deployed in the United States to support aviation navigation throughout the country and across southern Canada. New systems are being installed and expanded in Europe, Japan and China as well.

LORAN-C is a pulsed, hyperbolic system operating at a center frequency of 100 kHz. LORAN stations are arranged in "chains", each composed of a minimum of three stations. These chains provide reliable ground-wave service over large areas, typically 1000 nautical miles across. The coverage area can be extended by use of more sensitive receivers. Within the United States, LORAN-C is maintained by the U.S. Coast Guard. LORAN service is provided 24 hours a day, and is available more than 99% of the time within the stated coverage areas. Accuracy is relatively stable with time, but varies with location. Absolute accuracy (95%) is specified to be 0.25 nm (0.46 km), but relative and repeatable accuracy is much better, typically 20-100 meters.

The FAA and U.S. Coast Guard jointly sponsored expansion of the LORAN-C system to close the mid-continent coverage gap in the United States. This project was completed in June of 1991, providing LORAN-C coverage throughout the continental U.S. and coastal areas. LORAN-C is the chief system in use for coastal maritime radionavigation, and is used extensively by general aviation. The Federal Aviation Administration (FAA) has accepted LORAN-C as a supplementary enroute navigation system.

Efforts have been made by the US and Russia to form a joint Russia/American Bering Sea Radionavigation Chain. Once completed, the 500 nautical mile wide coverage gap which currently exists between the CHAYKA Eastern Chain and the North Pacific LORAN-C chain in the Bering Sea will be closed. The joint chain is comprised of the U.S. LORAN station at Attu, Alaska, and two CHAYKA facilities in Russia at Petropavlovsk and Aleksandrovsk. CHAYKA closely emulates LORAN in signal characteristics and provides the same navigation service. The joint LORAN/CHAYKA Chain is currently in a test/evaluation stage.

The wide areas covered by LORAN and the availability of inexpensive receivers make it attractive for vehicle tracking, and a number of trucking companies utilize LORAN-C. While land users are not currently numerous, there are many potential uses of LORAN-C.

## B. VOR, VOR/DME, TACAN

The three systems that provide the basic guidance for enroute air navigation in the U.S. are VHF Omni-directional Range (VOR), Distance Measuring Equipment (DME), and Tactical Air Navigation (TACAN). VOR provides bearing with respect to the ground installation, DME similarly provides range, and TACAN provides both, primarily to military users.

Since these are line-of-sight systems operating at VHF/UHF, ground coverage is quite limited, but at 20,000 foot (6100 meters) altitude their signals can be received to typically 200 nm (370 km).

Due to the large network of ground installations, the coverage and availability over the U.S. is quite high. If one ground station fails, the overlapping coverages of the nearby facilities insure that navigation service is still available over most of the coverage area. Most of the U.S. is covered by the network, although there are some remote and mountainous regions where low-altitude coverage is not available. Due to advanced solid state construction and the use of remote maintenance monitoring techniques, the reliability of the solid state VOR transmitters approaches 100%.

The absolute accuracy of the VOR system (2 sigma) is typically 1.4 degrees, which translates to 0.25 nm (.46 km) at a range of 10 nm (18 km), or 2.5 nm (4.6 km) at 100 nm (180 km). Relative and repeatable accuracy figures are typically 0.35 degrees. The DME ranging system is good to 0.1 nm (0.18 km) (2 sigma), absolute, relative and repeatable. TACAN performance is similar.

## C. DECCA

The DECCA NAVIGATOR system is a major navigation system for air and maritime users, with facilities in Western Europe, the Baltic Area, South Africa, the Arabian Gulf, India, Japan and Australia. Like LORAN-C it is a hyperbolic system which uses time-delay differences between three or more stations to establish horizontal position. The user measures signal phase differences, resolving ambiguities by utilizing periodic, simultaneous, synchronized transmissions of several frequencies, one from each station in a cluster (multipulse). For position fixing modern receivers use either the normal tracking and/or the multipulse signals. The multipulse signal improves the night performance and is used in simple low-cost receivers. Cross chain fixing receivers are used widely. A few chains are specially sited and calibrated for harbor and harbor approach.

There are five sub-bands of operation, all at LF. They are located in two bands: one at 70-90 kHz, the other at 110-130 kHz. The accuracy of the systems is about 20-50 meters at ranges of up to 120 nm (220 km). Due to sky-wave limitations the nighttime accuracy degrades at ranges beyond 120 nm. Depending on station separation, accuracy beyond 120 nm degrades to typically 500 meters.

## D. RADIOBEACONS

Radiobeacons are nondirectional radio transmitting stations which operate in the low frequency (LF) and medium frequency (MF) bands to provide ground wave signals to a receiver. A radio direction finder (RDF) is used to measure the bearing of the transmitter with respect to the aircraft or vessel. Radiobeacons are widely used throughout the world.

Radiobeacons operate in the following bands: aeronautical non-directional beacons, or NDBs, 190-415 kHz and 510-535 KHz; maritime radiobeacons, 283.5-325 kHz. Bearing accuracy is largely dependent on the RDF receiver design, but typical accuracies are about 3 degrees (2 sigma). This translates into 0.5 nm at 10 nm, and about 2.5 nm at 50 nm from the station.

Radiobeacons are relatively inexpensive to install and maintain. As a result, coastal waters around the world have transmitters, and most vessels have receivers. While coastal coverage is not continuous everywhere, it is sufficient to enable a mariner to obtain frequent fixes or lines of bearing at a low cost.

Airborne units are automatic, and heading-to-station information is displayed as a needle indicator, with straight-up (zero degrees) indicating the station to be directly ahead of the aircraft. In the U.S. the network provides enough coverage that an aircraft is usually within range of at least one NDB. Most aircraft are equipped with NDB receivers.

## E. TRANSIT

TRANSIT is a space-based radiodetermination system consisting of four or more satellites in approximately 600 nm polar orbits. Users can obtain a fix every 1-3 hours when a satellite comes into view. Satellites are typically visible for about 20 minutes; only one is required to get a fix.

Coverage of TRANSIT is world-wide. Since the orbits are polar, satellite availability varies from about 20% at the equator to 45% near the poles. The system uses two frequencies: 150 MHz and 400 MHz. Only one frequency is required to get a fix, but the effect of the ionosphere can be essentially eliminated by the use of two frequencies.

Accuracy of TRANSIT depends on the number of passes used to compute position and whether a single or dual frequency receiver is used. With a single satellite pass using a single frequency receiver, an accuracy of about 500 meters (2drms) is achievable; a dual frequency receiver will provide about 25 meters. By incorporating a simultaneous measurement by a receiver at a known location (a differential technique, called "translocation"), 10 meters accuracy is possible. This can be improved to better than 5 meters for fixed sites, where multiple satellite measurements are used over a period of time.

TRANSIT is operated by the U.S. Navy for military use, but there are currently thousands of civil users. It is anticipated that operation of TRANSIT will be terminated at the end of 1996.

## F. GPS

The Global Positioning System (GPS) was developed by the Department of Defense under Air Force Management through the GPS Joint Program Office at the USAF Space Division. It is expected that by mid-1993, 24 satellites will be operating. At this point, the Secretary of Defense will declare an Initial Operational Capability, as the constellation will provide 24 hour, worldwide radionavigation service. The satellites that will make up the constellation when Initial Operating Capability is declared in 1993 will consist primarily of Block II satellites, but those Block I satellites which are still operating will be utilized. As they fail, they will be replaced by Block II satellites to maintain 24 satellites. Subsequently, the DoD will pursue a replacement program that supports a 98% availability of at least 21 satellites.

GPS is a coarse/fine system which uses the coarse signal (C/A code) for acquisition and data, and the fine system (P-code) for high-accuracy military navigation and positioning. It is the present policy of the U.S. government to provide a Standard Positioning Service (SPS) at a 100 meter (95%) accuracy level without restriction to the international civilian user community. The SPS is provided using the C/A code portion of the GPS signals.

The planned constellation consists of 24 satellites in 6 orbital planes of 4 satellites each. The orbital planes are oriented at about 55 degrees from equatorial. Each satellite transmits at the same frequency, but employs a unique code. The signals are of the spread spectrum type, using biphase coding with a chipping rate of 1 MHz and a repeating sequence of 1023 chips. The frequency of operation is 1575.42 MHz for the Standard Positioning Service (SPS).

In addition to the signal described above, military sets will have access to the two-frequency Precise Positioning Service (PPS), which employs very long, encrypted sequences to ensure security of transmission. The second frequency increases the accuracy because the effects of the ionosphere can be ameliorated.

The satellites transmit data at a 50 bps rate. The data message provides health status, identification, ephemeris (orbital) information, satellite clock correction, ionospheric correction coefficients, and a host of other data. The ephemerides of the satellites are referenced to the DoD's World Geodetic System of 1984 (WGS-84).

A user receiver times the arrival of each satellite signal by synchronizing an internal signal having that satellite's code with the satellite signal (code-tracking). Knowledge of the satellite's position is derived from the data transmission. This knowledge, along with the time-of-arrival measurements from 4 or more satellites, enables the user to estimate his position and time. In addition to the code-tracking measurement, it is also possible to phase-lock onto the carrier. This enables a similar estimate of velocity. Advanced processing techniques use the carrier phase measurements to improve position estimates.

There are a number of different receiver design techniques, each tailored to different operating environments. They can be grouped into three basically different approaches; multi-channel parallel, single-channel multiplexed, and single (or dual) sequential designs. In the multi-channel parallel design, each channel is dedicated to one satellite. In the multiplex design, each satellite signal is sampled very rapidly; it has the multi-channel feature of essentially continuous tracking, with a loss of signal-to-noise ratio. In the sequential design, the receiver dwells for a short time on each satellite. There are variations: some multi-channel designs employ a fifth channel to pre-track the next rising satellite. A dual-channel design for multiplex or sequenced receivers enables the second channel to quickly acquire satellite data. Due to the fact that the cost for additional channels is becoming a small fraction of the overall receiver costs, it is expected that most new receivers will be multi-channel.

The possibility of having a navigation instrument which can be used everywhere, which is available 24 hours a day, and which provides 100 meter accuracy, is a prospect which will be welcomed in many quarters of the user community. However, there are other interests that would like much greater accuracy for their applications. For them, differential GPS may offer an economically viable solution.

## G. GLONASS

Developed and operated by Russia, the Global Navigation Satellite system (GLONASS) is similar to the US GPS in that it is a space-based navigation system providing global, 24 hour, all-weather access to precise position, velocity and time information to a properly equipped user. Fully deployed, it will consist of 24 satellites in 3 orbital planes at 19,100 km altitude, corresponding to an 11h 15m period. Orbital inclination is 64.8 degrees, as opposed to the 55 degrees of GPS. As with GPS, each GLONASS satellite continuously broadcasts its own precise position (ephemeris) as well as less precise position information for the entire constellation (almanac). While like GPS the almanac consists of orbital parameters, GLONASS ephemeris data are in the form of Earth-Centered-Earth-Fixed (ECEF) position, velocity and lunar/solar-induced acceleration. In addition, GLONASS ECEF coordinates are referenced to the SGS-85 datum, not the WGS-84 datum used by GPS. Although the GLONASS control segment is similar in purpose and function to its GPS counterpart, less is known about it in the West. Parallel, multiplexed, and sequential receiver designs are possible, but most receivers are expected to be multichannel.

Each GLONASS satellite uses two carrier frequencies in the L band, which, contrary to the GPS implementation, are different for each satellite. The L1 band ranges from 1602.5625 MHz to 1615.5 MHz in jumps of 0.5625 MHz, while the L2 band ranges from 1246.4375 MHz to 1256.5 MHz in steps of 0.4375 MHz. Each of these signals is modulated by either or both of a 5.11 MHz precision (P) signal and/or a 0.511 MHz coarse/acquisition (C/A) signal. The binary signals are formed by a P-code or a C/A-code which is modulo-2 added to L1 in phase quadrature (only P is present on L2). The P code is a pseudorandom sequence with a period of one second, while the C/A code is a pseudorandom sequence with a period of 1 ms. Contrary to GPS where all codes are unique to a specific satellite, a single GLONASS code is used for all satellites. GLONASS receivers duplicate the P and/or C/A codes and the transmission time is determined by measuring the offset that is to be applied to the locally generated code to synchronize it with the code received from the satelite. For unauthorized users, the accuracy achievable with GLONASS is actually superior to that achievable with GPS since there is no Selective Availability implementation on GLONASS.

As of May 1993 there are twelve operational GLONASS satellites in orbit, with plans to launch six more in 1993. At any earth location, four or more satellites are visible above the horizon for at least 20 hours a day. Full deployment is anticipated to occur in 1995.

The accuracy achievable with GLONASS has not yet been fully demonstrated, as the SGS-85 to WGS-84 transformation still needs to be defined. Early tests with the C/A code indicate a bias on the order of 0 to 10 meters and a dispersion of 5 to 15 meters. No data are yet available for the P code accuracy. Velocity accuracy of 0.3 knots have also been observed.

GLONASS time is related to UTC(SU) whereas GPS time is related to UTC(USNO).

A differential GLONASS implementation for both the code and carrier phase is obviously both useful and feasible. It is the intent of this committee to issue DGLONASS standards in the near future.

## H. RADIOLOCATION SYSTEMS

There are a number of radiolocation systems privately developed and operated. They operate in the radiolocation frequency bands using a variety of measurement techniques. A partial list of these systems and their frequencies of operation are given below, approximately in order of decreasing range.

| | |
|---|---|
| Pulse 8 (Racal) | 100 kHz |
| Geoloc (Sercel) | 1600-2300 kHz |
| TORAN (Sercel) | 1800-2000 kHz |
| SPOT (ONI) | 1700-2100 kHz |
| Raydist-N/RAC (Hastings) | 3300 kHz, 1650 kHz |
| Raydist-DRS (Hastings) | 3300 kHz, 1650 kHz |
| Hyperfix (Racal) | 1600/3400 kHz |
| ARGO (Cubic) | 1646.7 kHz |
| Hydrotrac (Odom) | 1720 kHz |
| Maxiran (Maxiran) | 430 MHz |
| Syledis (Sercel) | 430 MHz |
| Microfix (Racal) | 5520/5560 MHz |
| Mini-Ranger (Motorola) | 5570/5480 MHz |
| Trisponder (Del Norte) | 9480/9325 MHz |

Each of these systems has its areas of application, its strengths and weaknesses. They are used where radiodetermination coverage is not available, not accurate enough, or not available continuously.

## 1.3 DIFFERENTIAL GPS DESCRIPTION

Differential operation of the GPS offers the possibility of accuracies of 1-10 meters for dynamic, navigation applications. Utilizing kinematic carrier phase techniques, differential GPS can achieve accuracies better than 10 cm for short baselines, i.e., less than about 20 km. The basic concept of differential GPS is similar to that employed in differential LORAN-C, differential OMEGA, and the translocation mode using TRANSIT. A reference receiver is placed at a known, surveyed-in point. By comparing the known location with that predicted by the GPS, corrections can be determined. These corrections can then be broadcast to nearby users, who use them to improve their position solutions. The differential technique works if the preponderant errors are bias errors due to causes outside the receiver. This is the case for GPS. The major sources of error are the following:

1. Selective Availability errors - artificial errors introduced at the satellites for security reasons. Pseudorange errors of this type are about 30 meters, 1-sigma. PPS users have the capability to eliminate them entirely.

2. Ionospheric delays - signal propagation group delay, which is typically 20-30 meters during the day to 3-6 meters at night. In two-frequency operation this effect is largely removed by applying the inverse square-law dependence of delay on frequency.

3. Tropospheric delays - signal propagation delays caused by the lower atmosphere. While the delays are as much as 30 meters at low satellite elevation angles, they are quite consistent and modellable. Variations in the index of refraction can cause differences (between reference station and user) in signal delays of 1-3 meters for low-lying satellites.

4. Ephemeris error - differences between the actual satellite location and the location predicted by the satellite orbital data. Normally these are quite small, less than 3 meters, but they could be more than 30 meters under Selective Availability.

5. Satellite clock errors - differences between the satellite clock time and that predicted by the satellite data. The oscillator that times the satellite signal is free-running; the GPS ground control station monitors it, and establishes corrections, which are sent up to the satellite to set the data message. The user reads the data and adjusts the signal timing accordingly.

Satellite clock errors are completely compensated by differential operation, as long as both reference and user receivers are employing the same satellite data. Ephemeris errors, unless they are quite large (30 meters or more) are similarly compensated by differential operation. Selective Availability errors affecting the timing of the signals are also compensated by differential operation, except that the corrections lose their validity after a period of time. For users near the reference station, the respective signal paths to the satellites are sufficiently close so that compensation is almost complete. As the user-reference station separation is increased, the different ionospheric and tropospheric paths to the satellites may be sufficiently far apart that the atmospheric inhomogeneities cause the delays to differ somewhat. To the extent they differ, they constitute an error in the differential GPS measurement, called spatial decorrelation. This type of error will be greater at larger user-station separations.

Differential GPS also provides an integrity monitoring function which detects or ameliorates large satellite signal errors.

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# 2. THE NEED FOR DIFFERENTIAL GPS SERVICE

## 2.1 GENERAL

GPS and GLONASS will provide global, 24-hour-a-day, highly accurate navigation and positioning service over the entire world, a set of capabilities which are significantly better than other radiolocation and radionavigation systems. For example, LORAN-C, and DECCA provide similar accuracy service continuously, but only in certain equipped regions of the world. Omega provides global and continuous service, but the service is 30-70 times less accurate. TRANSIT provides global, high-accuracy service, but it is intermittent. Radiolocation systems are usually local.

Most radiolocation and radionavigation systems can be operated in a differential mode (if they aren't inherently so), and consequently provide improved accuracy. GPS is no exception. To provide differential coverage anywhere, it is only necessary to establish a reference station, with an appropriate data link or data link network.

The features of continuous service, high update rate, and potentially large coverage areas make it possible for differential GPS to provide "real-time" positional information that could be obtained otherwise only in a "post-processing" mode of operation.

This combination of capabilities of differential GPS make it very attractive for a variety of applications. As the price of receivers falls to the level of competing systems, many users will choose GPS. It can be confidently anticipated that many new applications will be found which exploit these unique capabilities.

The following sections describe some of the applications of differential GPS that have been identified by the user community. The requirements have been developed from the Federal Radionavigation Plan (FRP, DoD/DOT, 1992, Part 2), from RTCM members who have specific requirements, from published papers, from a telephone survey, and from a questionnaire sent out from the RTCM. Tables 2-1 to 2-3, taken from the FRP, give a summary of the maritime user requirements in the oceanic, coastal and harbor approach/harbor areas.

## 2.2 NAVIGATION AND GUIDANCE APPLICATIONS

### 2.2.1 Marine Navigation

The ability of GPS to provide global coverage with an accuracy of 100 meters is expected to make it very attractive to ships that sail in international waters. Even without differential operation, the navigation service is adequate for oceanic and coastal marine operations. The FRP (1992, pp. 2-26 to 2-28) cites the requirements for oceanic and coastal navigation accuracy as 0.25 nm (0.46 km).

# TABLE 2-1. CIVIL MARINE REQUIREMENTS – OCEAN PHASE*

| REQUIREMENTS | MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ACCURACY (2 drms) | | | COVERAGE | AVAILABILITY | RELIABILITY | FIX INTERVAL | FIX DIMENSION | SYSTEM CAPACITY | AMBIGUITY |
| | PREDICTABLE | REPEATABLE | RELATIVE | | | | | | | |
| SAFETY OF NAVIGATION - ALL CRAFT | 2-4nm (3.7-7.4km) minimum 1-2nm (1.8-3.7km) Desirable | - | - | Worldwide | 99% fix at least every 12 hours | ** | 15 minutes or less desired; 2 hours maximum | Two | Unlimited | Resolvable with 99.9% confidence |

| BENEFIT | MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| LARGE SHIPS MAXIMUM EFFICIENCY | 0.1-0.25nm* (185-460m) | - | - | Worldwide, except polar regions | 99% | ** | 5 minutes | Two | Unlimited | Resolvable with 99.9% confidence |
| RESOURCE EXPLORATION | 10-100m* | 10-100m* | - | Worldwide | 99% | ** | 1 minute | Two | Unlimited | Resolvable with 99.9% confidence |
| SEARCH OPERATIONS | 0.1-0.25nm (460m) | 0.25nm | 185m | National maritime SAR regions | 99% | ** | 1 minute | Two | Unlimited | Resolvable with 99.9% confidence |

* Based on stated user need
** Dependent upon mission time

# TABLE 2-2. CIVIL MARINE REQUIREMENTS – COASTAL PHASE*

| REQUIREMENTS | MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | ACCURACY (2 drms) | | COVERAGE | AVAILABILITY | RELIABILITY | FIX INTERVAL | FIX DIMENSION | SYSTEM CAPACITY | AMBIGUITY |
| | PREDICTABLE | REPEATABLE | | | | | | | |
| Safety of Navigation - All Ships | 0.25nm (460m) | - | U.S. coastal waters | 99.7% | ** | 2 minutes | Two | Unlimited | Resolvable with 99.9% confidence |
| Safety of Navigation - Recreation Boats & Other Smaller Vessels | 0.25nm-2nm (460-3,700m) | - | U.S. coastal waters | 99% | ** | 5 minutes | Two | Unlimited | Resolvable with 99.9% confidence |
| BENEFITS | MEASURES OF MINIMUM PERFORMANCE CRITERIA TO ACHIEVE BENEFITS | | | | | | | | |
| Commercial Fishing (Including Commercial Sport Fishing) | 0.25nm (460m) | 50-600 ft (15-180m) | U.S. coastal/ fisheries areas | 99% | ** | 1 minute | Two | Unlimited | Resolvable with 99.9% confidence |
| Resource Exploration | 1.0-100m* | 1.0-100m* | U.S. coastal areas | 99% | ** | 1 second | Two | Unlimited | Resolvable with 99.9% confidence |
| Search Operations, Law Enforcement | 0.25nm (460m) | 300-600 ft (90-180m) | U.S. coastal/ fisheries areas | 99.7% | ** | 1 minute | Two | Unlimited | Resolvable with 99.9% confidence |
| Recreational Sport Fishing | 0.25nm (460m) | 100-600 ft (30-180m) | U.S. coastal areas | 99% | ** | 5 minutes | Two | Unlimited | Resolvable with 99.9% confidence |

* Based on stated user need
** Dependent upon mission time

# TABLE 2-3. CIVIL MARINE REQUIREMENTS – HARBOR APPROACH & HARBOR PHASES*

| REQUIREMENTS | MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ACCURACY (meters, 2 drms) | | COVERAGE | AVAIABILITY | RELIABILITY | FIX INTERVAL | FIX DIMENSION | SYSTEM CAPACITY | AMBIGUITY |
| | PREDICTABILE | REPEATABLE | | | | | | | |
| SAFETY OF NAVIGATION - LARGE SHIPS & TOWS | 8-20*** | - | U.S. harbor & harbor approach | 99.7% | ** | 6-10 seconds | Two | Unlimited | Resolvable with 99.9% confidence |
| SAFETY OF NAVIGATION - SMALLER SHIPS | 8-20 | 8-20 | U.S. harbor & harbor approach | 99.7% | ** | *** | Two | Unlimited | Resolvable with 99.9% confidence |
| RESOURCE EXPLORATION | 1-5* | 1-5M*- | U.S. Harbor & harbor approach | 99% | ** | 1 second | Two | Unlimited | Resolvable with 99.9% confidence |

| BENEFITS | MEASURES OF MINIMUM PERFORMANCE CRITERIA TO ACHIEVE BENEFITS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| FISHING RECREATIONAL AND OTHER VESSELS | 8-20 | 4-10 | U.S. harbor & harbor approach | 99.7% | ** | *** | Two | Unlimited | Resolvable with 99.9% confidence |

* Based on stated user need
** Dependent upon mission time
*** Varies from one harbor to another. Specific requirements are being reviewed by the Coast Guard
* From U.S. Federal Radionavigation Plan, 1992, p. 2-26.

In the restricted channels of some harbors and inland waterways, however, more accuracy is required, and a monitoring function is needed to assure the integrity of the satellite signals. The FRP calls for 8-20 meters (95%) in the Harbor and Harbor Approach phases of navigation (Table 2-3).

Without differential operation, the absolute (predictable), repeatable, and relative accuracies of GPS are all about 100 meters (95%), which is not sufficiently accurate for harbor navigation. With differential GPS operation it is possible to meet these requirements. Extensive testing by the U.S. Coast Guard R&D Center has shown that 5 meter accuracy (95%) has been consistently achieved.

Maneuvering in Harbor and Harbor Approach areas to effect safe passing of ships requires knowledge of lateral position and lateral drift. In the presence of SA, GPS receivers can provide velocity information with accuracy of about 2 knots. Differential GPS may also be used to correct speed and lateral drift to 0.2 knots (2-sigma) or better. In a harbor channel with several turns, waypoint navigation will be used, and this type of navigation requires lateral position relative to a track, lateral drift, and time-to-waypoint. How these translate into accuracy requirements will require a considerable number of trials and tests. However, the basic accuracy and high-dynamics capability of GPS show promise that such stringent waypoint navigation will be achieved.

Inland waterway navigation, such as along the St. Lawrence Seaway, could benefit considerably from differential GPS service. In addition to providing guidance during periods of low visibility, it may prove possible to extend the period of safe passage by several weeks. Currently navigational buoys are removed during the winter, and there are several weeks during which passage is restricted not by ice, but by the absence of the buoys.

Fishermen have found that ground-based navigation systems are providing navigation and positioning service to repeatable accuracies of better than 100 meters (95%). They are unlikely to find GPS attractive unless differential operation is capable of providing good repeatability and accurate speed over ground.

### 2.2.2 Air Navigation

Except for the Precision Landing phase of air navigation, there is no requirement in the National Airspace System (NAS) for accuracies better than 100 meters (95%). Precision Landing requires highly accurate vertical guidance (3 meters, 2-sigma) as well as accurate lateral guidance (4-9 meters, 2-sigma) (FRP). Some advanced techniques show promise of meeting these requirements with differential GPS, and real-time kinematic techniques certainly can meet the accuracy requirements. (It remains to be shown that real-time kinematic techniques can work quickly and reliably enough in the aeronautical environment.)

However, there are air applications outside the NAS which may prove useful to some airborne users. In remote areas where the current air navigation system does not provide coverage, or in offshore areas such as the Gulf of Mexico, differential operation would provide highly accurate guidance as well as serve a monitoring function to assure the integrity of the satellite signals. Also, the current air navigation system does not extend to the earth's surface in most areas. Differential GPS is a viable technique for locating aircraft and airport vehicles on an airport surface.

Another application is agricultural operations such as crop spraying. These often take place at night. The pilot flies close to the ground, using flagmen to provide visual reference. Differential GPS could provide the aircraft with accurate guidance along the desired tracks.

### 2.2.3 Land Navigation and Vehicle Tracking

Land navigation is a relatively unexplored area, but one which will probably prove to have the largest market potential. Already, the automobile manufacturers in the U.S. are investigating LORAN-C and GPS receivers, and dead-reckoning instruments as navigation inputs to displays (visible and audible) to help travelers find their destinations. With differential GPS the user could distinguish the particular home or building he or she was seeking, which could be helpful at night when address numbers are difficult to see. Emergency vehicles, police cars, and delivery services will find this capability very useful.

When coupled with improved land mobile communication services which are also being developed, the locations of vehicles can be radioed to dispatching or fleet control centers. Urban, rural and state police forces, bus, trucking and taxi fleets, and trains can benefit from such a service. There already exist automatic vehicle locator systems currently in use. At first glance it does not appear that differential GPS accuracies would be required for such applications. However, without differential service it may prove difficult to unambiguously identify the street the vehicle is on, while with differential service there would be no doubt. Most potential users of vehicle tracking want the additional accuracy that differential GPS provides.

## 2.3 RADIOLOCATION APPLICATIONS

### 2.3.1 Marine Surveying Applications

A major use of differential GPS is in exploration of the geological layers below the ocean floor for oil and natural gas deposits. Geophysical survey companies previously relied on radio signals transmitted from TRANSIT satellites and terrestrial radiolocation systems to determine the position of their survey vessels in real time. The need for position determinations of increased accuracy, as well as the need to obtain these accurate determinations farther and farther from shore has pushed the survey industry to the limits of the available technology.

To the marine surveyor, the TRANSIT satellite system, providing position fixes on an irregular basis and only every hour or so, is useful to check the accuracy of real-time navigation solutions determined by other means. However, even under the most favorable circumstances, the

TRANSIT system is not capable of providing real-time position fixes which meet the accuracy requirements of modern geophysical surveys.

Neither the Omega nor the LORAN-C networks are capable of providing the positioning accuracy necessary for modern surveys. Many survey vessels do, however, compare the received LORAN-C signals to the output of a shipboard atomic time standard in order to derive an independent estimate of the ship's velocity over the earth.

Most of the positioning services used for offshore geophysical surveys and mentioned in Chapter 1 involve LF, MF, HF, VHF, UHF, or SHF radio signals transmitted from fixed stations on shore, offshore platforms or tightly-moored buoys. A survey must be planned so that the survey vessel is always within radio range of several stations and the distribution of these stations must be such that the lines of position generated cross at favorable angles. Lines of position are developed from measurements of the round-trip travel time of a radio signal from the vessel to a station and back, or from measurements of the relative arrival time or the relative phase of radio signals which arrive at the vessel from several stations.

These systems are limited in useful range by propagation characteristics. They exhibit problems associated with transmitting signals along the earth's surface, including shadowing due to the earth's curvature, as well as interference from reflections from the ionosphere (skywave interference). They require multiple transmitter sites which must be located in a favorable geometry relative to the survey area. Many of these systems can service only a limited number of vessels.

Differential GPS positioning is now being used as an alternative to these radiolocation systems. The position accuracies have shown to be comparable to or better than the systems they replace. Positioning with differential GPS can be achieved using corrections from a single reference site and position accuracy is limited only by the quality of the GPS equipment, data link characteristics, and separation between the reference site and the user.

There are many phases to oil and gas exploration which require accurate positioning. They are:

- Exploration
  - Hydrographic surveying
  - Target reconnaissance
  - Conventional seismic surveying
  - 3D seismic surveying
  - Well site surveying
  - Pipeline surveying
- Appraisal drilling -- structure verification
- Acoustic device positioning

- o Field development
    - Reservoir delineation
    - Rig positioning
- o Production -- developing field
- o Post-production -- jacket removal and site clearance
- o Geodetic control -- site location of land-based stations

Civil oceanography applications of differential GPS include the measurement of ocean currents, marine geology, and geophysics. Positional accuracies of 3-30 meters (95%), and velocity accuracies of a fraction of a meter/second are cited by the users as requirements. Only a few hundred users are anticipated worldwide. There may be difficulty in achieving the required accuracy in high sea states because of the vessel dynamics and the possible signal loss-of-lock which can occur as the antenna orientation varies.

Deep sea mining requires accurate maps of the ocean floor, and accurate platform positioning. Differential GPS accuracies will be beneficial, but the distance of the operations from a fixed reference station may prove problematic, due to accuracy degradation at large user-reference separations.

Hydrographic surveying in support of charting applications includes shoal location and location of hazards to navigation. Here, 5-meter (95%) accuracy is desired, a value consistent with large chart scales (i.e., 1:10,000 or larger).

Coastal and channel engineering, including dredging operations, breakwater construction, harbor design, and harbor maintenance need differential GPS. Surveys conducted by the harbor authority, the Army Corps of Engineers in the United States, to support dredging operations cite the need for meter-level accuracy in horizontal position. It is considered highly desirable to have differential GPS replace tidal gauges, an application where real-time kinematic techniques will be required to meet the decimeter accuracy requirement.

Other marine applications requiring differential GPS accuracies include, buoy positioning, buoy position verification, cable layout and repair, and commercial fishing. Commercial fisherman are primarily interested in repeatable accuracies, so that they can return to favorable fishing spots. With 20-meter (95%) repeatable accuracies, easily achievable with DGPS, lobster fishermen can submerge their trap markers to reduce poaching. Net retrieval and the avoidance of net damage are also made simpler by high-accuracy positioning.

### 2.3.2 Other Surveying Applications

The ability to obtain real-time, high-accuracy position fixes will be a great boon to land surveys. Survey markers are frequently bulldozed over, vandalized, or difficult to locate. In remote areas procedures are often time-consuming and subject to delays. Highway surveying, cadastral surveying, and geodetic surveying techniques will all be greatly simplified. Highway inventory, maintenance and traffic records can benefit from 10 meter accuracy as well. The number of possible users is believed to be in the thousands.

Differential GPS is expected to play a major role in land seismic surveys. Land seismic surveys are similar to offshore surveys, in that an acoustic wave is sent down into the ground, the reflected signals being picked up by sonophones strung out over the survey area. The acoustic wave is a frequency-modulated low-frequency signal generated by special vehicles called Vibe Trucks. By knowing where the Vibe Trucks and sonophones are, the geological layers can be mapped. 1-2 meter accuracy (95%) is required for land seismic applications.

The U.S. Census Bureau is particularly interested in using radiolocation techniques to identify township and county boundaries, and to locate homes that are off identified roads or which do not have addresses. The accuracy requirements have been estimated at 5-10 meters (95%).

## 2.4 SUMMARY

It is clear that there are a wide variety of applications which will immediately benefit from differential GPS service. It is also clear that once the service is available, new applications will be found by the business and scientific communities. It can safely be asserted that differential GPS will revolutionize the manner in which many important operations are performed. It is therefore essential to ensure that the necessary standards, frequency allocations, and institutional approvals are obtained now to make differential service available when GPS becomes operational.

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# 3. EQUIPMENT CONFIGURATION AND DESIGN REQUIREMENTS

## 3.1 GENERAL

Differential operation of GPS is achieved by placing a reference station with a GPS receiver at a known location, determining corrections to the satellite ranging signals, and broadcasting these corrections to users of the service. This removes most of the bias errors common to all receivers, and significantly improves the positional accuracy. The accuracy is then limited by user receiver noise, interchannel biases, and differential station uncertainty. The situation is shown in Figure 3-1.

The Committee decided early on that the corrections should be applied to the user pseudorange measurements, rather than to the measured positions, even though the message is considerably longer as a result. The reason for this is that user and reference station might use different satellites, for a number of reasons. If this happened, even if three out of four satellites were the same, the positional errors resulting from the one non-common satellite would be far too large. Reasons why different satellites might be employed include the following:

- The receiver criterion for selecting satellites could differ.
- Terrain or earth's curvature might block a low-lying satellite from the user or reference station.
- The user receiver might employ an all-in-view strategy, wherein all visible satellites are used to determine position.
- Satellites available at user location might differ from those available at reference location.

By broadcasting pseudorange corrections, any satellites that are visible to the reference station can be used by the user receiver in the differential mode to determine position.

## 3.2 REFERENCE STATION

### 3.2.1 Components

The reference station consists of a GPS sensor with antenna, a data processor, a data link transmitter with antenna, and interfacing equipment (see Figure 3-2). The GPS antenna is carefully surveyed to determine its phase center position. It and the data link antenna should be located for minimum blockage by surrounding buildings and terrain.

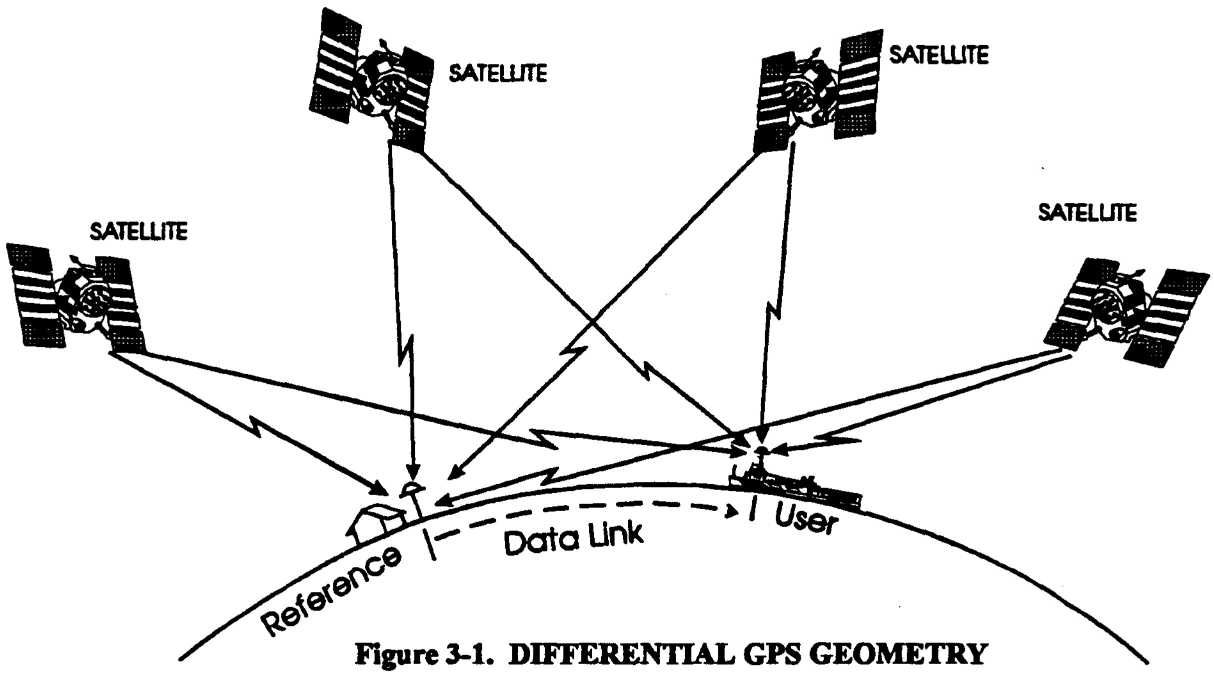


**Figure 3-1. DIFFERENTIAL GPS GEOMETRY**

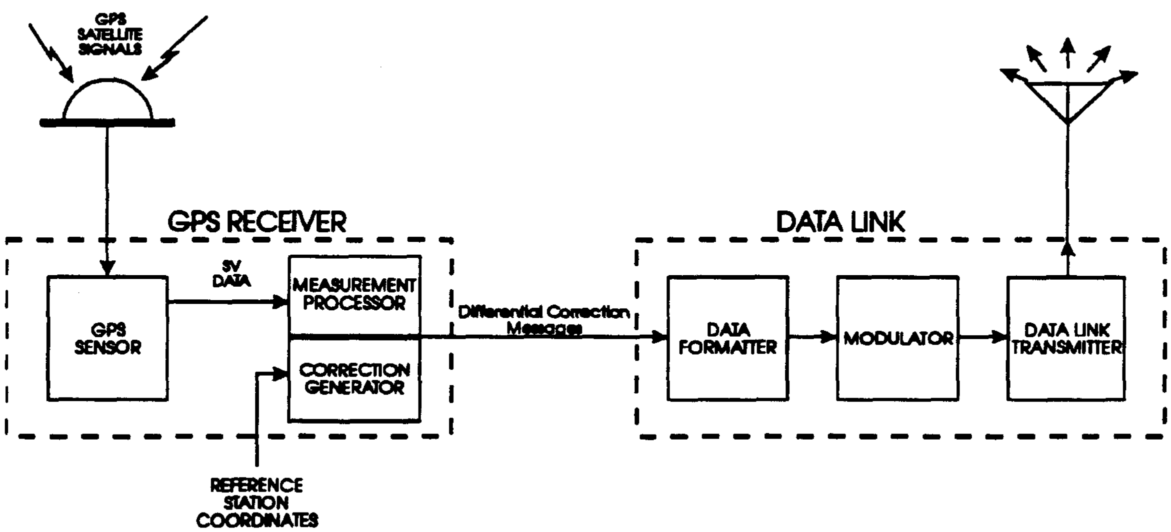


**Figure 3-2. DIFFERENTIAL REFERENCE STATION BLOCK DIAGRAM**

0092

### 3.2.2 Receiver Architecture

The ideal reference station sensor would be multi-channel, with a separate channel assigned to each satellite for which differential corrections are being generated. With the currently planned satellite constellation of 24 satellites, there will be as many as 11 satellites above the horizon. Consequently, an all-in-view receiver would be desirable. Another reason for continuously tracking each satellite is that the reference station should acquire the data on the satellite transmission sooner than the user receivers.

### 3.2.3 Satellite Acquisition

As a satellite rises, its signal will be received on one channel of the receiver. When the signal-to-noise ratio has reached an adequate level, and after the range measurement has stabilized sufficiently and pertinent data acquired, the station will broadcast the corrections for that satellite. It will continue to do so (as long as the satellite signal is deemed healthy) until the satellite has set. Sometimes as a satellite rises, its signal level may rise above the threshold, only to decrease before stabilizing; this is probably due to fading by specular reflection of the signal. Care will have to be taken to ensure that broadcast of the correction is not made prematurely. Any code/carrier filters should have time to settle, and the signal-to-noise should be high before corrections are generated. While a manufacturer may choose to implement a mask angle, there is no requirement to do so, as long as proper precautions are followed.

### 3.2.4 Method of Measurement

It is recommended that the reference receiver perform phase carrier tracking as well as code tracking. Code tracking is performed by aligning the time delay of an internal signal generator, phase modulated by the known code of the satellite, until it correlates with the satellite signal. The signal carrier can be recovered and synchronously tracked using phase-lock techniques. The time delay of the signal is usually rapidly increasing or decreasing, caused by the motion of the satellite; the motion also results in a Doppler shift of the carrier frequency. Since the satellite position is known quite precisely, the Doppler shift and time delay variation is highly predictable. As a result, the range measurement can be averaged over several tens of seconds to reduce the measurement uncertainty. Since the satellite and reference station positions are both known precisely, the range error can be determined. The range rate, having removed the effects of satellite motion, would be near zero if it were not for the artificial error introduced by Selective Availability, which limits the accuracy of the GPS. By using carrier phase tracking, this range rate can be measured quite accurately (typically 2-3 cm/sec).

### 3.2.5 Timing Reference of the Corrections

It has been suggested that by proper removal of effects of satellite motion and processing of the measurement data, the data could, in principle, be optimally filtered to provide predictions of the range and range rate errors for the next message to be broadcast. The range and range rate error for each satellite could be the value which provided the best rms estimates over the next message period. The reason for this suggestion is that the ground station, being stationary and processing the carrier phase information, could perform predictive filtering on the satellite signals and could provide better correction estimates than the user receiver could generate.

However, this would only be beneficial for applications where the user population applied corrections at predictable and uniform intervals relative to the corrections' time tags. For general purpose use, it is recommended that each pseudorange and range rate correction be the best estimates at that instant identified by the time tag.

The time tag applied to the DGPS corrections is the modified Z count contained in the message header. The relationship of this time tag ($t_o$) to real time (t) has broad effects on the way the user can apply the corrections. Three methods of reference station operation are presented here to give some insight into operating DGPS with different techniques.

> Past : the modified Z count could represent some value in the past that has sufficient measurement information before and after the modified Z count ($t_o$) to make a very accurate assessment of the PRC and RRC at the modified Z count ($t_o$). Transmitting corrections based on this technique implies some type of post processing on the part of the user. The user could be operating in near real time by running his solution with a lag of $t-t_o$. The pseudorange measurements would be retained until the correction for that moment is received. The user would then apply the corrections with no lag in the correction information. To obtain real-time navigation information, the user receiver would propagate the position to current time using velocity information, or inertial or other sensors. This technique applies equally well to the "present" method.
>
> Present : The modified Z count for PRC and RRC would be within 0.6 seconds of the last set of measurements used in forming that correction. In this case the only latency in the corrections would be caused by the delays in communicating the corrections out of the reference station through some transmission medium and reception at the user. This method should yield accurate results in real time. The user can compensate for data link latency as in the "Past" technique presented above.
>
> Future : The modified Z count can be propagated into the future to compensate for data link latency. This method would require accurate knowledge of pseudorange acceleration. This method will introduce error into the corrections if the pseudorange acceleration changes significantly between the measurement time and the prediction time. In this case the user would not be able to "back out" this error by applying the corrections at the time of the modified Z count. In a scenario where accelerations are significant and well known this technique could enhance real time user accuracy.

The method chosen by a service provider must be chosen to meet the requirements of the particular service. Many applications requiring high accuracy do not require real time DGPS updates. A near real time (< 30 seconds) capability could suffice. The "present" method provides the best real time performance without contaminating the corrections with the errors of prediction. For real time users the corrections are easily propagated forward to current time (t) and near real time users can get the best accuracy at the modified Z count time ($t_o$).

### 3.2.6 Satellite Health Assessment

The satellites themselves provide indications of the reliability and accuracy of their signals. The reference station provides an independent check, since it can compare the measured pseudorange against the known range between station and satellite position (as derived from the satellite ephemeris data). While it is unlikely that a satellite will transmit incorrect signals, there is a remote possibility that the signal could drift out of specification before the GPS control station could upload a new health message. The reference station is capable of detecting such a condition immediately, and should flag such a condition in the differential broadcast. It can also detect any significant variation in the signal or change in the signal that might be caused by Selective Availability or some error mechanism.

### 3.2.7 Ionospheric Effects

The ionosphere can cause a propagation group delay of a satellite signal by as much as 100 meters during peak solar cycle conditions, and more typically causes delays of 20-30 meters. While models exist which account for most of the delay, the Committee decided that the reference station should not attempt to model the ionosphere at all, for the following reasons. A user close to the reference station would receive signals from the satellites through signal paths that would be almost identical to those of the station. As a result, the corrections would exactly compensate for the signal group delays. For users farther away from the station, say several hundred kilometers, the signal paths diverge enough that the respective group delays could differ by as much as a few meters (see Figure 3-3, which is derived from the GPS ionospheric model).

By modelling the ionosphere, e.g., using the coefficients provided in the satellite messages, much of this group delay difference can be removed. The remaining errors are then caused by the deviations of the ionosphere from the model. It can be argued that if both reference station and user applied the model, the results can be improved (to the extent the models were valid). The reason for the Committee's recommendation is that since the user receiver knows the location of the reference station, it can apply the model to both the reference station and user and achieve the same improvement. Furthermore, as better models of the ionosphere are developed, they can be accommodated in newer receiver designs, without constraining the accuracy of future systems to models developed early in the program.

There is not enough accurate data available yet to predict the residual ionospheric errors at different user-station separations, but since the Global Positioning System is a natural source of unlimited data on the subject, it can be anticipated that improved models will be developed in the future. Moreover, spatial decorrelation caused by ionosphere, troposphere and Selective Availability ephemeris errors can be measured, separately or in composite, by a network of reference stations located around the coverage area.

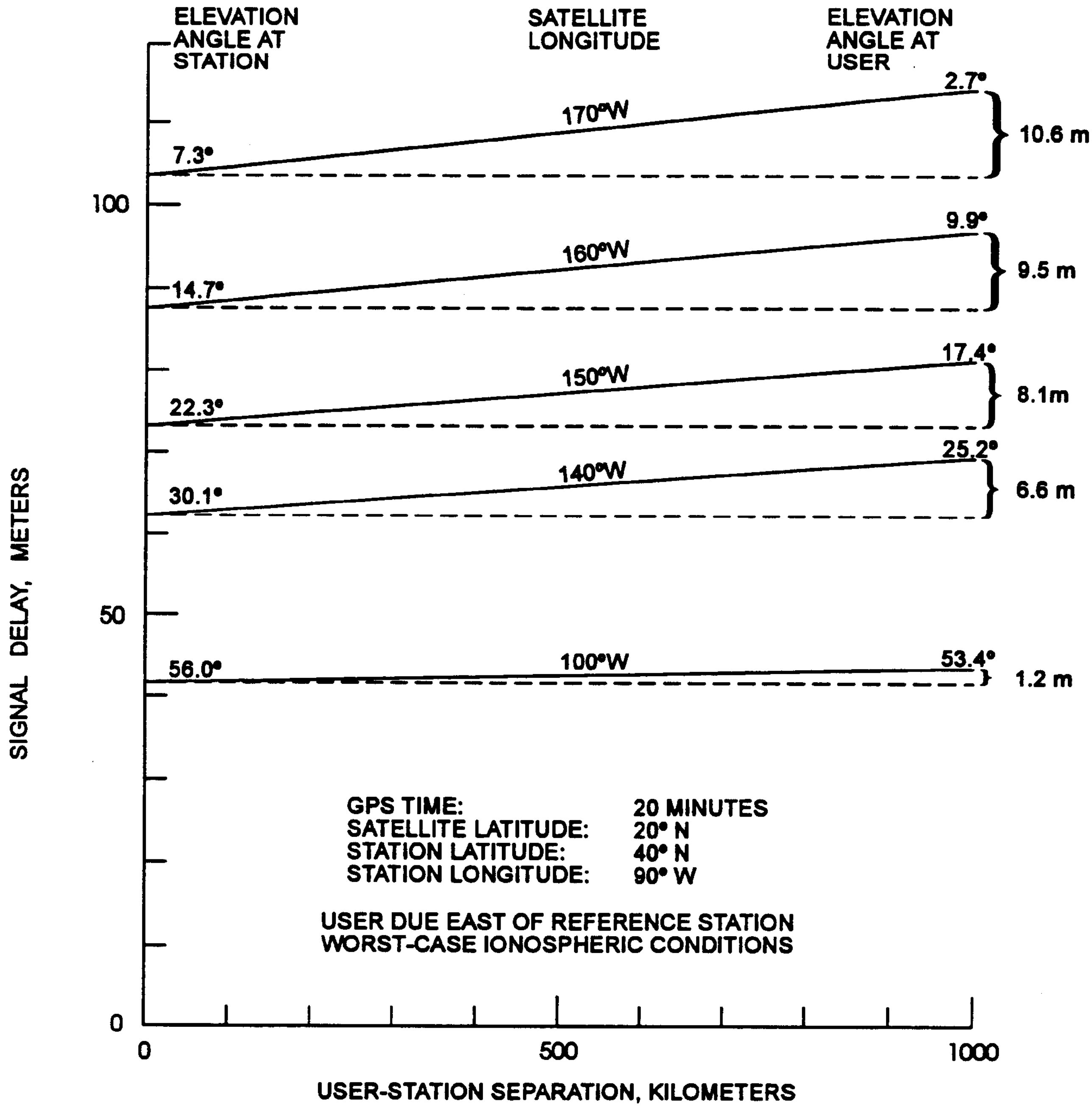


**FIGURE 3-3. EXPECTED IONOSPHERIC DECORRELATION**

0091

### 3.2.8 Tropospheric Effects

The index of refraction in the troposphere is almost, but not quite, unity. It approaches unity at the top of the troposphere. Its value (typically 1.0030) depends on the temperature, pressure, and the partial pressure of water vapor. While the time delay caused by the troposphere is typically 3 meters overhead to 50 meters at 3 degrees elevation, a simple model, i.e., one not involving any temperature or pressure measurements, can predict this quite well. Above 5 degrees elevation the unmodelled error is usually less than a meter. Consequently, it is not troublesome for navigation applications, but can be problematical for surveying applications. The model can be improved somewhat by a local measurement of the meteorological parameters. The Type 15 message, which is reserved for the broadcast of a composite time delay parameter based on local measurements, or for the measurements themselves, could be utilized.

As with the ionospheric correction, no model is used at the reference station, and the user is expected to bypass any tropospheric model that might be used in non-differential operation. The resulting error will be negligible unless the propagation paths traverse volumes which have significantly different water vapor pressures. A problem could occur if the station and user are at significantly different altitudes, e.g., by several thousand feet. Variations of the index of refraction with height are significant. It is therefore recommended that the user employ a tropospheric model which incorporates the different altitudes of user and reference station for applications where significant differences in height exist.

### 3.2.9 Reference Station Clock

Even with a quartz oscillator at the reference station it is possible to achieve high accuracy differential positioning. With such an oscillator it is possible to achieve time synchronization with the GPS of 100 nanoseconds. Thus it appears that for position location and navigation there is no need for a rubidium or cesium standard clock for the reference station. If all the corrections from the reference station are offset by the same amount, say 100 nanoseconds, the resulting positional error is zero, as long as all corrections in a message are referenced to the same instance of time. It is for this reason that it is recommended in Section 4 that Type 1 messages be ignored if any of the words fail parity: applying the corrections for some satellites and projecting the range rate of the others to estimate their corrections would introduce errors into the solution caused by reference station clock drift. With this caveat, it is adequate for the reference station to be driven by a quartz oscillator for most applications.

However, there are several specialized user applications where the use of a low-drift, high-quality clock for the reference station could be beneficial:

1. Users operating in a time-transfer mode, in which case the reference station clock drift error directly impacts their measurements. Differential operation might improve the time-transfer accuracy, but this needs to be demonstrated in the presence of Selective Availability dither.

2. For areas of limited visibility, users employing high-quality clocks at the mobile station can enable operation with 3 satellites or 2 satellites plus fixed altitude. This also requires a low-drift reference station clock, because time errors in the corrections caused by reference station clock drift would result in large errors. Under such conditions it would be possible to "clock-coast" with 3 satellites until a fourth one appeared. This is not recommended under normal circumstances.

3. For low-baud data links, the use of Type 9 messages provides improved performance in the presence of impulse noise conditions compared to the Type 1 messages. Use of a highly stable clock enables the use of Type 9 messages to reduce the average age of the corrections when the satellite differential corrections are arranged, for example, in groups of three. See Section 4.3.9.

As a result of these considerations, it is recommended for these specialized applications that the reference station employ a high-quality clock with good long-term drift characteristics.

#### 3.2.10 Multipath

Code phase multipath can introduce significant DGPS errors at both the reference station and user antennas. Reference station signal processing should be designed to minimize the effects of multipath. Also, reference station antennas should be situated to minimize multipath. It may be possible to compensate for multipath effects at fixed reference stations - see Appendix II. Message Types 19 and 21 provide for transmission of reference station multipath error estimates specifically, while the UDRE field in Message Type 1 provides for overall error estimates, which include multipath.

## 3.3 USER EQUIPMENT

### 3.3.1 Components

The user equipment consists of a GPS sensor with antenna, a data processor, a data link receiver with antenna, and interfacing equipment (see Figure 3-4). The data processor applies the corrections received from the reference station to the pseudoranges measured by the sensor.

### 3.3.2 Sensor Architecture

The GPS sensor architecture can be multi-channel or single/dual channel, employing parallel, sequential, or fast-sequential (multiplexed) techniques. It can operate with all satellites in view or with the "best" set, and can utilize independent measurements of altitude. As a result the receiver can be designed for particular applications without compromising other features to accommodate the differential operation.

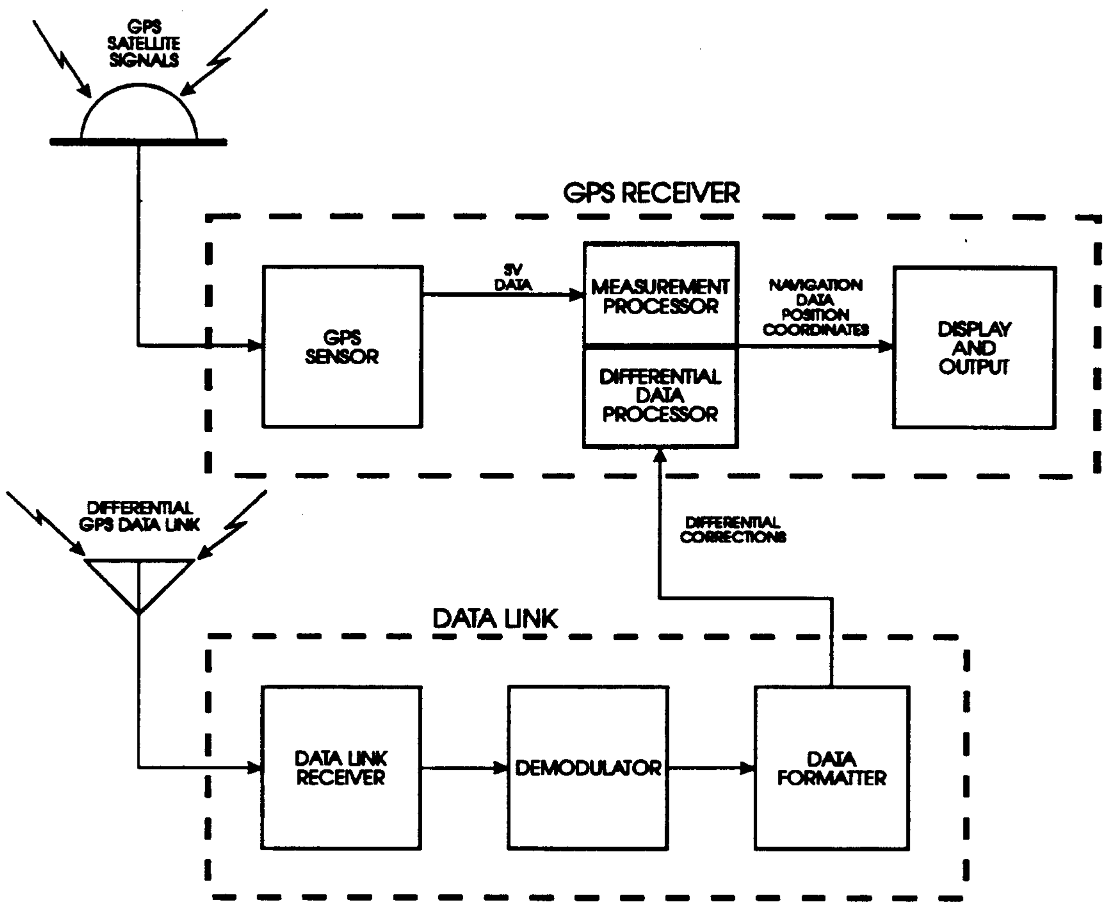


**Figure 3-4. USER EQUIPMENT BLOCK DIAGRAM**

0093

### 3.3.3 Application of the Differential GPS Corrections

For each satellite employed by the user receiver, the correction obtained from the reference station (Message Type 1) is added to the pseudorange measurement. The correction itself is derived from the range and range-rate, adjusted to account for the time elapsed between the time of reception of the correction and the time of the user pseudorange measurement, as follows:

$$PRC(t) = PRC(t_0) + RRC \bullet [t-t_0]$$

where PRC(t) is the correction to be applied, $PRC(t_0)$ is the range correction from the message, RRC is the range-rate correction from the message, $t_0$ is the time reference of the correction (see section 3.2.5), and t is the time associated with the pseudorange measurement.

The differential correction message contains information on the satellite health as determined by the ground station. It is described in Section 4.3.1. How the user receiver utilizes the information is left to the receiver designer.

Every so often a Type 2 message is sent, interspersed among the correction messages, which provides a secondary correction. This is done to allow a user to operate with old satellite ephemeris and satellite clock data (e.g., up to two hours old), while the reference station is operating with the most recent data. This correction, called the "delta correction," is added to the normal correction for that satellite. Section 4.3.2 discusses this in detail. The reference station will usually decode the satellite data before the user does, since it is constantly monitoring the data. In the unlikely event that the user does decode the satellite earlier, the receiver should be prevented from using the new satellite data until the reference station has indicated it is using the new data.

The user can utilize carrier phase tracking if required by the application. It is often used for aiding of the code tracking, especially for sequential sets. It can also be used to measure the velocity of the vessel, vehicle, or aircraft. With Selective Availability imposed on the SPS signal, the velocity measurements are typically accurate to about 2 knots (95%). The range rate corrections, which are actually velocity corrections, can be used to improve this. Differentially corrected velocity measurements can achieve velocity accuracies of 0.2 knots, or about 0.1 meters per second (95%) or better.

For surveying applications the instantaneous carrier phase is the primary measurement of each of the satellites. The code tracking is performed primarily for acquisition and removal of ambiguities. A special message (Type 4) had been designed for surveying applications, which provided the carrier phase count to a fraction of a cycle at intervals, referenced to the station clock frequency. It was thought there might be some interest in the broadcast of measurements of a control point. However, it did not find extensive usage, and has been retired. The new real-time kinematic messages, Types 18-21, have all the information necessary to support such an application.

Real-time kinematic applications of GPS are now possible using the new Message Types 18-21. In brief, a number of kinematic techniques can be performed in real-time (or more accurately, near real time) utilizing these messages. In addition, new "on-the-fly" techniques for rapid determination of integer ambiguities will remove the need for static calibration points.

## 3.4 DATA LINK

The data link, which communicates the corrections from the reference station to the user receiver, can take a number of forms and operate at any of several frequencies. The chief requirement is that the messages be reliably communicated at a data rate of at least 50 baud (continuous transmission). Figure 3-2 shows the reference station data link functions, and Figure 3-4 shows the user data link functions.

In its simplest form, the data link continuously carries the differential GPS data message without interruption, at a constant data rate of at least 50 baud. However, it is transparent to the GPS receiver whether the data is transmitted continuously or in bursts, or whether protocol overhead is added. For example, each message (or multiple messages, or any fraction of a message) could be transmitted as a short burst at 2400 baud, along with a data link protocol preamble, parity, and even error correction bits. These would be stripped off at the receiver end, and the differential correction bits would be stored in the buffer, to be transferred to the receiver at will.

Differential GPS broadcasts intended for general public use would require that the data link be a standard, published design. For non-public use, however, the reference station, data link, and receivers could be part of an integrated differential GPS system. In such a case, the data might be encrypted to limit the service to paying customers. The format allows for such operation.

At the minimum rate of 50 baud it appears that there is considerable robustness in the data link. If a satellite correction message had a single or double error, the parity scheme of Section 4 would detect it (them). The corrections are broadcast frequently enough that the loss of as many as three consecutive corrections can be tolerated, and still provide 5-meter accuracy. This is discussed further in Section 4.4 and Figure 4-13.

An attractive candidate technique for broadcasting corrections to mariners involves modulating the marine radiobeacon transmitter signals with the differential GPS message. This technique has the property of over-the-horizon propagation at low powers. It is also relatively straightforward and inexpensive to implement. It has the further advantage that no new frequency allocations would be required. A design and testing program sponsored by the U.S. Coast Guard demonstrated that a minimum shift keying (MSK) modulation scheme offers spectrally efficient operation which does not interfere with marine direction-finding radiobeacon receivers. This program demonstrated that the data format of this standard performs well in the maritime environment. Based on these considerations, the U.S. Coast Guard plans to deploy radiobeacon transmitters around the coast of the country and throughout the Great Lakes. Australia, Canada, Denmark, Finland, Germany, Norway, Sweden, the United Kingdom, and the United States have either deployed, or are planning to deploy, DGPS broadcasts on existing marine radiobeacons.

## 3.5 PSEUDOLITE TECHNIQUE

A pseudolite (short for pseudo-satellite) is a specific implementation of differential GPS. In the conventional approach, an external data link is required involving a separate broadcast frequency. The pseudolite signal is designed to resemble the satellite signal, i.e., it uses the same modulation, coding and frequency as the GPS. The individual codes of the pseudolites, while having the same length, are distinct from the satellite codes but chosen to give low intermodulation products. The data, of course, has a different meaning than the data associated with a real satellite: it includes the differential GPS corrections.

By broadcasting the corrections at the same frequency as the GPS satellites, the receivers don't require a separate antenna, data link receiver, and interface. This is a considerable advantage. In addition, receivers can obtain pseudorange measurements from the ground station in addition to those obtained from satellites. This both increases the reliability of the measurement (since only three satellites would be required) and improves the accuracy by improving the dilution of precision measures.

The fact that the GPS frequency is at L-band means that the pseudolite technique is limited to line-of-sight propagation. As a consequence, it is expected to be most useful for air applications and for land/marine applications within a small area.

The major issue to be resolved for pseudolite operation is whether it can be designed so as not to interfere with the normal reception of GPS satellites. If the satellite modulation/coding technique were used without modification, receivers near the pseudolite station would be saturated by the pseudolite signal.

## 3.6 REAL-TIME KINEMATIC OPERATION

Version 2.1 of the Standard includes new messages to support real-time kinematic applications, wherein decimeter accuracy or better can be achieved. GPS carrier phase measurements have been routinely used for the determination of precise positions using static, kinematic and pseudo-kinematic surveying techniques. All of these require the initial placement of a rover antenna over a known location, or require several minutes of data recording at a fixed point. Recent developments indicate the feasibility of conducting kinematic surveys "on-the-fly" without requiring this initialization process. However, these techniques are all post-processing techniques, not real-time.

Other recent developments have shown that the "on-the-fly" techniques can operate in real-time as well, an important feature which holds promise of decimeter positioning accuracy, hence the term real-time kinematic, or RTK. This can be achieved by the addition of a data link.

However, the data update requirements of RTK is much higher than conventional differential GPS, since it involves double-differencing of carrier measurements. Data must be updated every 0.5 -2 seconds, rather than every 10 seconds. As a consequence, the data links are more likely to utilize UHF/VHF, with transmission rates of 1200-9600 baud.

Spatial decorrelation limits the range of decimeter accuracy to a few kilometers or tens of kilometers, so line-of-sight transmission is appropriate for RTK applications.

Potential applications for RTK techniques include construction, dredging, hydrographic survey, land survey, seismic survey, tidal datum determination, aircraft CAT-II and CAT-III approach and landing navigation, vehicle navigation, photogrammetric survey control, reference benchmarks for land surveys, robotic guidance and control, range control and sensor calibration.

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# 4. RECOMMENDED DATA MESSAGE FORMAT

## 4.1 INTRODUCTION

The committee has determined the data required by various types of differential GPS users to correct, to the extent possible, for GPS errors that are common to the reference station and the user. These GPS errors are the following:

1. Satellite Ephemeris prediction errors
2. Satellite clock prediction errors
3. Ionospheric delay errors
4. Tropospheric delay errors as they appear at the reference station
5. Artificial errors induced by Selective Availability (SA) techniques
6. Differential tropospheric delay errors, if desired
7. Reference station clock offsets

The first six of these errors are common to both the user and the reference station for small baselines between reference station and user. This commonality will be reduced for 1, 3, 4, 5, and 6 as the baseline increases. The seventh only affects the user's ability to determine absolute time, unless pseudolites are employed. Detailed discussions of these effects are provided below.

In addition to measurement correction data, the standard also provides for almanac and health data. The data are separated into types, where the type of data varies either in its frequency of transmission, the type of user it is intended for, or whether or not it is error correction data or almanac data. Each Message Type has a unique identification (one of 64). Several basic message types have been defined in their final form. Several others are defined in preliminary form; manufacturers implementing these standards are advised that these may change after field tests have been performed. A number of the remaining available message types have been left undefined, but are reserved for future use for designated applications.

To provide commonality in user software, provide a strong error detection capability, and support the use of GPS pseudolites for data transmission, the data format was patterned after the GPS data format, although it diverged from that somewhat as different requirements surfaced. However, the GPS word size, word format, parity algorithm and other features survived. The biggest difference is that the differential standard utilizes a variable length message format, whereas the GPS format has fixed length subframes. The surviving features are justified for the following reasons:

1) A strong parity algorithm is required to detect errors in the data, preventing the use of erroneous corrections that could affect user safety.

2) The GPS parity algorithm is a known and proven algorithm with which the users are familiar.

3) The parity algorithm overlaps word boundaries and resolves sign ambiguities encountered in bi-phase modulation data transmissions.

4) The 30 bit words (as opposed to 32 bit words) coupled with a 50Hz transmission rate provides a convenient timing capability where the times of word boundaries are a rational multiple of 0.6 seconds. Every 5th word boundary lands on a multiple of 3 seconds. If 32 bit words had been used, word boundaries would run on multiple integer-seconds only once per 16 seconds.

The minimum data rate is required to be 50 bits per second, the same as that of GPS (and highly desirable if pseudolites are employed). The main driver for the minimum data rate is the expected error variations, dominated by the expected SA. However, except for the pseudolite reference station, there is no reason that data rates cannot be reduced in the future if DOD policies reduce the level of SA. On the other hand, the data rate and message repetition rate can be as high as desired, subject only to the limitations of the communications channel. Furthermore, there is no requirement that the broadcast be continuous, so that a short burst of high-rate transmission is quite feasible. It should also be noted that real-time kinematic data rates should be significantly higher (see Section 3.7).

The remainder of this chapter presents the details of the recommended Data Message Format and the Message Content.

## 4.2 GENERAL MESSAGE FORMAT

The general message format is illustrated in Figure 4-1 with details of the first two thirty-bit words of each frame or message type. Each frame is N+2 words long, N words containing the data of the message. N varies with message type as well as within a message type. The word size and parity algorithm are identical to that of the GPS navigation message as described in the public release of ICD-GPS-200 [Navstar GPS/JPO, 3 July 1991].

### 4.2.1 First and Second Words

The first two words of each frame contain data that is pertinent to any type of message: Reference Station information, reference time and information required for user's frame synchronization. Their content is summarized in Figure 4-1 and tabulated in Table 4-1. It should be noted that the Station ID refers to the identification of the differential reference station. It does not, in general, identify the data link station.

**FIRST WORD OF EACH MESSAGE**

| 1 2 3 4 5 6 7 8 | 9 10 11 12 13 14 | 15 16 17 18 19 20 21 22 23 24 | 25 26 27 28 29 30 | |
|---|---|---|---|---|
| PREAMBLE | MESSAGE TYPE (FRAME ID) | STATION I.D. | PARITY | WORD 1 |
| 0 1 1 0 0 1 1 0 | MSB LSB | MSB LSB | | |

First Bit Transmitted — Last Bit Transmitted

**SECOND WORD OF EACH MESSAGE**

| 1 2 3 4 5 6 7 8 9 10 11 12 13 | 14 15 16 | 17 18 19 20 21 | 22 23 24 | 25 26 27 28 29 30 | |
|---|---|---|---|---|---|
| MODIFIED Z-COUNT | SEQ'NCE NO. | LENGTH OF FRAME | STATION HEALTH | PARITY | WORD 2 |
| MSB LSB | | MSB LSB | | | |

**Figure 4-1. 2-WORD HEADER FOR ALL MESSAGES**

### TABLE 4-1. CONTENT OF FIRST AND SECOND WORDS

| WORD | CONTENT | NUMBER OF BITS | SCALE FACTOR AND UNITS | RANGE |
|---|---|---|---|---|
| FIRST WORD | PREAMBLE | 8 | -- | -- |
| | FRAME ID/MSG TYPE | 6 | 1 | 1-64* |
| | STATION ID | 10 | 1 | 0-1023 |
| | PARITY | 6 | See ICD-GPS-200 | |
| SECOND WORD | MODIFIED Z-COUNT | 13 | 0.6 sec | 0-3599.4 sec |
| | SEQUENCE NO. | 3 | 1 | 0-7 |
| | LENGTH OF FRAME (N+2) | 5 | 1 Word | 2-33 Words |
| | STATION HEALTH | 3 | -- | 8 States |
| | PARITY | 6 | See ICD-GPS-200 | -- |

* 64 is indicated with all zeros.

Frame synchronization can be achieved by the user in a similar manner as performed for the GPS data, with exceptions associated with the variable length frames. The beginning of the first word is a fixed 8-bit preamble (identical to GPS) for which the user searches. Message type numbers are those in this document. Station ID is arbitrary, and set by the reference station provider.

For pseudolite transmissions, the modified Z-count is the time of the start of the next frame (beginning of preamble) as well as the reference time for the message parameters. In the case of non-pseudolite type transmission, it is only the reference time for the message parameters. The modified Z-count is different from the GPS Z-count in that the LSB has a scale factor of 0.6 seconds, instead of 6 seconds, to account for the variable length frames. This is required only for pseudolite transmissions. Also, the range of the Z-count is only one hour in order to conserve bits. The reasoning behind this is that all differential GPS users will have already initialized via the GPS system and will know what the time is. It should be noted that the DGPS Z-count is referenced to GPS time, not UTC.

The sequence number aids in frame synchronization for non-pseudolite type transmissions, replacing the sequencing Z-count as an incrementing parameter. It will increment on each frame. The frame length is two more than the number of words (N) following the header. Thus a zero in the frame length field would mean that the frame length would be 2, and no words would follow the header.

Version 2.1 of the standard has redefined the meaning of the three Reference Station Health bits, in the following sense: rather than requiring a fixed definition of the field, 6 states are made available to the system provider to define their meaning. However, "111" shall continue to indicate that the reference station is not working properly, and "110" shall indicate that the transmission is unmonitored, as shown in Table 4-1a. Systems currently in operation can continue to operate with the meaning previously defined in Versions 1.0 and 2.0. However, for new applications, the system provider is now allowed to tailor them to the application. For example, the U.S. Coast Guard plans to utilize the field to denote a scale factor for the UDRE field in the differential correction messages.

**TABLE 4-1a. REFERENCE STATION HEALTH STATUS INDICATOR**

| CODE | | INDICATION |
|---|---|---|
| 111 | - | Reference Station Not Working |
| 110 | - | Reference Station Transmission Not Monitored |
| 101 | - | Specified by Service Provider |
| 100 | - | Specified by Service Provider |
| 011 | - | Specified by Service Provider |
| 010 | - | Specified by Service Provider |
| 001 | - | Specified by Service Provider |
| 000 | - | Specified by Service Provider |

## 4.3 MESSAGE TYPE CONTENT AND FORMATS

To date there are 26 of a possible 64 message types defined, either tentatively or in final fixed form, retired, or reserved. They are given in Table 4-2. Details of the message type contents and formats are given in sections 4.3.1 through 4.3.25.

**TABLE 4-2. MESSAGE TYPES**

| MESSAGE TYPE NO. | CURRENT STATUS | TITLE |
|---|---|---|
| 1 | Fixed | Differential GPS Corrections |
| 2 | Fixed | Delta Differential GPS Corrections |
| 3 | Fixed | Reference Station Parameters |
| 4 | Retired | Surveying |
| 5 | Fixed | Constellation Health |
| 6 | Fixed | Null Frame |
| 7 | Fixed | Beacon Almanacs |
| 8 | Tentative | Pseudolite Almanacs |
| 9 | Fixed | Partial Satellite Set Differential Corrections |
| 10 | Reserved | P-Code Differential Corrections (all) |
| 11 | Reserved | C/A-Code L1, L2 Delta Corrections |
| 12 | Reserved | Pseudolite Station Parameters |
| 13 | Tentative | Ground Transmitter Parameters |
| 14 | Reserved | Surveying Auxiliary Message |
| 15 | Reserved | Ionosphere (Troposphere) Message |
| 16 | Fixed | Special Message |
| 17 | Tentative | Ephemeris Almanac |
| 18 | Tentative | Uncorrected Carrier Phase Measurements |
| 19 | Tentative | Uncorrected Pseudorange Measurements |
| 20 | Tentative | RTK Carrier Phase Corrections |
| 21 | Tentative | RTK Pseudorange Corrections |
| 22-58 | -- | Undefined |
| 59 | Tentative | Proprietary Message |
| 60-63 | Reserved | Multipurpose Usage |

### 4.3.1 Message Type 1 - Differential GPS Corrections (Fixed)

Figure 4-2 and Table 4-3 present the content of Message Type 1, the differential corrections. This is the primary message type which provides the pseudorange correction (PRC(t)) for any user receiver GPS measurement time "t":

$$PRC(t) = PRC(t_0) + RRC \bullet [t - t_0] \qquad \text{(Eq. 4-1)}$$

where $PRC(t_0)$ is the 16 bit pseudorange correction, RRC is the 8-bit rate of change of the pseudorange correction (range rate correction), and $t_0$ is the 13-bit modified Z-count of the second word. These parameters are all associated with the satellite indicated by the 5-bit Satellite ID, which indicates its PRN number. The pseudorange measured by the user, PRM(t), is then corrected as follows:

$$PR(t) = PRM(t) + PRC(t) \qquad \text{(Eq. 4-2)}$$

Note that the correction is <u>added</u> to the measurement. PR(t) is the differentially corrected pseudorange measurement that should be processed by the User Equipment navigation filter. Also provided is a 1-bit Scale Factor (see Table 4-4) and 2-bit User Differential Range Error ("UDRE" - see Table 4-5). The UDRE is a one-sigma estimate of the uncertainty in the pseudorange correction as estimated by the reference station, and combines the estimated effects of multipath, signal-to-noise ratio, and other effects. It should be noted that the real-time kinematic messages use signal quality indicators which separate out multipath effects from other effects, as described in Appendix II.

The Type 1 Message contains data for all satellites in view of the reference station (N(s)). Since 40 bits are required for the corrections from each satellite, there won't always be an exact integer number of words required. There will be messages that require 8 or 16 bits of fill to finish the frame. The fill will be alternating 1's and 0's so as not to be confused with the "preamble" synchronization code. The format of the Type 1 Message is illustrated in Figure 4-2. Each word has one of five formats unless it is the last word in the message. If N(s) is not a multiple of 3, the last word has one of two formats, containing either 8 or 16 fill bits.

The pseudorange correction $PRC(t_0)$ will diverge from the proper value as it "grows old." Because of this characteristic, it will be updated and transmitted as often as possible. The User Equipment should update the corrections accordingly.

The range rate correction (RRC) is designed to compensate for the predicted rate of change of the pseudorange correction. This is an attempt to "extend the life" of the pseudorange correction as it "grows old." The RRC can also be used to correct the user receiver's velocity. The User Equipment should not use the RRC as a carrier phase correction -- it may degrade that type of measurement. Carrier phase measurements should be corrected only using Message Types 18 or 20.

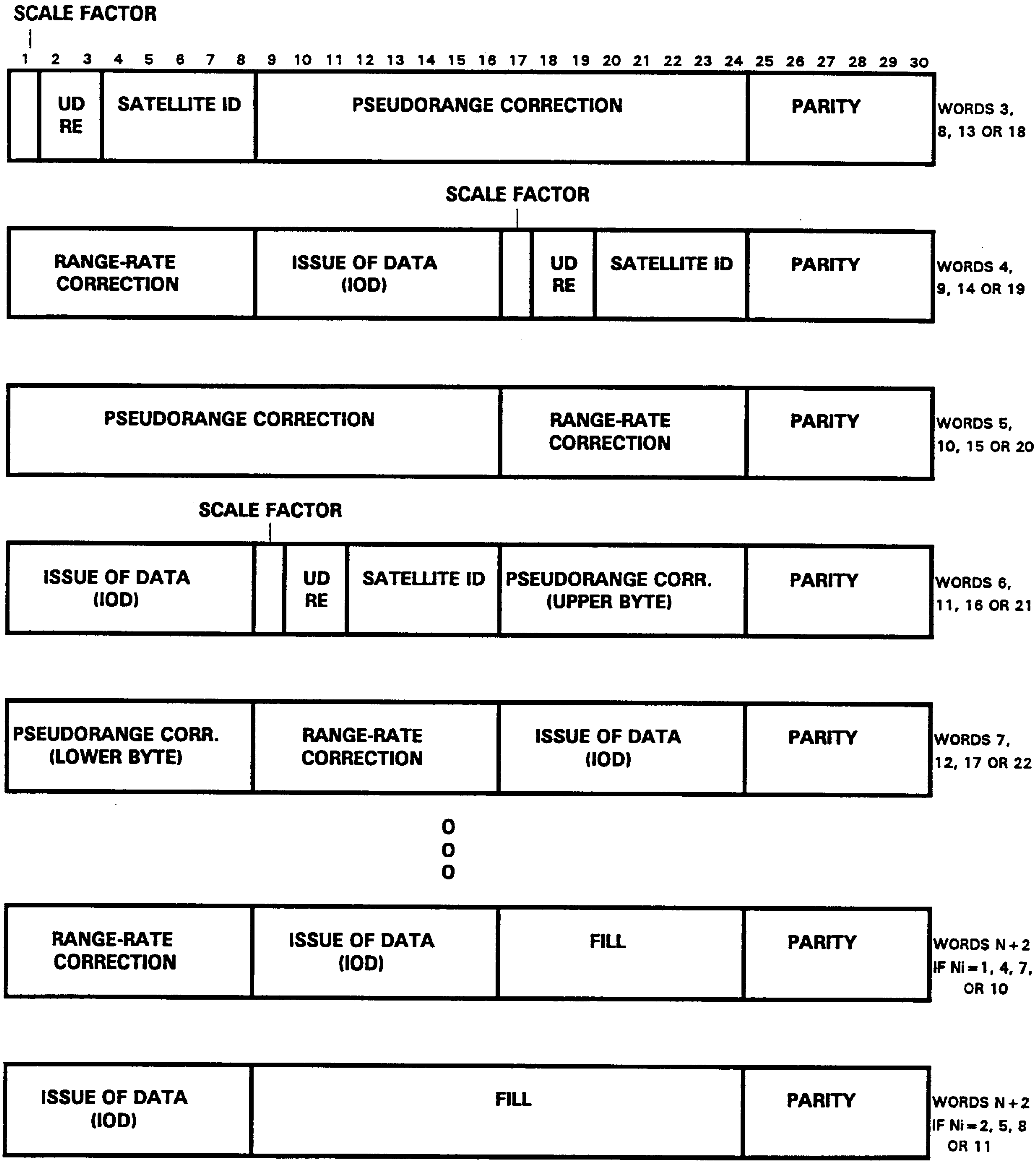


**Figure 4-2 TYPE 1 MESSAGE FORMAT**

**TABLE 4-3. CONTENTS OF A TYPE 1 MESSAGE**

| PARAMETER | NO. OF BITS | SCALE FACTOR AND UNITS | RANGE |
|---|---|---|---|
| SCALE FACTOR | 1 | See Table 4-4 | 2 states |
| UDRE | 2 | See Table 4-5 | 4 states |
| SATELLITE ID | 5 | 1 | 1-32**** |
| $PRC(t_0)$* | 16 | 0.02 or 0.32 m | ±655.34 or ±10485.44 m** |
| RRC* | 8 | 0.002 or 0.032 m/s | ±0.254 or ±4.064 m/s*** |
| ISSUE OF DATA | 8 | See ICD-GPS-200 | |
| | $40 \times N_s$ | | |
| FILL | $8 \times [N_s \bmod 3]$ | bits | 0, 8, or 16 |
| PARITY | N x 6 | See ICD-GPS-200 | |

* 2's complement.

** Binary 1000 0000 0000 0000 indicates a problem and the User Equipment should immediately stop using this satellite.

*** Binary 1000 0000 indicates a problem and the User Equipment should immediately stop using this satellite.

**** Satellite number 32 is indicated with all zeros (00000).

$N_s$ = Number of satellite corrections contained in message.

N = Number of words in message containing data. Message length = N+2 words.

The reference station will not apply ionospheric and tropospheric delay models in deriving the differential corrections. The effect of satellite clock and relativistic parameters will be determined using ICD-GPS-200 algorithms. The reference station clock offsets will be a common offset in all pseudorange corrections, which does not affect position calculations.

The Issue of Data (IOD) is included in the message so that the User Equipment may compare it with the IOD of the GPS navigation data being used. The IOD is the key that ensures that the User Equipment calculations and reference station corrections are based on the same set of broadcast orbital and clock parameters. If they don't agree, it is the responsibility of the differential User

Equipment to take the appropriate actions to acquire parameters that match the ones in use at the reference station. This can be done two ways: test the present IOD for a match to the IOD in a Type 1 or Type 2 messages, or acquire another navigation data message from the appropriate satellite. In general, the reference station attempts to use the present navigation data being broadcast by a satellite. Unless there is a major problem with the navigation data, the Type 1 Message will begin using new navigation data within a few minutes of a change. Note that the Type 5 Message also contains useful information concerning navigation data.

Under no circumstances should a "partial" differential solution be attempted, i.e., processing both differentially corrected and non-differentially-corrected pseudoranges in the same position calculation. The resulting position will usually be no better than a non-differential solution.

### TABLE 4-4. SCALE FACTOR

| CODE | NUMBER | INDICATION |
|---|---|---|
| 0 | (0) | Scale factor for pseudorange correction is 0.02 meter and for range rate correction is 0.002 meter/second |
| 1 | (1) | Scale factor for pseudorange correction is 0.32 meter and for range rate correction is 0.032 meter/second (also refer to Table 4-3) |

The rationale for the two-level scale factor is to maintain a high degree of precision most of the time, and allow the ability to increase the range of the corrections on those rare occasions when it is needed.

### TABLE 4-5 USER DIFFERENTIAL RANGE ERROR (UDRE)

| CODE | NUMBER | ONE-SIGMA DIFFERENTIAL ERROR |
|---|---|---|
| 00 | (0) | $\leq$ 1 meter |
| 01 | (1) | > 1 meter and $\leq$ 4 meters |
| 10 | (2) | > 4 meters and $\leq$ 8 meters |
| 11 | (3) | > 8 meters |

### 4.3.2 Message Type 2 - Delta Differential GPS Corrections (Fixed)

Message Type 2 is provided for situations where the user equipment may not immediately decode new satellite ephemerides in the satellite data. Since the reference station should be designed to immediately decode the new ephemerides, there could be periods of time where the user and reference station are using different ephemerides, which could result in position errors, particularly after a satellite upload. In a particular application, Type 2's can be omitted if all the user receivers are designed to immediately decode new ephemerides.

If Type 2's are employed, the reference station shall transmit both Type 1 and Type 2 messages any time it starts using new GPS navigation message data to calculate satellite position and compensate for satellite clock offsets. This is indicated by a change in the Issue of Data parameter in the Type 1 Message. Each new set of satellite navigation data is identified with an Issue of Data (IOD) parameter. Differential User Equipment should not use new satellite navigation data until the reference station indicates the appropriate IOD in the Type 1 Message.

Upon a change in ephemeris, the reference station shall broadcast a Type 2 message paired with a Type 1 message, and continue to broadcast Type 2 messages over a period of several minutes following a change in satellite navigation data. During this period, the differential User Equipment will acquire the new navigational data and begin using the "new" Type 1 Message data. The Type 2 Message acts as a bridge to continue high accuracy navigation during this transition period. Accuracy is maintained if Type 2's are utilized correctly. It is preferred, but not required, to transmit the Type 2 message first; this may become a requirement in the future. If Type 2's are used with Type 9 transmissions, a Type 2 shall precede the Type 9's using the new ephemerides.

This message contains the difference in the pseudorange and range rate corrections caused by the change in satellite navigation data. At the reference station, two calculations will be performed for the pseudorange correction (PRC) and range rate correction (RRC). The first calculation will use the latest navigation data available from the satellite. The second calculation will use the navigation data that is being replaced by the most recent navigation data. The reference station will difference the corrections to determine the DELTA PRC and DELTA RRC needed for the Type 2 Message.

The DELTA PRC is equal to the PRC (calculated using the older navigation data) minus the PRCs (calculated using the latest navigation data), or:

$$\text{DELTA PRC} = \text{PRC (old IOD)} - \text{PRC (new IOD)} \qquad \text{(Eq. 4-3)}$$

In a similar manner, the DELTA RRC is equal to the RRC (calculated using the older navigation data) minus the PRC (calculated using the latest navigation data), or:

$$\text{DELTA RRC} = \text{RRC (old IOD)} - \text{RRC (new IOD)} \qquad \text{(Eq. 4-4)}$$

In order to use a Type 2 correction the User Equipment must:

1. Presently be using the satellite navigation data with an IOD that matches the Type 2 Message IOD for that satellite;

2. Acquire a Type 1 Message with a new IOD that does not match the present IOD being used; and

3. Calculate the correct pseudorange correction with the following equation using information from both the Type 1 and Type 2 Messages:

$$\begin{aligned} PRC(t) = \; & [PRC(\text{new IOD}) && \text{(from Type 1 Message)} \\ & + \\ & \text{DELTA } PRC(\text{old IOD})] && \text{(from Type 2 Message)} \\ & + \\ & [RRC(\text{new IOD})] \bullet [t - t_1] && \text{(from Type 1 Message)} \\ & + \\ & [\text{DELTA } RRC(\text{old IOD})] \bullet [t - t_2] && \text{(from Type 2 Message)} \qquad \text{(Eq. 4-5)} \end{aligned}$$

where

$t$ = the time of application of the correction,

$t_1$ = modified Z-count from Type 1 Message, and

$t_2$ = modified Z-count from Type 2 Message.

Note that this equation is a simple extension of Eq. 4-1.

The general format is the same as that of a Type 1 Message. In fact, the description of the 1-bit Scale Factor is found in Table 4-4 and the description of the 2-bit User Differential Range Error is found in Table 4-5. The content of the Type 2 Message is given in Table 4-6 and is illustrated in Figure 4-3.

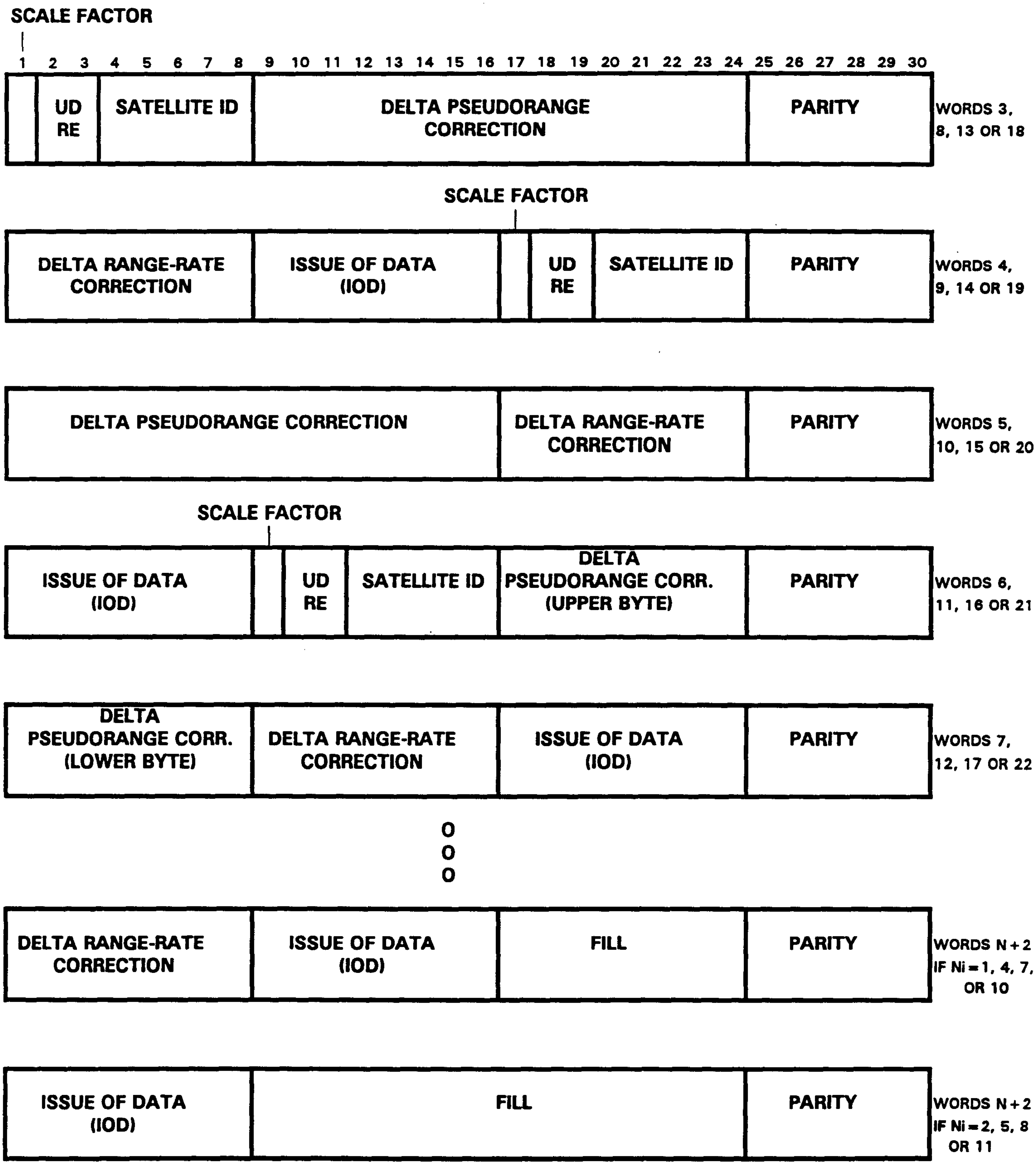


**Figure 4-3 TYPE 2 MESSAGE FORMAT - DELTA DIFFERENTIAL CORRECTIONS**

## TABLE 4-6. CONTENTS OF A TYPE 2 MESSAGE

| PARAMETER | NUMBER OF BITS | SCALE FACTOR AND UNITS | RANGE |
|---|---|---|---|
| SCALE FACTOR | 1 | See Table 4-4 | 2 states |
| UDRE | 2 | See Table 4-5 | 4 states |
| SATELLITE ID | 5 | 1 | 1-32**** |
| DELTA PRC* | 16 | 0.02 or 0.32m | ±655.34 or ±10485.44m** |
| DELTA RRC* | 8 | 0.002 or 0.032m/s | ±0.254 or ±4.064 m/s*** |
| ISSUE OF DATA | 8 | See ICD-GPS-200 | |
| | $40 \times N_s$ | | |
| FILL | $8 \times [N_s \bmod 3]$ bits | | 0, 8, or 16 |
| PARITY | N x 6 | See ICD-GPS-200 | |

* 2's complement.

** Binary 1000 0000 0000 0000 indicates a problem and the User Equipment should immediately stop using this satellite.

*** Binary 1000 0000 indicates a problem and the User Equipment should immediately stop using this satellite.

**** Satellite number 32 is indicated with all zeros (00000).

$N_s$ = Number of satellite corrections contained in message.

N = Number of words in message containing data. Message length = N+2.

### 4.3.3 Message Type 3 - Reference Station Parameters (Fixed)

Message Type 3 contains reference station information. Figure 4-4 and Table 4-7 give the contents of the Type 3 Message. It consists of four data words (N=4) for a total frame length of six 30-bit words. It includes the GPS coordinates (Earth-Centered-Earth-Fixed (ECEF)) of the reference station antenna to the nearest centimeter. WGS-84 is the reference datum.

TABLE 4-7. CONTENTS OF A TYPE 3 MESSAGE

| PARAMETER | NO. OF BITS | SCALE/FACTOR UNITS | RANGE |
|---|---|---|---|
| ECEF X - Coordinate* | 32 | 0.01 meter | ±21474836.47 meters |
| ECEF Y - Coordinate* | 32 | 0.01 meter | ±21474836.47 meters |
| ECEF Z - Coordinate* | 32 | 0.01 meter | ±21474836.47 meters |
| Parity | 24 | See ICD-GPS-200 | |

* 2's complement

If a datum other than WGS-84 is used, it is the responsibility of the service provider to inform the users of the datum being used for the reference station coordinates.

### 4.3.4 Message Type 4 - Surveying Parameters (Retired)

Message Type 4 was originally designed for surveying users who perform their positioning using continuously integrated carrier Doppler measurements, where the change in geometry of the satellites over time allows him to remove system biases and achieve accuracies to a submeter level. The intention was to provide a format for either real-time or post-mission surveying information to support a public or wide-area control point, so that a surveyor could perform the function with only one receiver.

However, there appears to have been little use made of this capability. Now that real-time kinematic messages have been defined (Message Types 18-21), such applications can use the new messages to achieve the same capability, as well as support real-time position applications.

As a consequence, Message Type 4 is being retired. The next revision of the standard may use the Type 4 for some totally different use entirely.

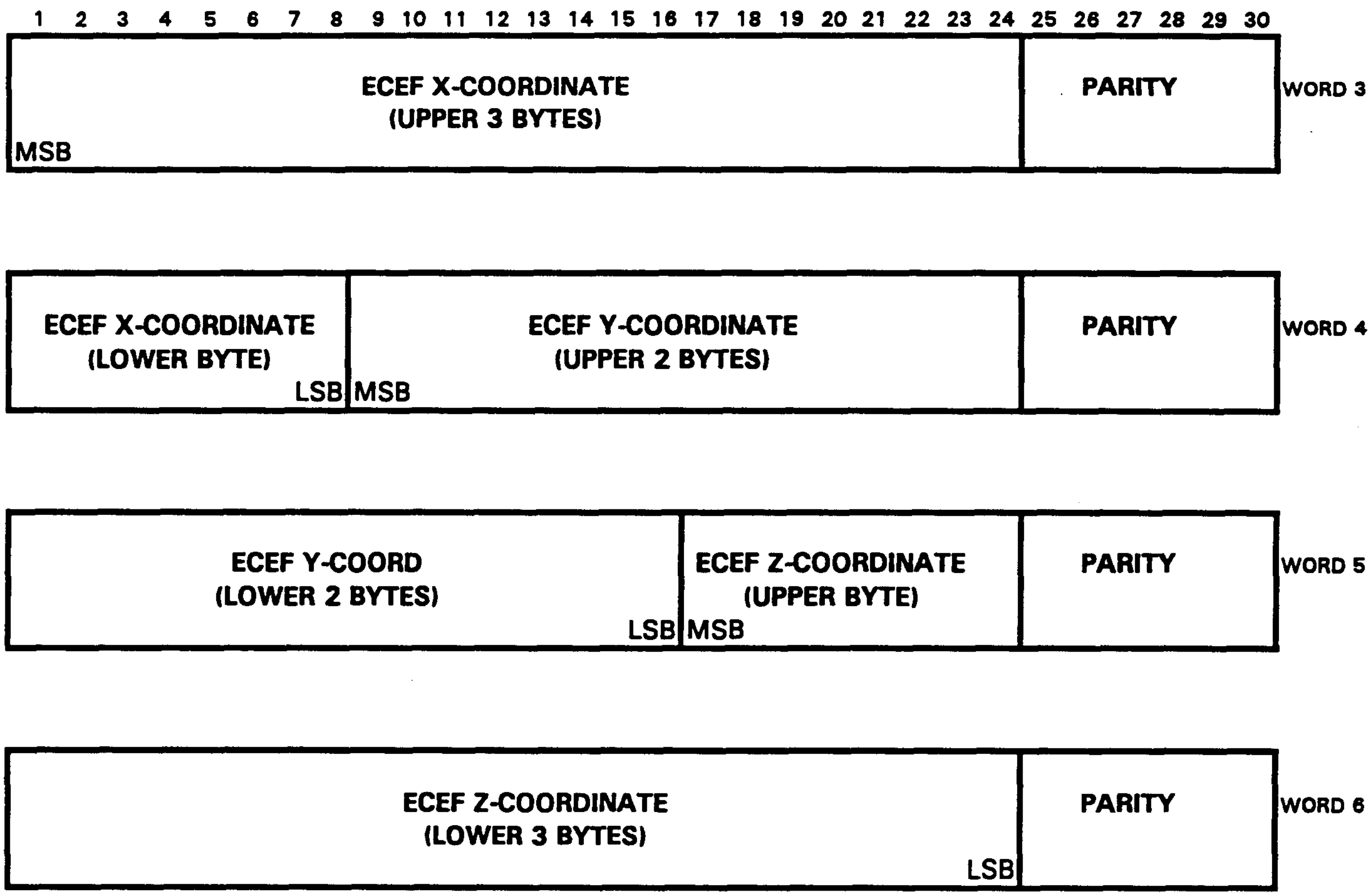


**Figure 4-4. TYPE 3 MESSAGE FORMAT - REFERENCE STATION PARAMETERS**

### 4.3.5 Message Type 5 - Constellation Health (Fixed)

The Type 5 Message provides information that can assist in the operation of differential User Equipment. It is a mechanism through which the observations made at the reference station can be automatically used by the User Equipment to improve performance without operator intervention. This message may contain information for only one satellite. The satellite may or may not be in view of the reference station. It will be transmitted periodically as determined necessary by the reference station. The content of a Type 5 Message is described in Table 4-8 and illustrated in Figure 4-5. The first bit is reserved for expansion of satellite ID's beyond 32 to accommodate non-GPS satellites. However, before this happens, a full-scale review of the applicability of the data content would be required.

**TABLE 4-8. CONTENTS OF A TYPE 5 MESSAGE**

| PARAMETER | BIT NUMBER | EXPLANATION |
|---|---|---|
| R | 1 | A single bit reserved for possible future expansion of satellite numbers beyond 32 |
| Satellite ID | 2-6 | Standard format, bit 6 is LSB, see Table 4-3 |
| IOD Link | 7 | Bit set to 0 indicates this information refers to navigation data with IOD in Message Types 1, 9, 20, and 21. Bit set to 1 indicates this information refers to navigation data with IOD in Type 2 Message. |
| Data Health | 8-10 | Standard information concerning satellite navigation data health, see Table 20-VII of ICD-GPS-200. This is a repeat of the three Most Significant Bits of the 8-bit ephemeris health status words provided in the GPS navigation message. |
| $C/N_o$ | 11-15 | Satellite signal to noise ratio as measured at reference station. Scale factor 1 dB-Hz. Range is 25 to 55 dB-Hz. Bit 15 is LSB. The value "00000" indicates that the satellite is not being tracked by the reference station. The value "00001" = 25 dB-Hz at the low end and the value "11111" = 55 dB-Hz at the high end. |
| Health Enable | 16 | Bit set to 1 indicates that satellite can be considered healthy by DGPS User Equipment despite the fact that satellite navigation data indicates the satellite is unhealthy. |

**TABLE 4-8. (Continued)**

| PARAMETER | BIT NUMBER | EXPLANATION |
|---|---|---|
| New Navigation Data | 17 | Bit set to 1 indicates that new satellite navigation data is being acquired by the reference station and being integrated into the pseudorange correction generation process. There will soon be a new IOD indicated in the Type 1 Message. |
| Loss of Satellite Warning | 18 | Bit set to 1 indicates that a change in a the satellite's health to "unhealthy" is scheduled. The "healthy" time remaining is estimated by the following 4 bits. |
| Time to Unhealthy | 19-22 | See bit 18 above. Scale factor is 5 minutes. Range is 0 to 75 minutes. Bit 22 is LSB. The value "0000" indicates that the satellite is about to go "unhealthy". The value "1111" indicates the satellite will go "unhealthy in about 75 minutes. |
| Unassigned | 23-24 | TBD |
| Parity | 25-30 | |

### 4.3.6 Message Type 6 - Null Frame (Fixed)

The Type 6 Message contains no parameters. It will be used as transmission fill, if required. Its purpose is to provide messages when the Reference Station has no other message ready to send, or to synchronize the beginning of a message to some unspecified epoch. There may never be a reason to send this message. It is only defined as a contingency. It could be used as message fill in the future if higher message rates are not required because of slow error growth. Since it is a short message, it provides the user with additional preambles. This should aid in establishing and maintaining frame synchronization.

The message contains the first two words as usual with N=O or 1, depending whether or not an even or odd transmission fill is required. If N=1, then the 24 data bits in the extra word should be filled with alternating 1's and 0's. Parity should be tested as usual.

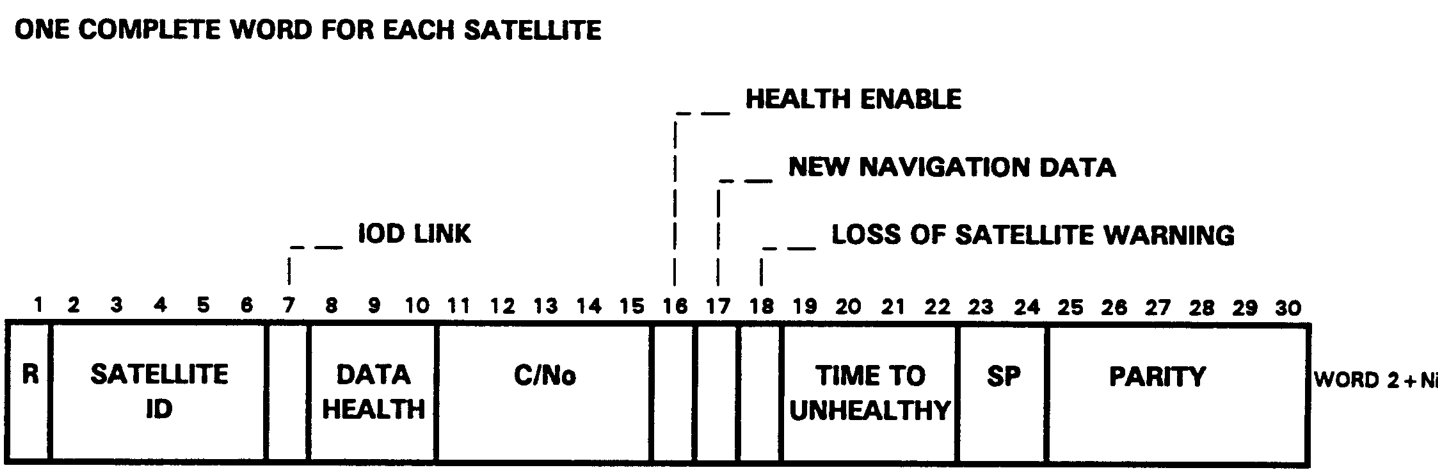


FIGURE 4-5. TYPE 5 MESSAGE - CONSTELLATION HEALTH

### 4.3.7 Message Type 7 -- Radiobeacon Almanac (Fixed)

The radiobeacon almanac provides the location, frequency, service range, and health information for a network of marine radiobeacons equipped to transmit differential GPS data. It also provides the identification of the broadcast station. The information will provide a properly equipped GPS receiver the capability of automatically selecting the optimum differential data transmitter. The radiobeacon location data resolution is coarse (0.3 Km in Latitude and 0.6 Km in Longitude), but it provides sufficient accuracy for determining the next nearest station. The range information is based on the usable signal range for data reception and is generally greater than the published radiobeacon service range. The frequency range covers both the marine and aircraft non-directional radiobeacon bands. The beacon health data provides three indications; normal, no health information available, and don't use. The content of this message is given in Table 4-9. The format is illustrated in Figure 4-6.

The message has been designed to accommodate either MSK or FSK modulation. It is left to the service provider to specify the modulation scheme used.

Provision has also been made to indicate both synchronous and asynchronous data synchronization. The preamble of each message type provides the "sync" character for MSK broadcasts. The "start" and "stop" bits provide character synchronization for asynchronous broadcasts. While all bits in a synchronous broadcast are "data" bits, only 6 or 8 bits of each character are "data" bits in an asynchronous broadcast and that convention needs to be established by the provider of the service.

A variety of Forward Error Correcting (FEC) codes (and Forward Error Detection) can be used to improve broadcast performance. A provision is included to indicate that a FEC process is being used to encode the broadcast. Again the provider of the service will have to provide information about the particular code being used in their service.

The radiobeacon almanac update rate does not have to be very high. One message every 10 minutes should be adequate for marine service. A change in the health state of the radiobeacon should prompt it to issue a new message immediately.

In order to implement Type 7 messages properly, the transmitting radiobeacon must have access to information from all the radiobeacons listed in the almanac message. The service provider must implement the network to make this possible. In addition, neighboring service providers may share information in order to facilitate transitions between different jurisdiction zones. In this manner a differential user will always be provided with current almanac data in traversing from one radiobeacon service area to the next.

THREE WORDS FOR EACH BEACON TRANSMITTER

| 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 | 17 18 19 20 21 22 23 24 | 25 26 27 28 29 30 | |
|---|---|---|---|
| LATITUDE | LONGITUDE (UPPER BYTE) | PARITY | WORD 3Nb |

| 1 8 | 9 18 | 19 24 | 25 30 | |
|---|---|---|---|---|
| LONGITUDE (LOWER BYTE) | RADIOBEACON RANGE | FREQUENCY (UPPER 6 BITS) | PARITY | WORD 3Nb + 1 |

| 1 6 | 7 8 | 9 18 | 19 21 | 22 | 23 | 24 | 25 30 | |
|---|---|---|---|---|---|---|---|---|
| FREQUENCY (LOWER 6 BITS) | HLTH | BROADCAST STATION ID | BIT RATE | MOD | SYNC | CODE | PARITY | WORD 3Nb + 2 |

**Figure 4-6. TYPE 7 MESSAGE - BEACON ALMANAC**

Table 4-9. TYPE 7 MESSAGE - BEACON ALMANAC

| PARAMETER | NO. OF BITS | SCALE/FACTOR UNITS | RANGE |
|---|---|---|---|
| LATITUDE* | 16 | 0.002747° | ±90° *** |
| LONGITUDE* | 16 | 0.005493° | ±180° *** |
| RADIOBEACON RANGE | 10 | 1 km | 0 to 1023 km |
| FREQUENCY | 12 | 100Hz | 190 (all 0's) to 599.5 kHz (all 1's) |
| RADIOBEACON HEALTH ** | 2 | See Table below | 4 states |
| BROADCAST STATION ID | 10 | 1 | 0 to 1023 |
| BROADCAST BIT RATE**** | 3 | See Table below | 8 states |
| MODULATION CODE | 1 | "0" - MSK<br>"1" - FSK | 2 states |
| SYNCHRONIZATION TYPE | 1 | "0" - Asynchronous<br>"1" - Synchronous | 2 states |
| BROADCAST CODING | 1 | "0" - No added coding<br>"1" - FEC coding | 2 states |
| | $72 \times N_b$ | $N_b$ -- Number of radiobeacons in message | |
| PARITY | N x 6 | | |

* "+" values indicate North Latitude or East Longitude

** Radiobeacon Health:
00 (0) Radiobeacon Operation Normal
01 (1) No Integrity Monitor Operating
10 (2) No information available
11 (3) Don't Use this Radiobeacon

*** 2's complement

**** Broadcast Bit Rate:

| | | | |
|---|---|---|---|
| 000 (0) | 25 bits/sec | 100 (4) | 150 bits/sec |
| 001 (1) | 50 bits/sec | 101 (5) | 200 bits/sec |
| 010 (2) | 100 bits/sec | 110 (6) | 250 bits/sec |
| 011 (3) | 110 bits/sec | 111 (7) | 300 bits/sec |

### 4.3.8 Message Type 8 - Pseudolite Almanac (Tentative)

Table 4-10 shows the proposed pseudolite almanac message. It is similar to the beacon almanac message. Latitude and longitude are two's complement binary numbers defining the approximate pseudolite position with a resolution of 180/65,536 degrees for latitude and 360/65,536 degrees for longitude. The appropriate Gold code number is given by the code number in binary form. The health bits are defined by the note below the table. Four 7-bit ASCII alphanumeric characters are provided to name the pseudolite, e.g., LAX1 or JFK3. Four spare bits are included for future use and to round the message to three whole 30-bit words per pseudolite. The entire almanac message describes three pseudolites, requires 330 bits, and takes 6.6 seconds to transmit.

**Table 4-10. CONTENTS OF A TYPE 8 PSEUDOLITE ALMANAC MESSAGE**

| PARAMETER | NUMBER OF BITS | SCALE FACTOR | RANGE |
|---|---|---|---|
| Latitude* | 16 | 0.002747° | ± 90°*** |
| Longitude* | 16 | 0.005493° | ± 180°*** |
| Code No.**** | 6 | 1 | 0- 63 |
| Health | 2 | -- | See note** |
| 4 alphanumeric | 28 | -- | 7-bit ASCII |
| Spare | 4 | -- | |
| Parity | 18 | -- | |
| | 90 x $N_p$, where $N_p$ = the number of pseudolites in the message | | |

* "+" values indicate north latitude and east longitude.

** Pseudolite health states are:
00 Pseudolite Operation Normal
01 Undefined
10 Status Unknown
11 Station Down or Do Not Use This Pseudolite

*** 2's complement

**** The Code Numbers indicate codes that don't duplicate GPS codes

### 4.3.9 Message Type 9 – Partial Satellite Set Differential Corrections (Fixed)

The Type 9 Message serves the same purpose as the Type 1 Message, in that it contains the primary differential corrections. However, unlike Type 1's, Type 9 Messages do not require a complete satellite set. As a result, they require the use of a more stable clock than a station transmitting only Type 1's, because the satellite corrections have different time references. To prevent degradation of navigation accuracy due to unmodellable clock drift that can occur between Type 9 messages, a highly stable clock source is required. Type 9's are useful in the presence of SA for providing additional updates for satellites whose rate correction variations are high. They are also useful for slow data links in the presence of impulse noise, such as that encountered in radiobeacon operation. During high noise periods, the higher rate of preambles supports a faster re-synchronization.

The average correction age is reduced by packing the corrections in groups of three in a Type 9 message, thereby improving performance. Grouping partial sets of satellite corrections, the age of the corrections can be reduced because the corrections can be applied immediately, instead of waiting until the entire Type 1 message is received. Also, if impulse noise results in a loss of data, only those satellites in the group are affected.

The content and the format of the Type 9 Message is identical to that of the Type 1 Message, except that $N_s$, the number of satellites, and N, the number of 30 bit words will be much less.

### 4.3.10 Message Type 10 - P-Code Differential Corrections (Reserved)

Message Type 10 has been assigned to the P-code users, who will want differential corrections for both L1 and L2 frequencies. Its form and content are TBD. It should be noted that the new Message Types 19 and 21 can be used with P-code signals.

### 4.3.11 Message Type 11 - C/A Code L2 Corrections (Reserved)

Message Type 11 has been reserved for C/A-code L2 corrections, in case future GPS satellites transmit the C/A code on the L2 frequency. It is expected to be similar to the Message Type 1. It should be noted that the new Message Types 19 and 21 can be used for this purpose.

### 4.3.12 Message Type 12 - Pseudolite Station Parameters (Reserved)

Message Type 12 has been reserved for a Pseudolite Station Parameter message which will provide clock offset parameters and the location of the phase center of the pseudolite transmitter antenna. It will also give the location of the GPS antenna. The details are TBD.

### 4.3.13 Message Type 13 - Ground Transmitter Parameters (Tentative)

Message Type 13 identifies the location and estimated range of the data link transmitter emitting the differential corrections. In RTCM SC-104 Version 1.0, this information was incorporated in a Message Type 3. It is a brief message, consisting of two words. Table 4-11 gives the details.

If the Status Message flag in bit 1 is set, it indicates that something unusual is happening or is going to happen, and that the details can be found in a Type 16 message. It also means that a Type 16 (ASCII) message will be broadcast sometime soon. Such a message might, for example, state that the transmitter may be going down for maintenance, and provide the planned outage period. It might also indicate that bad weather is forecast which might reduce the range of the broadcast or disrupt communications.

**TABLE 4-11. CONTENTS OF A TYPE 13 MESSAGE**

| PARAMETER | NO. OF BITS | SCALE FACTOR/UNITS | RANGE |
|---|---|---|---|
| STATUS MESSAGE | 1 | See Msg 16 | Y/N |
| XMTR RANGE FLAG | 1 | -- | Y/N |
| SPARES | 6 | | |
| XMTR LATITUDE* | 16 | 0.01° | ± 90° ** |
| XMTR LONGITUDE* | 16 | 0.01° | ± 180° ** |
| XMTR RANGE | 8 | 4 km | 4-1024 km*** |
| PARITY | 12 | | |

* 2's complement

** "+" values indicate North Latitude or East Longitude

*** All zeros indicates 1024 kilometers

If the Transmitter Range Flag is set, it indicates that the estimated range is different from that found in the Type 7 message (which contains the beacon's listed range). This could be for reasons of atmospheric noise, or because the transmitter power is being reduced.

### 4.3.14 Message Type 14 - Surveying Auxiliary Message (Reserved)

Message Type 14 has been reserved for surveying applications to provide auxiliary data such as monument coordinates, or order-of-survey supported. Content and details are TBD.

### 4.3.15 Message Type 15 - Ionosphere (Troposphere) Message (Reserved)

Message Type 15 has been reserved for parameters of models of the ionosphere and troposphere yet to be defined. The ionosphere model might be similar to the GPS model of ICD-GPS-200, but based on more timely measurement data. The troposphere model might be temperature, pressure and humidity. The content and format are TBD.

### 4.3.16 Message Type 16 - Special Message (Fixed)

Message Type 16 is a special ASCII message that can be displayed on a printer or CRT. Each Type 16 message can be up to 90 characters long. To be consistent with the other messages, the MSB is transmitted first, which means that the "data roll" described in 5.3.2 applies to this message type as well. The 8-bit ASCII code is employed, but it is anticipated that the MSB will usually be zero, because there is no standard on the meaning of other than 7-bit ASCII characters. If for special purposes a commercial operation or agency elects to use IBM graphics characters, for example, they could be sent using the Type 16 message. Fill bits are zeros for this message, in order to avoid accidental misinterpretation of the alternating 1's and 0's found as the fill pattern in other messages.

Figure 4-7 shows how the word "QUICK" would look as a Type 16 message.

| 1 2 3 4 5 6 7 8 | 9 10 11 12 13 14 15 16 | 17 18 19 20 21 22 23 24 | 25 26 27 28 29 30 | |
|---|---|---|---|---|
| "Q" | "U" | "I" | PARITY | WORD 3 |
| 0 1 0 1 0 0 0 1 | 0 1 0 1 0 1 0 1 | 0 1 0 0 1 0 0 1 | | |
| MSB LSB | | | | |

| 1 2 3 4 5 6 7 8 | 9 10 11 12 13 14 15 16 | 17 18 19 20 21 22 23 24 | 25 26 27 28 29 30 | |
|---|---|---|---|---|
| "C" | "K" | FILL | PARITY | WORD 3 |
| 0 1 0 0 0 0 1 1 | 0 1 0 0 1 0 1 1 | 0 0 0 0 0 0 0 0 | | |

FIGURE 4-7. MESSAGE TYPE 16 - ASCII ("QUICK")

### 4.3.17 Message Type 17 - Ephemeris Almanac (Tentative)

Message 17 contains satellite ephemeris information. In the event that the IODC does not match the IODE, the differential reference station would continue to base corrections on the previous good satellite ephemeris. Under this condition, the DGPS would need to broadcast the old ephemeris data. This would allow the User Equipment just entering the differential system to utilize the corrections being broadcast for that ephemeris. This would enable the use of the satellite for differential navigation despite the fact that the satellite ephemeris was in error. It is anticipated that this message type would be broadcast every 2 minutes or so while this condition persisted. The schedule would be maintained until the satellite broadcast was corrected, or until the satellite dropped below the coverage area of the reference station.

Table 4-12 defines the parameters of Message 17, showing the locations within the words.

**TABLE 4-12. CONTENTS OF TYPE 17 EPHEMERIS MESSAGE**

| WORD | PARAMETER | NUMBER OF BITS | FACTOR/ UNITS | EFFECTIVE RANGE** |
|---|---|---|---|---|
| 3 | Week Number | 10 | 1 week | |
| 3 | I DOT | 14 | $2^{-43}$ semi-circles/second | |
| 4 | IODE | 8 | $2^{11}$ seconds | |
| 4 | $t_{oc}$ | 16 | $2^{4}$ seconds | 604,784 |
| 5 | $a_{f1}$ | 16 | $2^{-43}$ sec/sec | |
| 5 | $a_{f2}$ | 8 | $2^{-55}$ sec/sec$^2$ | |
| 6 | $C_{rs}$ | 16 | $2^{-5}$ meters | |
| 6/7 | Delta n | 16 | $2^{-43}$ semi-circles/second | |
| 7 | $C_{uc}$ | 16 | $2^{-29}$ radians | |
| 8/9 | Eccentricity (e) | 32 | $2^{-33}$ | 0.03 |
| 9 | $C_{us}$ | 16 | $2^{-29}$ radians | |

TABLE 4-12. CONTINUED

| WORD | PARAMETER | NUMBER OF BITS | FACTOR/ UNITS | EFFECTIVE RANGE** |
|---|---|---|---|---|
| 10/11 | $a^{1/2}$ | 32 | $2^{-19}$ meters $^{1/2}$ | |
| 11 | $t_{oe}$ | 16 | $2^{4}$ seconds | 604,784 |
| 12/13 | $\Omega_o$ | 32 | $2^{-31}$ semi-circles | |
| 13 | $C_{ic}$ | 16 | $2^{-29}$ radians | |
| 14/15 | $i_o$ | 32 | $2^{-31}$ semi-circles | |
| 15 | $C_{is}$ | 16 | $2^{-29}$ radians | |
| 16/17 | $\Omega$ | 32 | $2^{-31}$ semi-circles | |
| 17 | $C_{rc}$ | 16 | $2^{-5}$ meters | |
| 18 | $d\Omega/dt$ (OmegaDot) | 24 | $2^{-43}$ semi-circles/second | |
| 19/20 | $M_o$ | 32 | $2^{-31}$ semi-circles | |
| 20 | IODC | 10 | $2^{11}$ seconds | |
| 20/21 | $a_{f0}$ | 22 | $2^{-31}$ seconds | |
| 21 | PRN ID | 5 | 1 | 1-32 |
| 21 | FILL | 3* | | |
| 22 | $t_{GD}$ | 8 | $2^{-31}$ seconds | |
| 22 | Code on L2 | 2 | 01 - P-code ON<br>10 - C/A-code ON | |
| 22 | SV Accuracy | 4 | 0-6: acc = $2^{(1+N/2)}$ m<br>6-14: acc = $2^{(N-2)}$ m<br>15: Use at own risk | |
| 22 | SV Health | 6 | See ICD-200, Section 20.3.3.3.1.4 | |

TABLE 4-12. CONTINUED

| WORD | PARAMETER | NUMBER OF BITS | FACTOR/ UNITS | EFFECTIVE RANGE** |
|---|---|---|---|---|
| 22 | L2 P-code Data Flag | 1 | 0 - L2 P-code data ON<br>1 - L2 P-code data OFF | |
| 22 | FILL | 3* | | |

* FILL bits consist of alternating 1's and 0's

** Range is that obtainable by bit allocation and scale factor unless otherwise indicated

### 4.3.18 Real-Time Kinematic Messages (Tentative)

Message Types 18-21 contain information useful for surveying and highly accurate positioning and navigation. The data they provide supports real-time kinematic applications which utilize real-time interferometric techniques to resolve integer ambiguities. Type 18 provides carrier phase measurements, while 19 provides pseudorange measurements. The measurements are not corrected by the ephemerides contained in the satellite message. Types 20 and 21 are corrected by the ephemerides, and are thus referred to as "corrections". Message Type 21 is very similar to the standard Type 1 message, but has additional measurement quality information, and can be used to support cross-correlation receivers.

The four new message types which support real-time kinematic applications are the following:

TABLE 4-13. REAL-TIME KINEMATIC (RTK) MESSAGES

| MESSAGE TYPE NO. | MESSAGE NAME |
|---|---|
| 18 | UNCORRECTED CARRIER PHASE MEASUREMENTS |
| 19 | UNCORRECTED PSEUDORANGE MEASUREMENTS |
| 20 | RTK CARRIER PHASE CORRECTIONS |
| 21 | RTK PSEUDORANGE CORRECTIONS |

The messages have similar formats. Word 3, the first data word after the header, contains a GPS TIME OF MEASUREMENT field which is used to increase the resolution of the MODIFIED Z-COUNT in the header. Word 3 is followed by pairs of words containing the data for each satellite observed. Appropriate flags are provided to indicate L1, L2, ionospheric free pseudorange or ionospheric difference carrier phase data, C/A or P-code, and half or full-wave L2 carrier phase measurements. The carrier smoothing interval for pseudoranges and pseudorange corrections also is furnished.

#### A. DATA QUALITY REPRESENTATION

A non-linearly quantized data quality indicator is provided for carrier phase measurements and corrections. The carrier phase data quality indicator is discussed in Appendix I.

Since reference station code multipath and receiver noise have different temporal characteristics, data quality indicators for both are provided for pseudorange measurements and corrections. In the Type 21 PSEUDORANGE CORRECTIONS message, the range of the pseudorange data quality indicator is coupled to the pseudorange correction scale factor. A change to the coarse scale factor is caused by either large pseudorange correction errors or pseudorange corrections which are larger than the fine resolution range. At the range change, the data quality error levels are consistent with the pseudorange correction resolutions. The use of separate scale factors for pseudorange corrections and pseudorange rate corrections allows fine resolution to be maintained on pseudorange corrections when Selective Availability forces transmission of coarse resolution pseudorange rate corrections. The pseudorange and multipath data quality indicators are further discussed in Appendix II.

## B. CARRIER PHASE CORRECTION

A carrier phase correction is similar to a pseudorange correction, but is computed using reference station carrier phase measurements. At the reference station it is computed as:

> CARRIER PHASE CORRECTION = Predicted Satellite to Reference Station Range (in carrier cycles) - Measured Carrier Phase for the GPS TIME OF MEASUREMENT.

To avoid large biases in the corrections, the initial whole cycle ambiguity is reduced to a small value at the initial epoch. L1 and L2 CARRIER PHASE CORRECTIONs are corrected for reference receiver clock offset but not for ionospheric or tropospheric delay. Ionospheric difference CARRIER PHASE CORRECTIONs are corrected for reference receiver clock offset but not for tropospheric delay.

At the user receiver, CARRIER PHASE CORRECTIONs are applied as:

> Corrected User Carrier Phase = Measured User Carrier Phase + CARRIER PHASE CORRECTION.

Computation and application of carrier phase corrections are further discussed in Appendix IV.

## C. IMPLEMENTATION ISSUES

### a. <u>Satellite Position Computation Accuracy</u>

For precise differential positioning, common satellite positions and satellite clock offsets must have common values (to centimeter accuracy) for both reference and user receivers. When raw measurements are used, generally the same algorithms are used for both sites so that algorithmic errors (nearly) cancel when differenced. When CARRIER PHASE CORRECTIONs are used, the reference and user receivers may well use different algorithms. Therefore, a manufacturer must assure a high level of accuracy in computing satellite positions and satellite clock offsets. Appendix III provides sample computations and describes the format of additional data files which can be used to validate satellite position and clock offset computation.

### b. <u>Antenna Phase Center Stability</u>

The apparent phase center location of an antenna may vary with direction of signal incidence. The phase center stability characteristics can differ for different antenna designs and ground plane configurations. For precise (centimeter level) positioning, the phase center characteristics of the reference and user receiver antennas must be matched or differences compensated. For local use systems, this often is accomplished by using the same antenna and ground plane design at both locations. Common variations in phase center shift cancel when differenced. The system designer may have little control over the phase shift characteristics of antennas used with public access systems. In this case, the reference station operator must provide the reference station antenna characteristics so users can select antennas with similar characteristics or make appropriate compensations when processing the data. An alternative would be to compensate the reference station carrier phase data to a fixed antenna phase center based on antenna calibration data. At this time, no standards for antenna phase center stability are proposed. The system designer must insure the errors are within the system error budget.

c. Issue of Data

When using broadcast ephemeris and satellite clock correction data, the same issue of data must be used at the reference and user sites. When raw measurements are processed for differential positioning, usually the same ephemeris data is used for all sites. When corrections are computed at the reference station and applied at the user's site, the possibility exists that they may be different. Rather than computing and broadcasting corrections for two different issues of data, it is recommended that the reference station wait 60 seconds after acquiring a new issue of data before transmitting corrections computed with the new issue of data. This allows the user receiver sufficient time to acquire the new data set. The issue of data used to compute corrections always is transmitted with the corrections.

d. Bad Reference Station Data

Erroneous or invalid data for any satellite should not be included in any messages sent by the reference station.

## D. MESSAGE FORMAT STATUS

The recommended new message formats are expected to prove useful for their intended purposes. However, the formats have not yet been implemented, and have thus not been subjected to field experience. It is expected that these will be declared as "Fixed" in approximately one year after the publication of this document.

#### 4.3.19 Message Type 18 - Uncorrected Carrier Phase Measurements (Tentative)

**THIRD WORD**

| 1 2 | 3 4 | 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 | 25 26 27 28 29 30 | |
|---|---|---|---|---|
| F | SP | GPS TIME OF MEASUREMENT | PARITY | WORD 3 |

**EACH SATELLITE - 2 WORDS**

| 1 | 2 | 3 | 4 5 6 7 8 | 9 10 11 | 12 13 14 15 16 | 17 18 19 20 21 22 23 24 | 25 26 27 28 29 30 | |
|---|---|---|---|---|---|---|---|---|
| H F | P C | R | SATELLITE ID | DATA QUAL | CUM. LOSS OF CONTINUITY | CARRIER PHASE UPPER BYTE | PARITY | WORD 2Ni+2 |

| 1 – 24 | 25 – 30 | |
|---|---|---|
| CARRIER PHASE LOWER THREE BYTES | PARITY | WORD 2Ni+3 |

**FIGURE 4-8. MESSAGE TYPE 18 - UNCORRECTED CARRIER PHASE**

F = FREQUENCY COMBINATION INDICATOR
L1 = 00, L2 = 10, IONOSPHERIC DIFFERENCE = 01, SPECIAL = 11
(SPECIAL indicates a special purpose or experimental application. Users must insure data indicated as SPECIAL are compatible with their system.)

SP = Spare

GPS TIME OF MEASUREMENT
RESOLUTION: 1 microsecond
RANGE: 0 to 599999 microseconds

Expanded Time of Measurement = GPS TIME OF MEASUREMENT + MODIFIED Z-COUNT (from header). The time shall be referenced to GPS time.

All CARRIER PHASEs in the message shall be determined for the Expanded Time of Measurement. The GPS TIME OF MEASUREMENT for a message containing L2 or ionospheric difference data shall be the same as that in the corresponding message containing L1 data.

$N_s$ = Number of satellites; $N = 2N_s + 3$; message length $= 2N_s + 5$.

H/F = HALF/FULL L2 WAVELENGTH INDICATOR FULL = 0, HALF = 1
H shall be set to 0 for L1.

P/C = C/A-Code/P-Code INDICATOR C/A-Code = 0, P-Code = 1
L1 C/A-code and P-code carriers are transmitted in quadrature. Transmitted L1 P-code uncorrected phase measurements shall not be adjusted to C/A-code equivalent measurements or vice versa. The C/A-Code/P-Code INDICATOR shall indicate whether the L1 C/A-code or P-code carrier was used to compute an ionospheric difference. Ionospheric difference measurements shall not be adjusted for differences in quadrature.

R = Reserved for future expansion of Satellite ID

SATELLITE ID
RESOLUTION: 1
RANGE: 1-32 (Satellite number 32 is indicated by 0.)

DATA QUALITY
The carrier phase data quality indicator is the estimated one sigma phase measurement error indicated by $\frac{1}{256}e^{X/\sqrt{3}}$ cycles where X is the decimal equivalent of the 3-bit indication

### TABLE 4-14. DATA QUALITY INDICATOR QUANTIZATION

| CODE (X) | DATA QUALITY INDICATION |
|---|---|
| 000 (0) | Phase Error ≤ 0.00391 cycle |
| 001 (1) | ≤ 0.00696 |
| 010 (2) | ≤ 0.01239 |
| 011 (3) | ≤ 0.02208 |
| 100 (4) | ≤ 0.03933 |
| 101 (5) | ≤ 0.07006 |
| 110 (6) | ≤ 0.12480 |
| 111 (7) | > 0.12480 |

CUMULATIVE LOSS OF CONTINUITY INDICATOR
RESOLUTION: 1
RANGE: 0 to 31

The CUMULATIVE LOSS OF CONTINUITY INDICATOR shall be incremented each time continuity of the CARRIER PHASE measurement is lost (unfixed cycle slip or loss of lock.) For ionospheric differences, the CUMULATIVE LOSS OF CONTINUITY INDICATOR shall be incremented each time continuity of either or both of the L1 or L2 carrier phase measurements is lost.

CARRIER PHASE

RESOLUTION: 1/256 Full Cycle, 1/128 Half Cycle
RANGE: ±8,388,608 Full Cycles, ±16,777,216 Half Cycles

$$\Phi_{IONODIFF} = \frac{60}{77}\Phi_{L1} - \Phi_{L2} \qquad \text{(full wavelength L2 cycles)}$$

$$\Phi_{IONODIFF} = \frac{120}{77}\Phi_{L1} - \Phi_{L2} \qquad \text{(half wavelength L2 cycles)}$$

Where:
$\Phi_{IONODIFF}$ = Ionospheric Difference Phase Measurement
$\Phi_{L1}$ = L1 Carrier Phase Measurement
$\Phi_{L2}$ = L2 Carrier Phase Measurement

Full cycle carrier phase data shall not be transmitted until the correct polarity has been resolved.

CARRIER PHASE data for a given satellite shall not be transmitted for those GPS TIMES OF MEASUREMENT when valid data are not available.

The data range for CARRIER PHASE is less than the total possible range measured by the reference receiver. The user must detect "rollovers" in the data and reconstruct the complete phase measurement.

### 4.3.20 Message Type 19 - Uncorrected Pseudorange Measurements (Tentative)

**THIRD WORD**

| 1 2 | 3 4 | 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 | 25 26 27 28 29 30 | |
|---|---|---|---|---|
| F | SM | GPS TIME OF MEASUREMENT | PARITY | WORD 3 |

**EACH SATELLITE - 2 WORDS**

| 1 | 2 | 3 | 4 5 6 7 8 | 9 10 11 12 | 13 14 15 16 | 17 18 19 20 21 22 23 24 | 25 26 27 28 29 30 | |
|---|---|---|---|---|---|---|---|---|
| SP | P/C | R | SATELLITE ID | DATA QUAL | MULTIPATH ERROR | PSEUDORANGE (UPPER BYTE) | PARITY | WORD 2Ni+2 |

| | | |
|---|---|---|
| PSEUDORANGE (LOWER 3 BYTES) | PARITY | WORD 2Ni+3 |

**FIGURE 4-9. MESSAGE TYPE 19 - UNCORRECTED PSEUDORANGE MEASUREMENTS**

F = FREQUENCY COMBINATION INDICATOR
L1 = 00, L2 = 10, IONOSPHERIC FREE = 01, SPECIAL = 11
(SPECIAL indicates a special purpose or experimental application. Users must insure data indicated as SPECIAL are compatible with their system.)

SM = SMOOTHING INTERVAL

Indicates the interval for carrier smoothing of pseudorange data.

**TABLE 4-15. SMOOTHING INTERVAL CODING**

| SMOOTH CODE | Smoothing Interval (Minutes) |
|---|---|
| 00 (0) | 0 to 1 |
| 01 (1) | 1 to 5 |
| 10 (2) | 5 to 15 |
| 11 (3) | Indefinite |

GPS TIME OF MEASUREMENT

RESOLUTION: 1 microsecond

RANGE: 0 to 599999 microseconds

Expanded Time of Measurement = GPS TIME OF MEASUREMENT + MODIFIED Z-COUNT (from header). The time shall be referenced to GPS time.

All PSEUDORANGES in the message shall be determined for the Expanded Time of Measurement. The GPS TIME OF MEASUREMENT for a message containing L2 data shall be the same as that in the corresponding message containing L1 data.

$N_s$ = Number of satellites; $N = 2N_s + 3$; message length $= 2N_s + 5$.

SP = SPARE

P/C = C/A-Code/P-Code INDICATOR    C/A-Code = 0, P-Code = 1

R = Reserved for future expansion of Satellite ID

SATELLITE ID

RESOLUTION: 1

RANGE: 1-32 (Satellite number 32 is indicated by 0.)

DATA QUALITY

The data quality indicator is the estimated one sigma pseudorange measurement error indicated as $0.02e^{0.4X}$ meters where X is the decimal equivalent of the indicator code.

**TABLE 4-16. PSEUDORANGE DATA QUALITY INDICATOR QUANTIZATION**

| CODE (X) | DATA QUALITY INDICATION |
|---|---|
| 0000 (0) | Pseudorange Error ≤ 0.020 meter |
| 0001 (1) | ≤ 0.030 |
| 0010 (2) | ≤ 0.045 |
| 0011 (3) | ≤ 0.066 |
| 0100 (4) | ≤ 0.099 |
| 0101 (5) | ≤ 0.148 |
| 0110 (6) | ≤ 0.220 |
| 0111 (7) | ≤ 0.329 |
| 1000 (8) | ≤ 0.491 |
| 1001 (9) | ≤ 0.732 |
| 1010 (10) | ≤ 1.092 |
| 1011 (11) | ≤ 1.629 |
| 1100 (12) | ≤ 2.430 |
| 1101 (13) | ≤ 3.625 |
| 1110 (14) | ≤ 5.409 |
| 1111 (15) | > 5.409 |

MULTIPATH ERROR

The multipath error indicator is the estimated multipath error indicated as $0.1e^{0.4X}$ meters where X is the decimal equivalent of the indicator code. An X of 15 indicates that multipath error was not determined.

**TABLE 4-17. PSEUDORANGE MULTIPATH ERROR INDICATOR QUANTIZATION**

| CODE (X) | MULTIPATH INDICATION |
|---|---|
| 0000 (0) | Multipath Error ≤ 0.100 meter |
| 0001 (1) | ≤ 0.149 |
| 0010 (2) | ≤ 0.223 |
| 0011 (3) | ≤ 0.332 |
| 0100 (4) | ≤ 0.495 |
| 0101 (5) | ≤ 0.739 |
| 0110 (6) | ≤ 1.102 |
| 0111 (7) | ≤ 1.644 |
| 1000 (8) | ≤ 2.453 |
| 1001 (9) | ≤ 3.660 |
| 1010 (10) | ≤ 5.460 |
| 1011 (11) | ≤ 8.145 |
| 1100 (12) | ≤ 12.151 |
| 1101 (13) | ≤ 18.127 |
| 1110 (14) | > 18.127 |
| 1111 (15) | Multipath error not determined |

PSEUDORANGE

RESOLUTION: 0.02 meter

RANGE: 0 to 85,899,345.90 meters

Ionospheric free pseudoranges shall be calculated from dual frequency measurements, not computed from single frequency measurements and the broadcast ionospheric model parameters.

4.3.21 Message Type 20 - RTK Carrier Phase Corrections (Tentative)

**THIRD WORD**

| Bits 1–2 | Bits 3–4 | Bits 5–24 | Bits 25–30 | |
|---|---|---|---|---|
| F | SP | GPS TIME OF MEASUREMENT | PARITY | WORD 3 |

**EACH SATELLITE - 2 WORDS**

| Bit 1 | Bit 2 | Bit 3 | Bits 4–8 | Bits 9–11 | Bits 12–16 | Bits 17–24 | Bits 25–30 | |
|---|---|---|---|---|---|---|---|---|
| H F | SP | R | SATELLITE ID | DATA QUAL | CUM. LOSS OF CONTINUITY | ISSUE OF DATA | PARITY | WORD 2Ni + 2 |

| Bits 1–24 | Bits 25–30 | |
|---|---|---|
| CARRIER PHASE CORRECTION | PARITY | WORD 2Ni + 3 |

**FIGURE 4-10. MESSAGE TYPE 20 - CARRIER PHASE CORRECTIONS**

F = FREQUENCY COMBINATION INDICATOR
L1 = 00, L2 = 10, IONOSPHERIC DIFFERENCE = 01, SPECIAL = 11
(SPECIAL indicates a special purpose or experimental application. Users must insure data indicated as SPECIAL are compatible with their system.)

GPS TIME OF MEASUREMENT
RESOLUTION: 1 microsecond
RANGE: 0 to 599999 microseconds

Expanded Time of Measurement = GPS TIME OF MEASUREMENT + MODIFIED Z-COUNT (from header). The time shall be referenced to GPS time.

All CARRIER PHASE CORRECTIONs in the message shall be determined for the Expanded Time of Measurement. The GPS TIME OF MEASUREMENT for a message containing L2 or ionospheric difference data shall be the same as that in the corresponding message containing L1 data.

$N_s$ = Number of satellites; $N = 2N_s + 3$; message length $= 2N_s + 5$.

H/F = HALF/FULL L2 WAVELENGTH INDICATOR: HALF = 1, FULL = 0
H shall be set to 0 for L1.

SP = SPARE

R = Reserved for future expansion of Satellite ID

SATELLITE ID
RESOLUTION: 1
RANGE: 1-32 (Satellite number 32 is indicated by 0.)

DATA QUALITY
The carrier phase data quality indicator is the estimated one sigma phase measurement error indicated by $\frac{1}{256}e^{X/\sqrt{3}}$ cycles where X is the decimal equivalent of the 3-bit indication.

**TABLE 4-18. DATA QUALITY INDICATOR QUANTIZATION**

| CODE (X) | DATA QUALITY INDICATION |
|---|---|
| 000 (0) | Phase Error ≤ 0.00391 cycle |
| 001 (1) | ≤ 0.00696 |
| 010 (2) | ≤ 0.01239 |
| 011 (3) | ≤ 0.02208 |
| 100 (4) | ≤ 0.03933 |
| 101 (5) | ≤ 0.07006 |
| 110 (6) | ≤ 0.12480 |
| 111 (7) | > 0.12480 |

CUMULATIVE LOSS OF CONTINUITY INDICATOR
RESOLUTION: 1
RANGE: 0 to 31

The CUMULATIVE LOSS OF CONTINUITY INDICATOR shall be incremented each time the CARRIER PHASE CORRECTION is reinitialized. For ionospheric differences, the CUMULATIVE LOSS OF CONTINUITY INDICATOR shall be incremented each time continuity of either or both of the L1 or L2 carrier phase measurements is lost.

ISSUE OF DATA (per ICD-GPS-200)

The ISSUE OF DATA shall be that of the data used to compute the predicted range for the CARRIER PHASE CORRECTION computation. The reference station shall delay use of a newly acquired data set for 60 seconds to allow remote receivers sufficient time to acquire the new ISSUE OF DATA.

CARRIER PHASE CORRECTION

RESOLUTION: 1/256 Full Wavelength, 1/128 Half Wavelength
RANGE: ±32768 Full Wavelengths, ±65536 Half Wavelengths

CARRIER PHASE CORRECTION = Predicted Satellite to Reference Station Range (in carrier cycles) - Measured Carrier Phase for the GPS TIME OF MEASUREMENT.

In order to avoid large biases in the phase corrections, the initial whole cycle value of the phase measurements shall be set to the code value at the initial GPS TIME OF MEASUREMENT. Alternatively, it can be set such that the phase correction at the initial time has a whole cycle value of zero. CARRIER PHASE CORRECTIONs shall be corrected for reference station receiver clock offset at the GPS TIME OF MEASUREMENT. L1 and L2 carrier phase corrections shall not be adjusted for ionospheric delay. Carrier phase corrections shall not be adjusted for tropospheric delay.

$$\Phi_{IONODIFF} = \frac{60}{77}\,\Phi_{L1} - \Phi_{L2} \qquad \text{(full wavelength L2)}$$

$$\Phi_{IONODIFF} = \frac{120}{77}\,\Phi_{L1} - \Phi_{L2} \qquad \text{(half wavelength L2)}$$

Where:

$\Phi_{IONODIFF}$ = Ionospheric Difference Phase Correction
$\Phi_{L1}$ = L1 Carrier Phase Correction
$\Phi_{L2}$ = L2 Carrier Phase Correction

L1 CARRIER PHASE CORRECTIONs shall be full wavelength and shall not be transmitted until the correct polarity has been resolved. P-code L1 carrier phase measurements, used to compute L1 or ionospheric difference CARRIER PHASE CORRECTIONs, shall be corrected for quadrature to match the C/A code carrier phase. (L1 Corrected Phase = L1 P-Code Phase - 90 degrees.)

CARRIER PHASE CORRECTIONs for a given satellite shall not be transmitted for those TIMEs OF MEASUREMENT when valid data are not available to compute the correction.

### 4.3.22 Message Type 21 - RTK Pseudorange Corrections (Tentative)

**THIRD WORD**

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

| F | SM | GPS TIME OF MEASUREMENT | PARITY | WORD 3 |
|---|---|---|---|---|

**EACH SATELLITE - 2 WORDS**

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

| R SF | P C | R | SATELLITE ID | PR SF | DATA QUAL | MULTIPATH ERROR | ISSUE OF DATA | PARITY | WORD 2Ni+2 |
|---|---|---|---|---|---|---|---|---|---|

| PSEUDORANGE CORRECTION | RANGE RATE CORRECTION | PARITY | WORD 2Ni+3 |
|---|---|---|---|

**FIGURE 4-11. MESSAGE TYPE 21 - PSEUDORANGE CORRECTIONS (tentative)**

F = FREQUENCY COMBINATION INDICATOR

L1 = 00, L2 = 10, IONOSPHERIC FREE = 01, SPECIAL = 11

(SPECIAL indicates a special purpose or experimental application. Users must insure data indicated as SPECIAL are compatible with their system.)

SMOOTH

Indicates the interval for carrier smoothing of pseudorange data.

**TABLE 4-19. SMOOTHING INTERVAL CODING**

| SMOOTH CODE | Smoothing Interval (Minutes) |
|---|---|
| 00 (0) | 0 to 1 |
| 01 (1) | 1 to 5 |
| 10 (2) | 5 to 15 |
| 11 (3) | Indefinite |

GPS TIME OF MEASUREMENT
RESOLUTION: 1 microsecond
RANGE: 0 to 599999 microseconds

Expanded Time of Measurement = GPS TIME OF MEASUREMENT + MODIFIED Z-COUNT (from header). The time shall be referenced to GPS time.

All PSEUDORANGEs in the message shall be determined for the Expanded Time of Measurement. The GPS TIME OF MEASUREMENT for a message containing L2 data shall be the same as that in the corresponding message containing L1 data.

$N_s$ = Number of satellites; $N = 2N_s + 3$; message length $= 2N_s + 5$.

R SF = Pseudorange Rate Correction Scale Factor
See PSEUDORANGE RATE CORRECTION below.

P = C/A-Code/P-Code INDICATOR C/A-Code = 0, P-Code = 1
If the L2 pseudorange is recovered in the presence of the Y-code, without using decryption, set P = 0 (C/A-code) and F = 10 (L2.)

R = Reserved for future expansion of Satellite ID

SATELLITE ID
RESOLUTION: 1
RANGE: 1-32 (Satellite number 32 is indicated by 0.)

PR SF = Pseudorange Correction Scale Factor
See DATA QUALITY and PSEUDORANGE CORRECTION below.

DATA QUALITY

The data quality indicator is the estimated one sigma pseudorange measurement error indicated as $0.02e^{0.4X}$ meters, for pseudorange correction scale factor = 0, and $0.4907e^{0.4X}$ meters, for pseudorange correction scale factor = 1, where X is the decimal equivalent of the indicator code.

**TABLE 4-20. PSEUDORANGE DATA QUALITY INDICATOR QUANTIZATION**

| CODE (X) | PSEUDORANGE ERROR | |
|---|---|---|
| | SCALE FACTOR = 0 | SCALE FACTOR = 1 |
| 000 (0) | ≤ 0.020 meter | ≤ 0.491 meter |
| 001 (1) | ≤ 0.030 | ≤ 0.732 |
| 010 (2) | ≤ 0.045 | ≤ 1.092 |
| 011 (3) | ≤ 0.066 | ≤ 1.629 |
| 100 (4) | ≤ 0.099 | ≤ 2.430 |
| 101 (5) | ≤ 0.148 | ≤ 3.625 |
| 110 (6) | ≤ 0.220 | ≤ 5.409 |
| 111 (7) | ≤ 0.329 | > 5.409 |

MULTIPATH ERROR

The multipath error indicator is the estimated multipath error indicated as $0.1e^{0.4X}$ meters where X is the decimal equivalent of the indicator code. An X of 15 indicates that multipath error was not determined.

**TABLE 4-21. PSEUDORANGE MULTIPATH ERROR INDICATOR QUANTIZATION**

| CODE (X) | MULTIPATH INDICATION |
|---|---|
| 0000 (0) | Multipath Error ≤ 0.100 meter |
| 0001 (1) | ≤ 0.149 |
| 0010 (2) | ≤ 0.223 |
| 0011 (3) | ≤ 0.332 |
| 0100 (4) | ≤ 0.495 |
| 0101 (5) | ≤ 0.739 |
| 0110 (6) | ≤ 1.102 |
| 0111 (7) | ≤ 1.644 |
| 1000 (8) | ≤ 2.453 |
| 1001 (9) | ≤ 3.660 |
| 1010 (10) | ≤ 5.460 |
| 1011 (11) | ≤ 8.145 |
| 1100 (12) | ≤ 12.151 |
| 1101 (13) | ≤ 18.127 |
| 1110 (14) | > 18.127 |
| 1111 (15) | Multipath error not determined |

ISSUE OF DATA See ICD-GPS-200

The ISSUE OF DATA shall be that of the data used to compute the predicted range for the PSEUDORANGE CORRECTION computation. The Reference Station shall delay use of a newly acquired set for 60 seconds to allow remote receivers sufficient time to acquire the new data corresponding to that ISSUE OF DATA.

PSEUDORANGE CORRECTION

RESOLUTION: 0.02 meter when PR SF = 0
0.32 meter when PR SF = 1

RANGE: ±655.34 meters when PR SF = 0
±10485.44 meters when PR SF = 1

PSEUDORANGE CORRECTION = Predicted Satellite to Reference Station Range (in meters) - Measured Pseudorange for the GPS TIME OF MEASUREMENT.

PSEUDORANGE CORRECTIONs shall be corrected for Reference Station receiver clock offset at the GPS TIME OF MEASUREMENT. Corrections for tropospheric delay shall not be applied. L1 and L2 PSEUDORANGE CORRECTIONs shall not be adjusted for ionospheric delay. Ionospheric free PSEUDORANGE CORRECTIONs shall be calculated from dual frequency measurements, not computed from single frequency measurements and the broadcast ionospheric model parameters. Corrections for multipath may be applied. Residual multipath errors shall be reflected in the MULTIPATH ERROR INDICATOR.

PSEUDORANGE CORRECTIONs for a given satellite shall not be transmitted for those GPS TIMEs OF MEASUREMENT when valid data are not available to compute the correction.

PSEUDORANGE RATE CORRECTION

| | |
|---|---|
| RESOLUTION: | 0.002 meters/second for R SF = 0 |
| | 0.032 meters/second for R SF = 1 |
| RANGE: | ±0.254 meters/second for R SF = 0 |
| | ±4.064 meters/second for R SF = 1 |

### 4.3.23 Undefined Messages

Message Types 22 through 58 are undefined at this time. They are available for future designation as new requirements are identified.

### 4.3.24 Message Type 59 - Proprietary Message (Reserved)

Message Type 59 is reserved for private use by operators who wish to use their data links to communicate proprietary information to their users. It is anticipated that if such operators wish to send more than one type of message, it is their responsibility to design their format to allow for multiple sub-message types. The first eight bits in the third word (the word immediately following the header) shall serve as the identification code for the operator.

### 4.3.25 Message Types 60-63 - Multipurpose Usage (Reserved)

Message Types 60-63 are reserved, at least temporarily, for use in exploring the use of multi-purpose data links. Since the standards for broadcast have already been set up by this Committee, the SC-104 format can be used to transmit differential Loran-C, differential Omega, weather messages, or other navigational information. Four message types have been reserved to explore such options.

## 4.4 MESSAGE RATE OF TRANSMISSION

The purpose of the variable length format of the differential GPS Messages is to maximize the rate of transmission of the Type 1 Messages. Estimates of that rate of transmission are provided here. The following discussion is provided for guidance only; for example, the message rates cited are not to be construed as requirements for implementation.

A typical scenario would be to transmit the Type 1 Message as often as possible, interleaved with Type 2, 3, 5, 7 and 16 Messages. If the Type 2 Message were transmitted at an approximate rate of once per minute, the Type 3 and 5 Messages alternated once per minute and the Types 7 and 16 Message (of length 9 words total) once per 5 minutes at a rate of 50 bits per second, the average transmission rate of the Type 1 Message would be as given in column two of Table 4-22 for 4, 7 and 11 satellites in view.

**TABLE 4-22. AVERAGE TRANSMISSION RATES AT 50 bps**

| NO. OF SATELLITES | AVERAGE TRANSMISSION RATE* (TYPE 1 MESSAGE) | AVERAGE TRANSMISSION RATE* USING TYPE 9 MESSAGES ONCE PER TYPE 1 TRANSMISSION | |
|---|---|---|---|
| | | NON-REPEATED SATELLITES | REPEATED SATELLITES |
| 4 | 1/6.67 SEC | 1/9.62 SEC | 1/4.81 SEC |
| 7 | 1/11.11 SEC | 1/14.11 SEC | 1/7.05 SEC |
| 11 | 1/18.18 SEC | 1/21.71 SEC | 1/10.85 SEC |

* Over 10 minutes.

The significance of these average transmission rates is illustrated in Figure 4-12. The SA error rates dominate the message update requirement. Based on data provided to the Department of Transportation by the GPS Joint Program Office a typical differential position error growth versus time is as illustrated in that figure for the SA data provided plus errors at twice that of the SA data provided. The one sigma positioning error growth for 4, 7 and 11 satellites is indicated, showing less than 3 meters in all cases.

These errors are, of course, qualitative. Not taken into account is the fact that HDOP will, in general, be better when there are more satellites in view, thus tending to flatten the error growth as a function of the number of satellites. On the other hand, during periods when the HDOP is larger than 1.5, the errors will be proportionately higher.

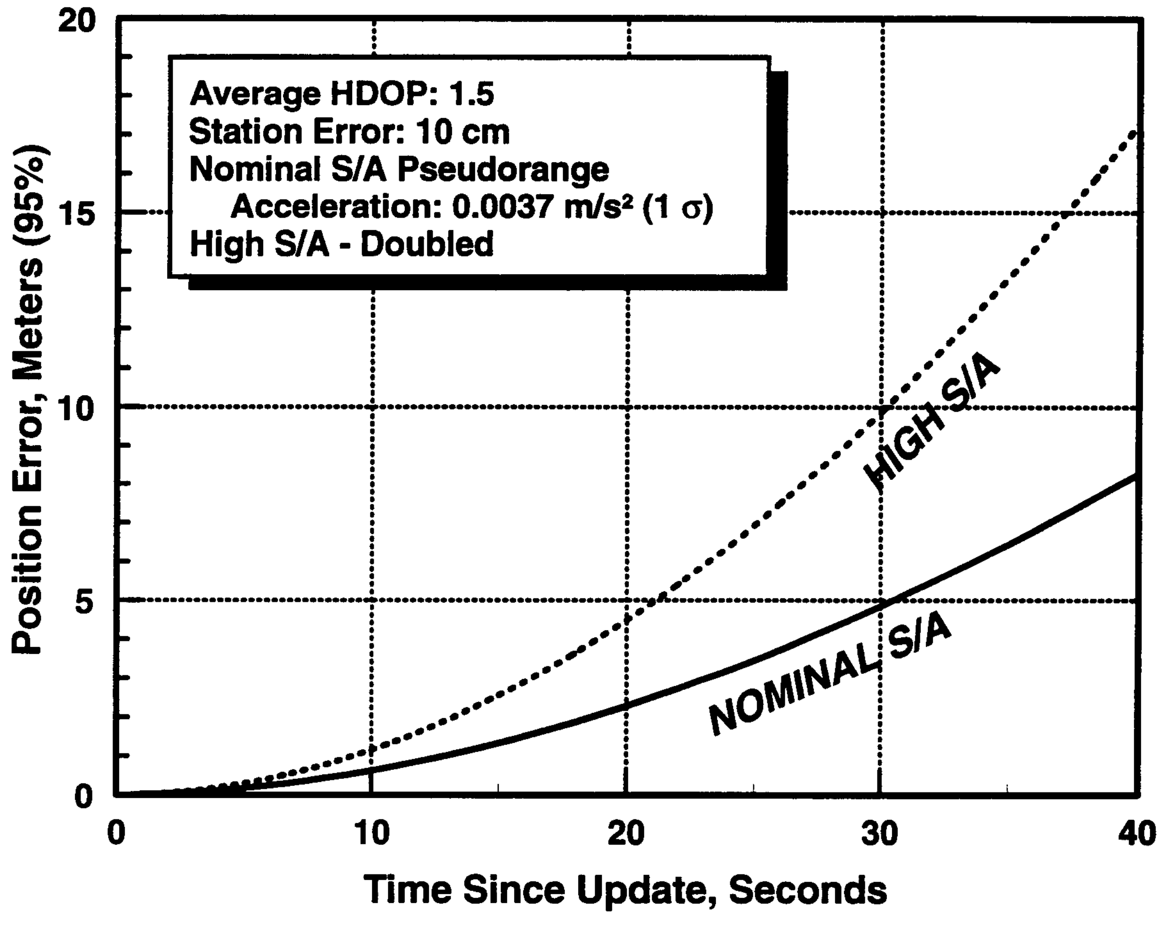


FIGURE 4-12. DIFFERENTIAL ERROR GROWTH DUE TO SELECTIVE AVAILABILITY

The Type 9 Message can also be used to improve the performance of data links which are susceptible to interference from impulse noise, such as radiobeacon data links. Grouping satellites in blocks of three significantly improves the data link performance in two ways. First, when Type 9 Messages contain the corrections for three satellites their initially lower ages of corrections more than compensates for their longer propagation time associated with the increased overhead. This is illustrated in Table 4-23. Second, the short length of the Type 9 Message provides an increased noise immunity and allows a more rapid resynchronization, due to the fact that the preamble is transmitted at a much higher rate. Note that unlike the case for Type 1 Messages, corrections from Type 9 Messages can be applied as soon as they are received (see Section 5.3.5.) thus further reducing the average PRC latency and lowering the susceptibility of the messages to channel noise.

**TABLE 4-23. PRC AGE OF CORRECTIONS AT 100bps**

| | MAX PRC LATENCY | |
|---|---|---|
| NO. OF SATELLITES | TYPE 1 | TYPE 9 (3 SATS/MSG) |
| 4 | 5.4 sec | 5.4 sec |
| 6 | 7.2 sec | 6.3 sec |
| 8 | 9.6 sec | 8.1 sec |
| 9 | 10.2 sec | 8.4 sec |

# 5. GPS RECEIVER TO DATA LINK EQUIPMENT INTERFACE

## 5.1 INTRODUCTION

In Chapter 4 the various message types and their digital format were presented. However, a data link is required to move this information from the differential GPS reference station to the mobile receiver. This section presents recommended standards on the operation of the data transmitter and data receiver that interface with the ground and mobile GPS receivers. It is recognized that it is possible to integrate the GPS receiver and data transmitter or receiver at either end of the link, in which case the interface requirements described here are not applicable.

Data link operation is described in Section 3.4. Figure 3-2 shows the reference station functions that are involved. The reference receiver processes the GPS sensor data and develops corrections, which are then fed to the data transmitter at a speed higher than the link data rate. The data transmitter formats and buffers the incoming data, then modulates the data onto a transmitter carrier for broadcast to mobile user equipments. Figure 3-4 shows the corresponding functions for the user. In both cases it is necessary to provide standards for the interfaces between GPS receivers and data transmitters and receivers in order to promote interoperability.

## 5.2 INTERFACE SPECIFICATION

The GPS equipment shall be designed in such a way that the digital data link information enters and exits through an asynchronous full duplex serial input/output port. Good general purpose commercial practices are recommended, rather than military or avionics standards. The choice of the electrical connector is left to the GPS user equipment manufacturer. The signal voltage levels should conform to either the EIA RS-232-C (1) or RS-422-A/RS-449 (2 and 3). A synopsis of these signals is contained in Table 5-1.

**TABLE 5-1. SYNOPSIS OF SIGNAL VOLTAGE LEVELS**

**RS-232-C INTERCHANGE**

| | | |
|---|---|---|
| SIGNAL VOLTAGE<br>SIGNAL PIN TO GROUND | -25 TO -3 | +3 TO +25 |
| BINARY STATE | 1 | 0 |
| SIGNAL CONDITION | MARKING | SPACING |

**RS-422-A INTERCHANGE**

| | | |
|---|---|---|
| DIFFERENTIAL SIGNAL VOLTAGE<br>SIGNAL PIN "A" TO "B" | -6 TO -2 | +2 TO +6 |

The American National Standards Institute (ANSI) X3.16 (4) and X3.15 (5) standards for eight-bit character structure shall govern the rules for serial data transfers. Note that the use of all eight bits in the transfer of serial data precludes the use of 7 bit parity formats. The recommended protocol being 8 bits, no parity, 1 stop bit. The serial data rate should be selectable at least over the 300 to 9600 baud range (300, 600, 1200, 2400, 4800, or 9600 baud). As a minimum the user equipment shall be designed to handle a continuous information rate of 30 eight bit bytes every second.

## 5.3 IMPORTANT INTERFACE RULES

Although the data is packaged in 8 bit bytes, the interpretation of what each of the 8 bits means is dictated by a combination of what was presented in Section 4 and rules that follow.

### 5.3.1 Byte Format Rule

A standard 8-bit byte is described as the "8-Bit Environment" in ANSI X3.16(4). This standard assigns the order of the start, stop, and eight data bits: the first data bit transmitted is designated "$a_1$" and the last is "$a_8$"; bit "$a_1$" is designated the least significant bit. This is a source of problems and is discussed in the next section (see 5.3.2).

All equipment shall support the use of the "6 of 8" format (data bits $a_1$ through $a_6$) to transfer the information contained in Chapter 4. As an indication that bits $a_1$ through $a_6$ are "message information", bit $a_7$ shall be set "marking" and $a_8$ shall be set "spacing". The appropriate mark and space signaling conditions are discussed in EIA RS-232-C(1) and EIA RS-422-A (2).

### 5.3.2. Most Significant Bit First Rule

The Data Link (see Section 3.4) binary information shall always be passed in the order it appears in Section 4. This is known as most significant bit first. This facilitates the introduction of pure synchronous data links between the reference station and user equipment. Unfortunately, the ANSI X3.15-1976 standard states that the least significant bit is first. Almost all integrated circuits designed for serial communications follow this convention. The use of X3.15 standard Universal Asynchronous Receivers and Transmitters (UARTs) introduces the need for a "byte roll" prior to leaving the reference station equipment and then again just after entering the GPS user equipment. The following is from ANSI standard X3.15-1976 (5): "The bit sequence for an ASCII character shall be least significant bit first to most significant bit - in terms of the 7-bit ASCII nomenclature (6) $b_1$ through $b_7$ in ascending (consecutive) order, or in terms of the 8-bit nomenclature (7) $a_1$ through $a_8$ in ascending (consecutive) order".

The "roll" process is performed on each byte prior to transmission. Rolling means that bits $a_1$ and $a_6$, $a_2$ and $a_5$, $a_3$ and $a_4$ are swapped. This same process is repeated after the user equipment accepts each byte.

### 5.3.3 Bit Slip Rule

In a typical installation the communications receiver or modem will assemble the received bits into 8-bit bytes. No specific (except bit synchronization) byte or "word" synchronization should be assumed. The user equipment shall be required to recover the message synchronization just as it is responsible for recovering the synchronization of the satellite navigation data. This simply means that the user equipment designer should not assume there will be any consistent relationship between the word boundaries of this standard's 30 bits words and the communications channel 8 bit bytes. Synchronization and decoding of this standard's data should be handled in a manner similar to that used by the GPS receiver to decode satellite broadcast navigation data.

### 5.3.4 Terminal Equipment Rule

If the manufacturer uses the standard connectors suggested in the RS-232-C or RS-449 standards, the connector shall be wired as though the GPS user equipment were a piece of DTE "terminal equipment".

### 5.3.5. Complete Message Decode Rule

The mobile equipment should generally avoid using message data until the message has been completely received. Otherwise the situation could arise where corrections for the first satellites received would be applied, but later words in the message would not pass parity. This would result in errors caused by drift in the reference station clock. Section 3.2.9 discusses this effect in more detail. For reference stations employing highly stable clocks, such as those transmitting Type 9's, this restriction does not apply.

## 5.4 EQUIPMENT OPTIONS

Reverse communications from the mobile receiver to the modem, communications equipment, or reference station are not required for differential operation but could be useful. Including features that control the flow of data to the user equipment, allow the operator to send commands from the mobile receiver to the communications equipment (such as dialing a telephone), and automatic functions to control the communications equipment, could enhance operation of the equipment and should be considered by manufacturers.

Some of the broadcast information (message Types 7 and 13) provides information about the broadcast system itself. The intent of some messages is to provide enough information so that automatic communications control can be done by the user equipment. For example, in the case where the communications receiver is a radio beacon receiver, a reception frequency is required. The user equipment may be able to perform automatic frequency and data rate selection. Other helpful information would include commands to shift bits (after frame synchronization has been established), do self test, and request status.

## 5.5 REFERENCES


1. Electronic Industries Association, "Interface Between Data Terminal Equipment and Data Communication Equipment Employing Serial Binary Data Interchange (EIA RS-232-C)", 2001 Eye Street, N.W., Washington, D.C. 20006

2. Electronic Industries Association, "Electrical Characteristics of Balanced Voltage Digital Interface Circuits (EIA RS-422-A, December 1978)", 2001 Eye Street, N.W., Washington, D.C. 20006

3. Electronic Industries Association, "General Purpose 37-Position and 9-Position Interface for Data Terminal Equipment and Data Circuit-Terminating Equipment Employing Serial Binary Data Interchange (EIA RS-449, November 1977)", 2001 Eye Street, N.W., Washington, D.C. 20006

4. American National Standards Institute, "American National Standard Character Structure and Character Parity Sense for Serial-by-Bit Data Communication in the American National Standard Code for Information Interchange (ANSI X3.16-1976 revision of X3.16-1966)", 1430 Broadway, New York, New York 10018

5. American National Standards Institute, "American National Standard for Bit Sequencing of the American National Standard Code for Information Interchange in Serial-by-Bit Data Transmission (ANSI X3.15-1976 revision of X3.15-1966)", 1430 Broadway, New York, New York 10018

6. American National Standards Institute, "American National Standard Code for Information Interchange (ANSI X3.4-1977 revision of X3.4-1968)", 1430 Broadway, New York, New York 10018

7. American National Standards Institute, "American National Standard Character Code Extension Techniques for Use with the 7-Bit Coded Character Set of American National Standard Code for Information Interchange (ANSI X3.41-1974)", 1430 Broadway, New York, New York 10018

## APPENDIX I

## DATA QUALITY INDICATOR FOR CARRIER PHASE CORRECTION AND MEASUREMENT MESSAGES

### I.1 INTRODUCTION

This appendix provides background information for the Data Quality Indicator for the Carrier Phase Correction and Measurement Messages. It includes the definition of the Reference Station receiver measurements used for the indicator, plus the conversion of those measurements to the 3-bit indicator for the messages. The definition is a suggestion. The measurements of data quality may be made using any method desired, as long as the net result provides the indication of quality specified in the message definition.

The definition described in this appendix only includes the effect of receiver tracking errors with respect to the observed phase of the composite received signal, which may include multipath signals and phase errors due to antenna phase variations, etc. Knowledge of those errors may indeed be included in the data quality indicator in a root-sum-squared sense, depending upon reference station design. If corrections of those errors are made, the data quality indicator should only include an indication of the "residual" error after correction.

### I.2 REFERENCE STATION RECEIVER MEASUREMENTS

The measurements defined here are those which are sometimes used to determine phase lock status of a phase-lock-loop (PLL). They are <u>not</u> the phase lock indicator itself, but are the signed magnitude of the measurements used for lock indication, which is usually a hard decision based on the comparison of the signed magnitude against a predetermined threshold. This measurement is a good indication of carrier phase tracking quality, if computed correctly. It is important to note, however, that this measurement does not include computational or systematic errors introduced in the "single difference" or "double difference" computations.

The lock indicator normally used for the so-called Costas PLL involves the computation of $I^2 - Q^2$ using the in-phase (I) and quadraphase (Q) components of the signal. In steady state, these component quantities would be integrated (or summed) over a 20 millisecond bit period, while the lock indicator value would be averaged over a period of a half second or so. This value is proportional to the cosine of twice the carrier phase error, and also proportional to the signal-to-noise ratio in a 50 Hz bandwidth. The problem is that it is "proportional", where the scale factor is only as known by the receiver designer and a computed signal-to-noise ratio. However, this problem can be overcome by using a "normalized" indicator of the form

$$Cos(2\Delta\phi) = \frac{\langle I^2 - Q^2 \rangle}{\langle I^2 + Q^2 \rangle} \tag{I.1}$$

where $\langle \bullet \rangle$ indicates an average value. This value is proportional to the cosine of twice the phase tracking error $\Delta\phi$ , but it can be mapped appropriately into a data quality indicator directly proportional to phase error in cycles as

$$DQI = \frac{1}{4\pi} Cos^{-1}(Cos(2\Delta\phi)) \tag{I.2}$$

quantized appropriately into the 3 bits allotted for the quality indicator.

The expected value of the quantity in Equation I.1 is plotted in Figure I.1 for an averaging time of 1 second. Its one sigma value is plotted in Figure I.2. They are both plotted against the carrier phase tracking error, assumed to be constant over that interval (such as a loop hang-off). They are also plotted for a range of carrier-to-noise density $\left(\frac{C}{N_0}\right)$ values between 26 and 50 dB-Hz. The expected value is compared against the cosine of twice the phase error, a value that would be achieved at infinite $\frac{C}{N_0}$ .

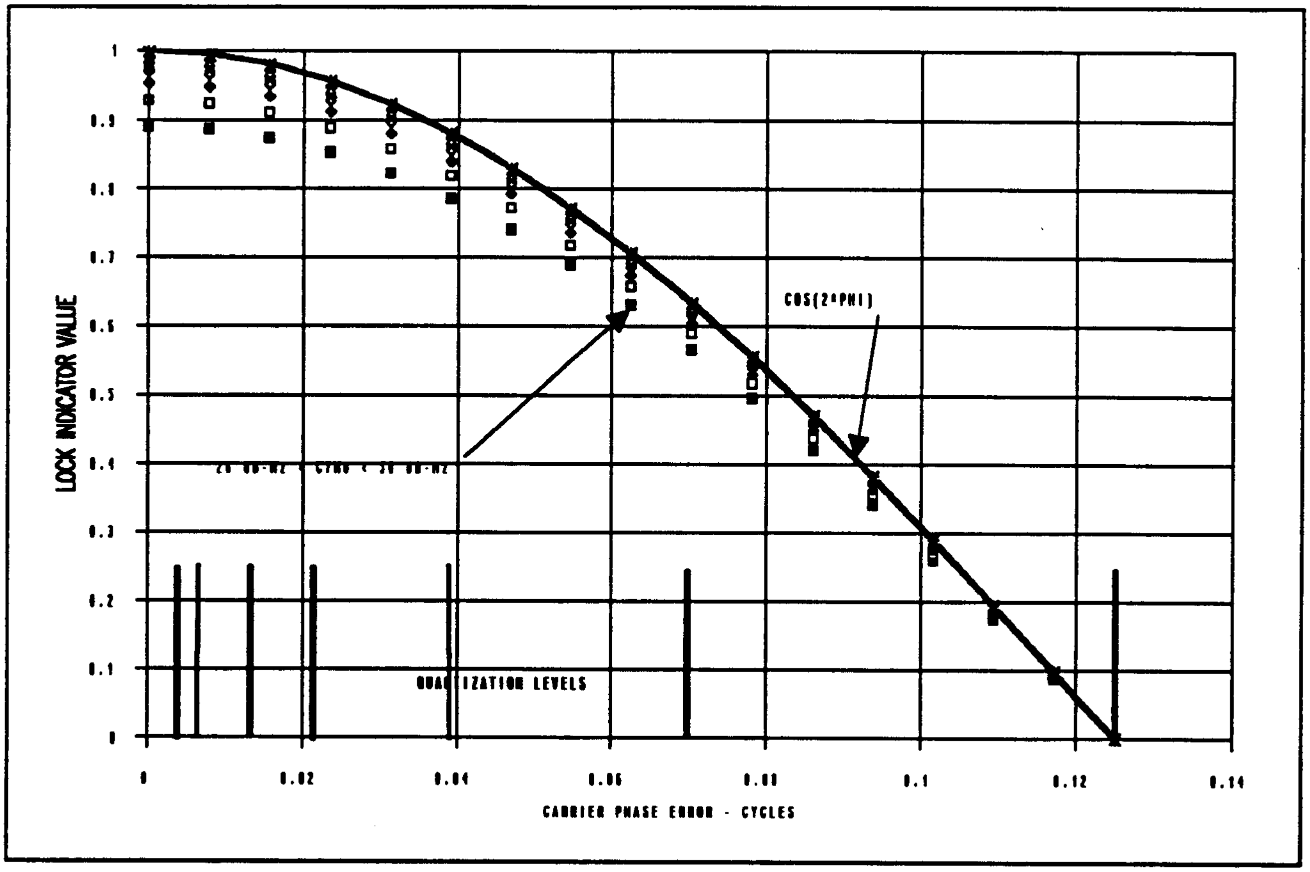


**Figure I.1. Expected Value of Phase Lock Detector**

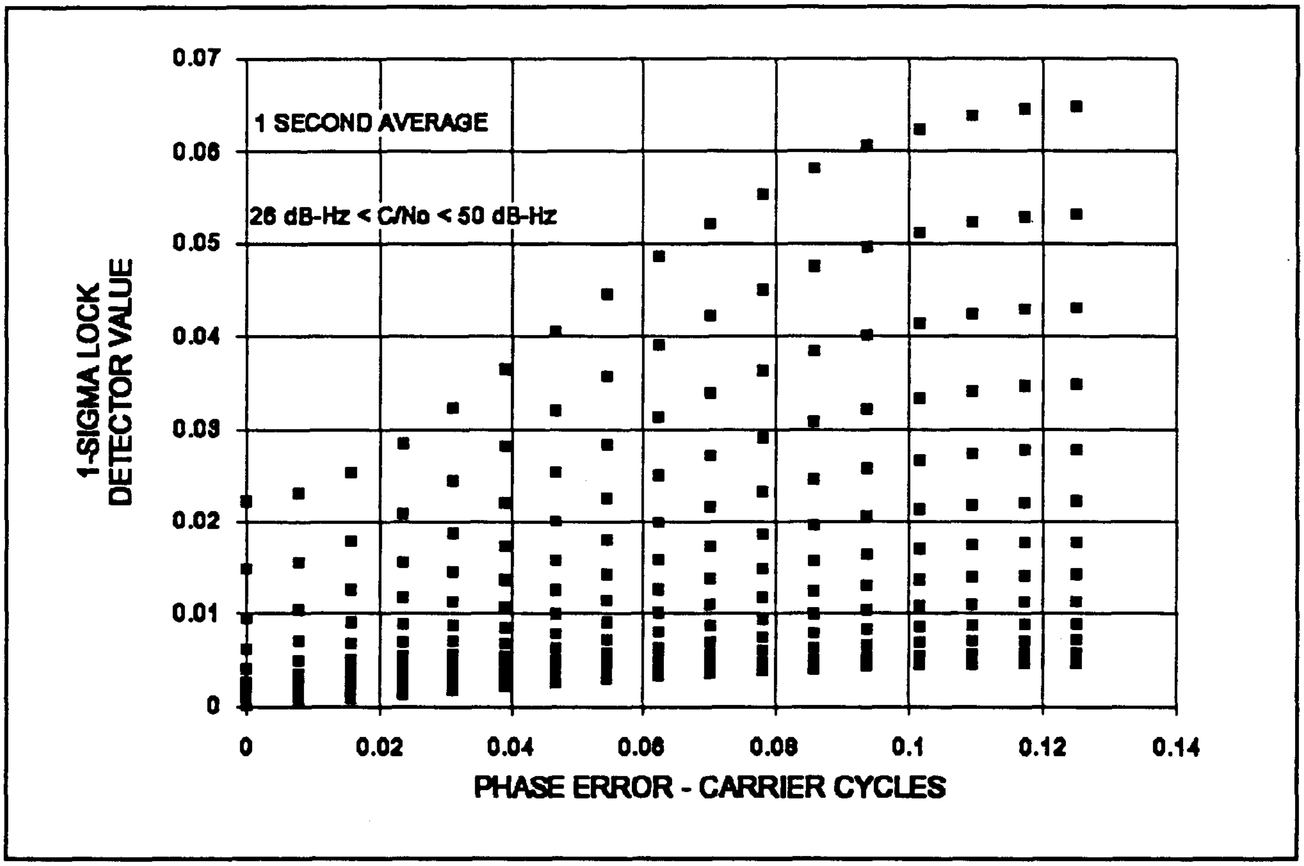


**Figure I.2. Phase Lock Detector 1-Sigma Values**

The question is, "What are the characteristics of the Data Quality Indicator given in Equation I.2?". Does it really reflect the phase error of the tracking loop? It certainly will indicate the "mean" phase error, but what about the one-sigma error due to thermal noise (or oscillator phase noise)? To evaluate that, the values plotted in Figure I.1 plus three times the values plotted in Figure I.2 were entered into Equation I.2 for the zero mean phase error conditions. Adding the three sigma value decreases the value of the data quality indicator because it increased the value of the cosine function. Thus, it indicates a minimum phase error. This evaluation is compared to the one-sigma PLL tracking error due to noise given as

$$\sigma_\phi = \frac{1}{2\pi}\sqrt{\frac{B_L N_0}{S}\left(1 + \frac{N_0}{2ST}\right)}\ cycles \qquad \text{(I.3)}$$

where $B_L$ is the loop bandwidth and T is 20 milliseconds. This quantity is plotted against the Data Quality Indicator for a 5 Hz bandwidth in Figure I.3. Note that the minimum Data Quality Indicator always exceeds the one-sigma loop noise for all signal-to-noise densities. This is because of the noise suppression of the phase lock detector, which reduces its value. That noise suppression works in our favor.

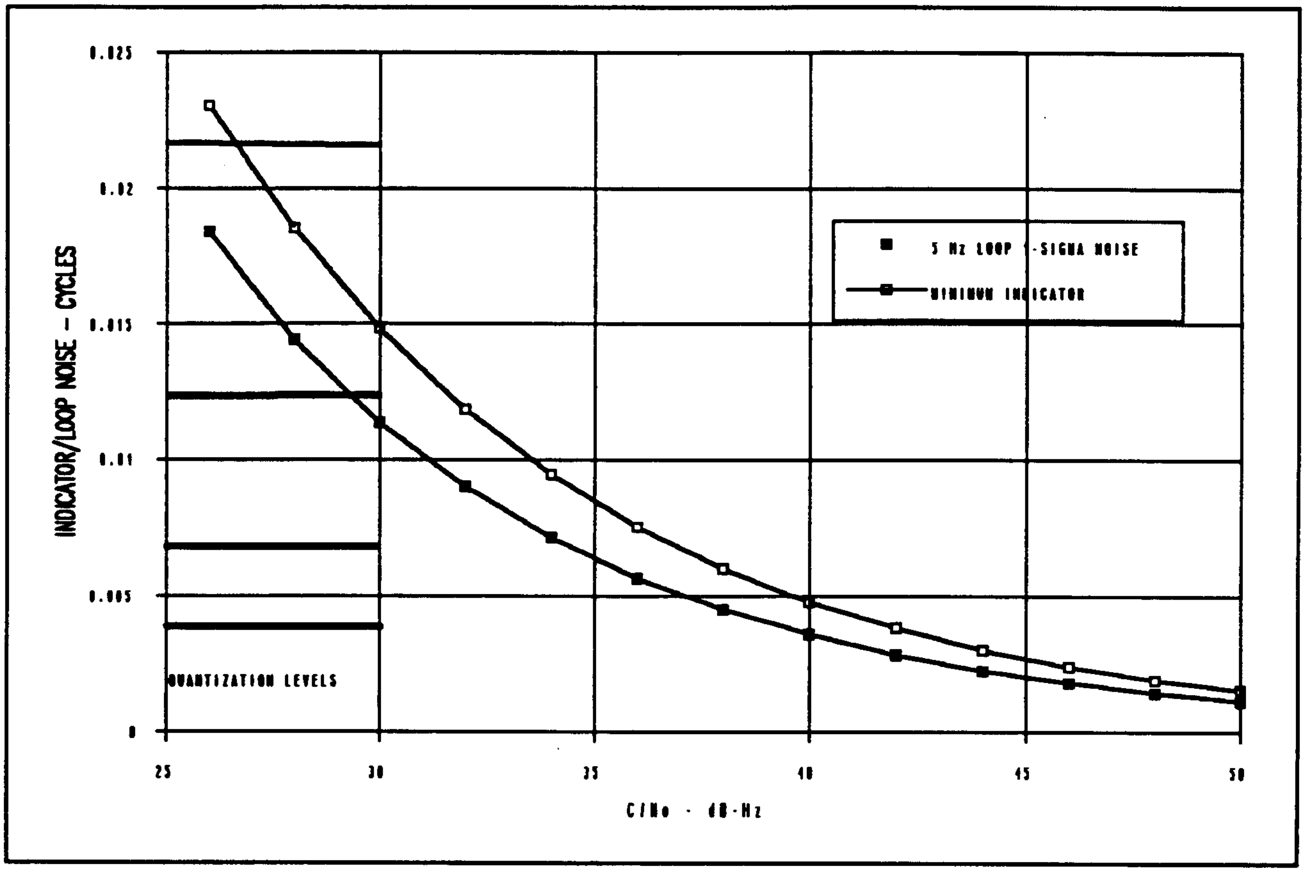


**Figure I.3. Data Quality Indicator Performance for Zero Mean Phase Error**

## I.3 DATA QUALITY INDICATOR QUANTIZATION

Figure I.3 also shows how the Data Quality Indicator should be quantized in to the 3-bit field. It is obvious that a linear quantization is not desirable because there would not be enough resolution to handle the smaller errors. A graduated scale for the quantization levels that are also indicated on Figures I.1 and I.3 is more desirable. Table I.1 is an interpretation of that exponential scale, which satisfies the equation

$$DQI(X) \le \frac{1}{256} e^{X/\sqrt{3}} \qquad \text{(I.4)}$$

where X is the decimal equivalent of the 3-bit indication.

**Table I.1. Data Quality Indicator Quantization**

| Bit Indication (X) | Phase Error Interpretation |
|---|---|
| 000 (0) | ≤ 0.00391 cycle |
| 001 (1) | ≤ 0.00696 cycle |
| 010 (2) | ≤ 0.01239 cycle |
| 011 (3) | ≤ 0.02208 cycle |
| 100 (4) | ≤ 0.03933 cycle |
| 101 (5) | ≤ 0.07006 cycle |
| 110 (6) | ≤ 0.12480 cycle |
| 111 (7) | > 0.12480 cycle or $\cos\Delta\phi < 0$ |

# APPENDIX II

# DATA QUALITY AND MULTIPATH ERROR INDICATORS FOR PSEUDORANGE CORRECTION AND MEASUREMENT MESSAGES

## II.1 INTRODUCTION

This appendix provides background information for the Data Quality and Multipath Error Indicators for the Pseudorange Correction and Measurement Messages. It includes suggestions for the Reference Station receiver measurements used for those indicators, plus the conversion of those measurements to the 4-bit indicators for the messages. The measurements of data quality and multipath error may be made using any method desired, as long as the net result provides the indication of quality and multipath error specified in the message definitions.

## II.2 DATA QUALITY INDICATOR

A suggested Pseudorange Data Quality Indicator is based on a short term estimate of the one-sigma pseudorange error due to ambient noise, where, for a simultaneous early power minus late power discriminator,

$$\sigma_\tau = \frac{c}{R_c}\sqrt{\frac{B_L\, d\, N_0}{2\, S}\left(1 + \frac{2\, N_0}{(2 - d)\, S\, T}\right)}\ \mathit{meters} \qquad \text{(II.1)}$$

where

$c = 3 \times 10^8$ meters/second

$R_c$ = the P or C/A code chipping rate in chips/second

$S/N_0$ = an estimated signal-to-noise density is ratio-Hz

$T = 0.02$ seconds

$d$ = early/late correlator spacing in chips

$B_L$ = the equivalent single-sided noise bandwidth of the pseudorange smoothing process in chips

For a dot product discriminator,

$$\sigma_\tau = \frac{c}{R_c}\sqrt{\frac{B_L\, d\, N_0}{2\, S}\left(1 + \frac{N_0}{S\, T}\right)} \qquad \textbf{(II.2)}$$

$B_L$ is not necessarily the delay lock loop bandwidth. For example, if post measurement smoothing of the pseudorange against the carrier phase is performed, then

$$B_L = \frac{1}{2\, T_I}\ Hz \qquad \textbf{(II.3)}$$

where $T_I$ is the smoothing interval in seconds.

This Data Quality Indicator does not include time-correlated errors such as multipath and changes in the ionosphere, nor does in include quantization errors. If pseudorange quantization is significant, its effect should be root-sum-squared (rss'd) with the quantity defined in Equation II.1. This can indeed be the case if the larger scale factor is used in conjunction with accurate pseudoranges in the Pseudorange Correction Message. Note that the only measured quantity that affects this indicator is the estimated signal-to-noise density.

Since the four bits allocated to the Data Quality Indicator are not enough to cover an entire range of implementations and smoothing intervals, an exponential function is applied to the indicator, providing more granularity to the indicator for smaller errors. This function is indicated in the definition of the Pseudorange Correction Message, Type 21.

## II.3 MULTIPATH ERROR INDICATOR

The pseudorange corrections in this message may or may not be corrected for multipath errors. That would be a function of the Reference Station design. The indicator is defined to be only a one-sigma estimate of the residual multipath error in the corrected pseudorange. As the Data Quality Indicator, the four bits allocated to the Multipath Error Indicator are not enough to cover an entire range of implementations and multipath correction schemes. Thus, an exponential function is also applied to the Multipath Error Indicator, providing granularity to the indicator for smaller errors. This function is indicated in the definition of the Pseudorange Correction Message.

It is not the purpose of this appendix to define any multipath correction schemes or Multipath Error Indicator estimation algorithms. However, two possibilities are given here. The first is to smooth the pseudorange measurements against the carrier phase over some extended time interval - say, two or three minutes, in order to average out the effect of the multipath. This time must be short enough so that the ionospheric delay divergence between the code and carrier does not dominate the multipath effects. The pseudorange corrections are then based on the carrier phase itself, corrected with the newly smoothed pseudorange. If this multipath correction is not applied, the longer term (smoothed) residuals of the correction process will provide an indication of the multipath error. In either case, longer term means that the effect of ambient noise is basically removed by smoothing, but the effects of multipath (or multipath correction error) are not.

A second possible correction scheme is to use a post processed estimation of the multipath error from previous days to correct the current day errors, adjusted in time by three minutes and 56 seconds. The assumption here is that the object of multipath reflection is the same each day for the same geometry. However, depending upon circumstances, the reflection coefficient may change from day-to-day, or the reflecting object may have moved. The "best" approach in this case is to move the antenna or the object so that the multipath doesn't occur. If this type of correction scheme is used, the estimation of the residual error could be performed as described above for the smoothing process.

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## APPENDIX III

## SATELLITE POSITION COMPUTATION TEST FILES

### III.1 INTRODUCTION

Whenever carrier phase or pseudorange corrections are broadcast from a Differential GPS Reference Station, that station computes the GPS satellite positions corresponding to the integrated carrier beginning and end times and the pseudorange measurement times in deriving those corrections. Thus, the accuracy of those computations directly affect the accuracy of the broadcast corrections. If the identical computations are performed at the remote user locations, any errors in those computations, if realistically small, will cancel in the differential positioning. This would be the case where the same software was used at the Reference Station and the remote user. However, if a different receiver manufacture produces the remote user equipment than that of the Reference Station, errors in general will not cancel. Thus, a standard for those computations is required. This appendix, along with a diskette containing test files, provides a mechanism for establishing that standard.

### III.2 TEST CASE GENERATION

The satellite position computations convert the orbital and clock parameters received from the GPS satellites in Subframes 1, 2 and 3 of the GPS Navigation message to the Earth-Centered-Earth-Fixed (ECEF) XYZ coordinates of the subject satellite versus time. The clock parameters are converted to the clock offset $\Delta t$ of the subject satellite, which also includes the general relativity correction that is based on the orbital parameters. The parameters received from the satellite are in the form of packed binary integers. The test cases developed for this standard converts these integer variables in decimal form first to floating point variables, and then to the XYZ and $\Delta t$ versus time. They do not convert the packed binary integers to decimal form.

The generation of the test cases implemented the equations provided in ICD-GPS-200B without the use of any short cut approximations, except that Kepler's Equation

$$E_k = e \sin E_k + M_k \tag{III.1}$$

was solved iteratively for $E_k$ at time $t_k$ to an accuracy of $1 \times 10^{-12}$ radians.

#### III.2.1 Earth's Rotation Correction

Two sets of test cases were generated. The first set made a correction to the XYZ coordinates for the earth's rotation of the ECEF coordinate frame for a fixed signal transit time, while the second set did not. This is because there are two methods to account for this rotation. In one method, the satellites position at time of signal transmission is rotated to the user's coordinate frame at time of signal reception, while in the other method, a correction to the measured pseudorange is made to account for the coordinate frame rotation. In the first method, the longitude of the satellite is adjusted with the amount in radians

$$\Delta\Omega_k = (\dot{\Omega} - \dot{\Omega}_e)\,\frac{R}{c} \qquad \text{(III.2)}$$

where $\dot{\Omega}$ is the rate of right ascension of the satellite, $\dot{\Omega}_e$ is the earth's rotation rate, $R$ is the estimated range to the satellite and $c$ is the speed of light. In the generated test cases, $R$ is set to a constant of 24,000,000 meters. The effect of this correction is an adjustment in the east-west direction of a few meters in the satellites position, thus changing both the X and Y coordinates, but not the Z coordinate. Although a constant range is not realistic, it is appropriate for the test case since it can be set at this maximum value, and thus, not sensitive to a user's location.

In the second method, the correction is made to the pseudorange measurement, which is given as

$$\Delta R = \frac{\dot{\Omega}_e}{c}\,(X_s Y_u - Y_s X_u) \qquad \text{(III.3)}$$

where $X_s$ and $Y_s$ are the coordinates of the satellite in the ECEF coordinate frame at the time of transmission and $X_u$ and $Y_u$ are the estimated coordinates of the user in the ECEF coordinate frame at the time of reception. In this case, no earth's rotation correction is made to the satellite's coordinates, which is the same as making a correction with an estimated range of 0. In fact, this is the method used for that test case, and the quantity of Equation III.3 was not computed.

### III.2.2 Test Case Details

The inputs to the test cases (six total for each earth rotation correction method) are the satellite's PRN number, the range used for the earth rotation correction and the integer clock and ephemeris parameters unpacked from GPS Navigation Message Subframes 1, 2 and 3 for six different satellite PRN numbers. These inputs were collected from live Block II satellites. The outputs of the test cases are the floating point versions of the integer parameters, some derived floating point parameters (in seconds, meters, radians and radians per second) and the XYZ ECEF coordinates (in meters) and $\Delta t$ (in seconds) evaluated at 10 minute intervals over the four hours of applicability of the parameters. The outputs are DOS files in the form of floating point ASCII variables with comma delimiters for the purpose of inputting them into a spread sheet program. A representative output is given in Table III.I for one satellite PRN number.

These test cases were evaluated against an independent source and were found to agree to within 0.2 to 0.3 millimeters. Further evaluation against other independent sources is continuing.

The files are available on DOS diskettes. The file names are XYZT.XLP and XYZEROT.XLP for no earth rotation correction and earth rotation correction, respectively.

| | | | | |
|---|---|---|---|---|
| prn range | 14 | 24000000 | | |
| integer clock and ephemeris parameters | | | | |
| toc af0 af1 af2 | 31500 | 393441 | 3 | 0 |
| crs deltan m0 cuc | 36 | 11925 | -607851560 | -60 |
| e cus sqra toe | 39103504 | 6381 | -1593052047 | 31500 |
| cic omega0 cis i0 | -1 | 504805826 | -58 | 656731450 |
| omgdot idot omga crc | -22026 | 357 | 1972752536 | 4738 |
| floating point clock and ephemeris parameters | | | | |
| toc af0 af1 af2 | 504000 | 1.832102425396e-04 | 3.410605100000e-13 | 0.000000000000 |
| toe sqra deln m0 | 504000 | 5.153494356155e+03 | 4.259106000000e-09 | -8.892370366347e-01 |
| e omega cus cuc | 4.552247002721e-03 | 2.885975350835e+00 | 1.188553900000e-05 | -1.117587100000e-07 |
| crc crs cic cis | 1.480625000000e+02 | 1.125000000000e+00 | -1.862645100000e-09 | -1.080334200000e-07 |
| i0 idot omg0 omgdot | 9.607443114283e-01 | 1.275053100000e-10 | 7.384895693748e-01 | -7.866756253000e-09 |
| a n0 n | 2.655850407893e+07 | 1.458691678037e-04 | 1.458734269097e-04 | |
| t | x | y | z | deltatsv |
| 496800 | -1.925132225385e+07 | 5.287213520833e+06 | 1.758197241879e+07 | 1.832174931499e-04 |
| 497400 | -1.852325341598e+07 | 4.111140955354e+06 | 1.863191927798e+07 | 1.832179922371e-04 |
| 498000 | -1.779609748114e+07 | 2.847861255577e+06 | 1.953977263714e+07 | 1.832184150563e-04 |
| 498600 | -1.708115246527e+07 | 1.505145628662e+06 | 2.029843978735e+07 | 1.832187598536e-04 |
| 499200 | -1.638891257552e+07 | 9.219638541095e+04 | 2.090194872206e+07 | 1.832190254656e-04 |
| 499800 | -1.572888937811e+07 | -1.380481227134e+06 | 2.134549869009e+07 | 1.832192113317e-04 |
| 500400 | -1.510945030926e+07 | -2.901230212362e+06 | 2.162550232157e+07 | 1.832193175004e-04 |
| 501000 | -1.453767741057e+07 | -4.457413637737e+06 | 2.173961885040e+07 | 1.832193446327e-04 |

**TABLE III.1 - Format of Test Files**

## APPENDIX IV

## CARRIER PHASE CORRECTIONS FOR REAL-TIME KINEMATIC NAVIGATION

### IV.1 INTRODUCTION

The typical method employed for kinematic navigation and survey, whether using a data link for real-time applications or in situations where post-processing is acceptable, is to transfer the data from the reference site to the user site (or vice versa) and then to implement double-differencing algorithms to determine the relative position. Several advantages can be obtained in real-time situations by an alternate approach. If rather than transmitting the raw data from one site to another, we transmit corrections, as is done for the standard differential code implementations, several advantages are obtained. Among the advantages are: (1) fewer bits need to be transmitted over the data link; (2) there is less sensitivity to the time lag or data latency encountered during the communication of the data; and, (3) the computational requirements imposed on the user are reduced.

The remainder of this appendix involves a discussion of some of the parameters of interest, how the correction scheme can be made to work, constraints on the algorithms and some sample carrier phase corrections with and without selective availability imposed.

### IV.2 TIME RECOVERY AND TIME SENSITIVITY CONSIDERATIONS

One of the most significant factors which affect the code measurements and carrier phase measurements differently is their sensitivity to the local receiver clock or time. This can be used to our advantage.

A code or pseudorange measurement involves determining the difference in the time (according to the satellite clock) at which the signal left the satellite and the time (according to the receiver clock) at which the signal arrived at the receiver. If this transit time is multiplied by the speed of light then a range to the satellite is determined. The measurement is usually referred to as a pseudorange measurement since the error in the receiver clock causes a common bias in the measurements. (The satellite clock errors are kept much smaller by providing predicted corrections to them in the satellite message.) The receiver can use measurements from a number of satellites to determine both its position and the receiver clock bias. Since code measurements are sensitive at the speed of light, a position determination to 30 meters accuracy results in a clock determination of about 100 nanoseconds accuracy.

The carrier phase measurements have a different sensitivity to receiver time accuracy. Carrier phase measurements are an integrated measure of the divergence in the clock rate. The clock rate received is different from the clock rate in the receiver due to the difference in the rate at which the two clocks run and due to the Doppler shift of the received frequency. The integral of this rate is a measure of the difference in the two clocks with a whole cycle ambiguity corresponding to the undetermined constant of integration. The dependence of the measurement on Doppler means its time sensitivity is proportional to the relative radial velocity between the satellite and receiver. This velocity is much lower than the speed of light and represents a dramatic reduction in time sensitivity. For example, if the code measurement is used to determine the receiver clock to 100 nanoseconds, as was suggested above, and the Doppler rate to the satellite is at its maximum of around 5000 Hertz, the maximum error in the carrier phase due to the time error is the product of these two numbers or .0005 cycles of the L1 frequency. At the 19 centimeter wavelength of the L1 frequency this error represents a distance of about 0.1 millimeters.

The conclusion of the above argument is that time recovery accuracy from the code measurements of even one microsecond (which is easy to obtain even when selective availability is imposed) is sufficient to give carrier phase measurement accuracy of 1 millimeter or better.

## IV.3 DIFFERENTIAL TIME RECOVERY AND TIME SENSITIVITY

The next question which arises is: how sensitive is the differential user position to differences in the time recovery accuracy at reference and user sites? The answer to this question is that the differential sensitivity is the same as the direct sensitivity - with the wise choice of user algorithm.

The code differential user typically implements an algorithm with an increased sensitivity to the time recovery error. Why? The typical code differential user implements a Kalman filter as a way of balancing a minimization of the noise in the position solution against the responsiveness of the position output to true navigation maneuvers. In the typical filter, the noise in the clock solution is also filtered with a reasonably long time-constant - even though the clock solution itself is of no particular usefulness. It is this clock smoothing which can introduce a heightened clock sensitivity into the differential solution - particularly in kinematic or differential carrier phase implementations.

The typical method by which GPS measurements are used in static survey applications involves the use of "double difference" algorithms. In a Kalman filter analogy the "double difference" algorithm is equivalent to modifying the filter gain on the position solution so that it exponentially decreases. This causes the position components to be the best average value over the entire data set. Meanwhile the gain on the clock bias state in the Kalman filter is kept at one. This causes the clock solution at each epoch to be that which best fits the specific measurements at that epoch. In other words, no clock smoothing or averaging is used.

One of the earliest survey algorithms to employ an alternative to the "double difference" algorithm (Hatch and Larsen, 1985), allowed the direct solution of the clock values rather than differencing their effect out of the data. The motivation for this alternate implementation was to make use of the clock correlation from epoch to epoch and obtain a better position solution. Surprisingly, no measurable improvement could be obtained using this alternate implementation. The explanation for this unexpected behavior is simply that even with the best of clocks the accuracy of the phase prediction for even one second is lower than the accuracy of the instantaneous clock solution when carrier phase measurements are employed.

The conclusion is that any algorithmic implementation of kinematic or differential carrier phase processing which smoothes or filters the clock can cause increased noise in the navigation solution. If the clock state is not allowed to remove the clock noise on an epoch by epoch basis the resulting clock error which remains can alias into the position states with adverse effects on the navigation solution. When the user solves for an independent clock state at each epoch then any error or even step change in the clock at the reference receiver will simply alias into the clock solution at the user site without compromising the user position solution.

## IV.4 GENERATING CARRIER PHASE CORRECTIONS AT THE REFERENCE SITE

The first step, in generating carrier phase corrections at the reference site, is to use some method to append to the carrier phase measurement the approximate number of whole cycles so that it represents a true range measurement. One acceptable method is to simply set the whole cycle such that the carrier phase measurement best agrees with the theoretical range to the satellite at the time the satellite is first acquired by the receiver. Another method, is to set the carrier phase whole cycle value to match the corresponding code measurement when the receiver first acquired the satellite.

The second step in generating carrier phase corrections is to implement an algorithm for removing the effect of biases and changes in the reference receiver clock from the corrections to be transmitted. As described above, as long as the clock bias is kept below one microsecond and as long as the user solves for an epoch by epoch clock bias, the user's navigation result should remain independent of any residual clock biases which find their way into the transmitted corrections.

Since there will probably always be those who improperly smooth the clock state at the user site, it is highly desirable that no sudden step changes be allowed in the reference receiver clock state or, more significantly, in the correction values transmitted to the user. In light of these constraints, the following method has been used to remove the reference receiver clock bias from the corrections: (1) At the first epoch at which the reference receiver commences tracking one or more satellites, the difference in the measured carrier phase range (carrier phase measurement with appended whole cycle) and the computed range to the satellite is formed. The mean value of this difference across all satellites is formed and treated as the clock bias. This clock bias can then be removed from the individual differences for each satellite. The result for each satellite can then be transmitted (with appropriate sign) as the corrections to be applied by the user. This procedure causes the mean value of the corrections for the first epoch to be zero. (2) At the second and each subsequent epoch all satellites which remained locked over the interval between epochs is used to compute the difference of the measured carrier phase range change and the computed range change. The mean value across the satellites of these change differences is formed and is ascribed to the change in clock bias and added to the prior clock bias value. As long as even one satellite tracked the satellite continuously between epochs this new clock bias will be an acceptable value. Now all satellites which are locked on at the latest epoch are used to form individual differences between the measured carrier phase range and the computed range.

The newly formed clock bias is removed from each of these satellite differences and the result transmitted as the correction value for that satellite.

The advantage of using the changes in the measured and theoretical values to generate clock changes is that the addition or deletion of a satellite to the set of satellites tracked at the reference site is not allowed to cause a step change in the clock bias. The disadvantage of the technique is that as satellites are added and deleted from the set being tracked the mean value of the corrections transmitted will deviate from zero. This deviation from mean zero can be counteracted by a very long (many hour) time constant which adds a small fraction of the mean value of the corrections to the clock bias state. The net result is a smoothly varying carrier phase correction for each satellite.

## IV.5 ADVANTAGES OF CARRIER PHASE CORRECTIONS

Some of the advantages of transmitting carrier phase corrections in place of the raw phase measurements were already mentioned in the introductory section. Here those advantages are discussed in some detail together with some additional benefits.

First, fewer bits are needed to transmit the correction information than are needed to transmit the raw data. The reason for this is obvious. A far smaller dynamic range is needed to characterize the variation of a dynamic parameter from its true value than is needed to characterize its full range.

Another advantage is obtained when a correction is transmitted rather than the raw measurement. Specifically, the time sensitivity of the data is reduced. This results in several advantages. First, since corrections change much more slowly than the raw measurements, the error in the correction caused by its delay is less serious. This means that time synchronization at the reference site and user site is less critical. An exact match is not required between the measurement time of the data used to generate the corrections at the reference site and the measurement time of the data to which the corrections are applied. Since the time of measurement need not match, the data latency and link reliability become less critical. Because they change slowly, corrections can be applied for some time by the user before they become unusable.

This last characteristic can be used to reduce the data transmission rate even further. Accuracy can be traded for lower transmission rates consistent with the dynamics of the correction value. For example if only 50 centimeter accuracy is needed and the correction and its rate of change can be used to predict the correction value forward for one minute, then new values of the correction and its rate of change need be transmitted only once per minute. Clearly, selective availability (SA) adversely affects the predictable accuracy of the corrections.

While with modern computer capabilities it is not particularly significant, the computational load of the user is reduced by sending corrections rather than raw data. With raw data the user must compute ranges to the satellite from the reference site. To do this he requires a precise location for the reference site. When corrections are sent the user need not compute ranges between reference site and satellite and his only need for reference location arises from the need to compute atmospheric refraction differences. The computation of tropospheric and ionospheric refraction effects are imposed by current differential transmission standards and require a much less precise knowledge of reference site location than does the computation of precise ranges.

## IV.6 DISADVANTAGES OF CARRIER PHASE CORRECTIONS

There are, of course, some disadvantages of transmitting carrier phase corrections instead of raw phase measurements. These are considered briefly.

First, the user is now dependent upon the integrity and reliability of computations performed at the control site. Furthermore, those computations must be completely compatible with the user's computations. For example, when the reference site computes the range between the reference site and the satellite that range computation must be precisely the same (to at least the centimeter level, if centimeter accuracy is desired) as what the user would obtain if he performed that same computation.

A second disadvantage, as with any distributed computational network, is that any system failure analysis becomes more difficult. It can become more difficult to find where a failure has occurred when the computational load is distributed.

## IV.7 SAMPLE CARRIER PHASE CORRECTIONS

Four figures have been selected to illustrate some of the characteristics of carrier phase corrections. Figures IV-1 and IV-2 show carrier phase corrections generated by two different reference sites located only one meter apart. The corrections generated are identical except for a multiple whole cycle offset. Since the user of carrier phase corrections must determine his initial whole cycle anyway, the offset is not significant. The data in Figures IV-1 and IV-2 were collected on Nov. 9, 1991 and is for satellite PRN 2. SA was not enabled at the time this data was collected.

The corrections shown in Figures IV-3 and IV-4 were collected on 9 March 1992. SA was enabled. The corrections for satellite PRN 18 in Figure IV.3 reflect the direct effect of SA and of the mean value of the SA corrections on the computed clock. The corrections for satellite PRN 11 reflects only the SA effect on the clock since the satellite is a Block I satellite and did not itself have SA enabled. If the estimated user range accuracy had been used to weight the solution for the clock the two Block I satellites would have dominated the clock solution and the corrections for the Block I satellites would have been much smoother. However, as the kinematic results show, the argument that clock biases need not affect the user accuracy was verified with this data.

## IV.8 SAMPLE KINEMATIC RESULTS

The motivation for including sample results is to show that: (1) the correction scheme works; and (2) that when properly implemented, the SA effects on the clock solution do not compromise the accuracy (at least over short distances where short distance orbit errors do not contribute).

Figure IV.5 shows results previously presented (Hatch,Keegan and Stansell, 1992). The position data used the corrections shown in Figures IV.3 and IV.4 and show that centimeter levels of accuracy across 8 kilometers (5 miles) is achievable even when SA is enabled.

## IV.9 CONCLUSIONS

The advantages and disadvantages for transmitting carrier phase corrections have been discussed. Both the theory and sample results have been presented. The benefits of the approach are significant and the disadvantages can be overcome.

## IV.10 REFERENCES

1. Hatch, R.R. and K. Larsen, 1985. "Magnet-4100 GPS Survey Program," Proceedings of the First International Geodetic Symposium on Precise Positioning with the Global Positioning System, Rockville, Maryland, April 15-19.

2. Hatch, R.R., R. Keegan, and T.A. Stansell, 1992. "Kinematic Receiver Technology from Magnavox," Proceedings of the Sixth International Geodetic Symposium on Satellite Positioning, Columbus, Ohio, March 17-20.

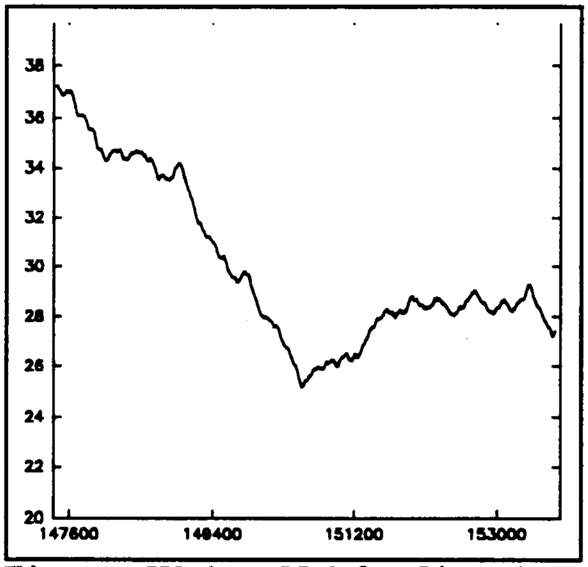


Figure IV.1 - PRN 2, Site 1

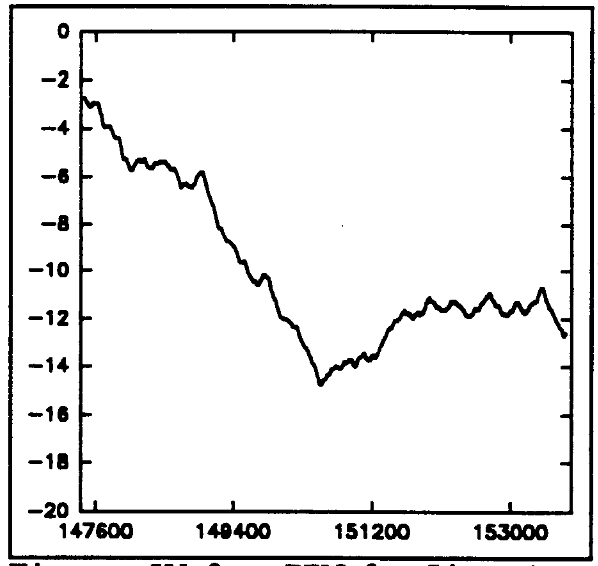


Figure IV.2 - PRN 2, Site 4

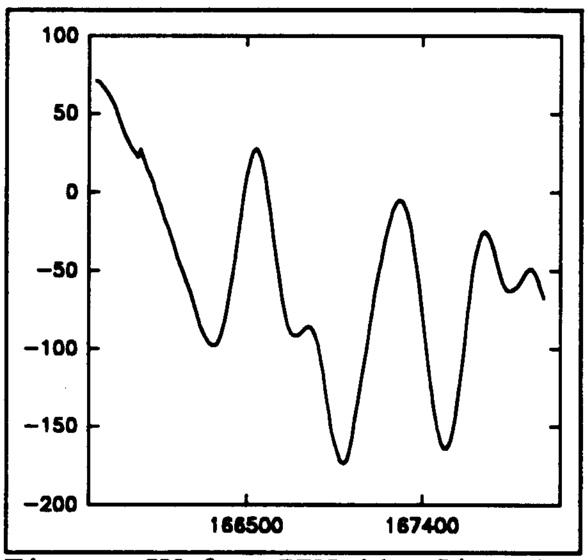


Figure IV.3 - PRN 11, Site 1

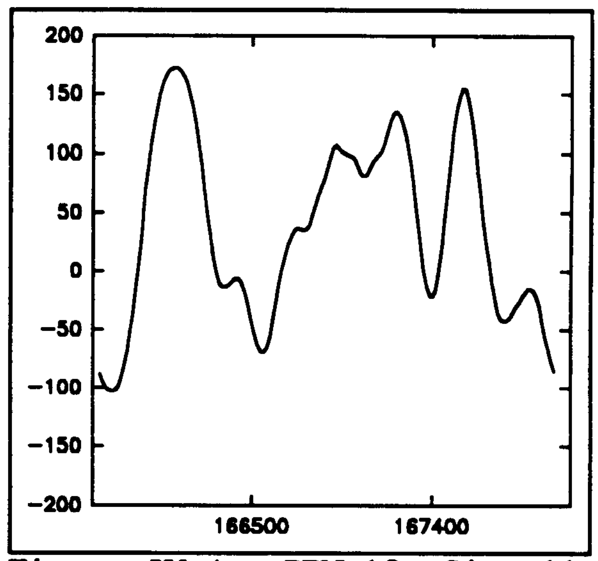


Figure IV.4 - PRN 18, Site 11

Vertical Axes - Carrier Phase Correction (L1 Cycles)
Horizontal Axes - Time (Seconds)

## FIGURE IV-5 - POSITION VERSUS TIME