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Synopsis and Recommendations of the TSC Workshop on Differential Operation of NAVSTAR GPS June 1983

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Workshop Synopsis

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16. Abstract

A workshop on Differential Operation of NAVSTAR GPS was held on June 9-10, 1983, at the Department of Transportation's Transportation Systems Center in Cambridge, Massachusetts. The workshop was sponsored by the DOT/Research and Special Programs Administration Office of Management and Programs, the U.S. Coast Guard Office of Research and Development, and the Satellite Navigation Division of the Institute of Navigation. Participants included system designers from major GPS receiver manufacturers, potential civil and military users of differential service, representatives from several U.S. and Canadian government agencies, and other industry and university technical professionals.

The primary purpose of the workshop was to initiate the development of a standard for the broadcast of differential corrections from a reference station for reception and use by a population of nearby users.

The result of the workshop was a strawman signal format that, if adopted as a standard, would enable receiver manufacturers to provide differential capability by the time the NAVSTAR GPS becomes fully operational. The proposed format, patterned after the NAVSTAR GPS satellite data format, is flexible enough to accommodate several communications techniques, and to provide high-accuracy service to a variety of air, marine and land users. It also allows room for future growth and for applications to specialized user groups.

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PREFACE

The concept of differential operation of NAVSTAR GPS, whereby a stationary receiver at a known location computes positional corrections and broadcasts them to nearby users, has been discussed for several years. A number of papers have appeared, all of which support the notion of greatly improved positional accuracy. A number of different implementations and concepts have been proposed, but until this workshop no concerted efforts had been made to resolve the differences of opinion and determine if a consensus could be reached on the form of the corrections and the implementation of a differential system.

The workshop was convened in the belief that enough experience has been gained to reach a consensus and that such an effort would be timely, in view of the high confidence in the GPS community that the satellite system will soon be operational. The experience of the workshop itself reaffirmed this belief. The participants, who included receiver designers and systems experts, were able to resolve a number of subtle technical issues and formulate a signal format which met the goals of the workshop in accuracy, feasibility, universality, and future growth capability.

The Workshop Chairman would like to thank the Session Chairmen, A.J. Van Dierendonck, Robert P. Denaro and Thomas A. Stansell, Jr. for their skill and efforts in addressing and resolving the technical issues in their sessions. They were successful beyond all expectations.

The Chairman would also like to thank Lois Bossman for her commendable job in coordinating the workshop and arranging accommodations for the participants. Norman Knable, John Kraemer and Janis Vilcans deserve special thanks for their technical support of the session chairmen. The efforts of summer students Nicolas Bliamptis, Shirish Dandekar and Ann Kouracles in maintaining the information flow to the participants was greatly appreciated. Mark Manozzi is gratefully acknowledged for working his usual magic with the word processor in preparing workshop notes and this workshop synopsis.

METRIC CONVERSION FACTORS

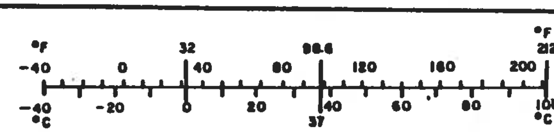
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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I. PURPOSE OF THE WORKSHOP

The purpose of the workshop was to begin the process of developing a standard format for the broadcast of local corrections to the NAVSTAR GPS satellite signals to users in a local area. By applying these corrections users will then be able to obtain greatly improved positional accuracies, typically better than 10 meters.

Before a format could be proposed, a number of issues needed to be resolved. The issues divided quite naturally into three groups:

1. Data message content -- data elements, resolution, and range must be fixed.

2. User/reference receiver algorithm compatibility -- data and atmospheric models must be handled similarly.

3. Communications technique -- interface hardware and communications frequencies must be defined.

The hope was that by convening a significant number of experts in the field, these issues could be discussed and resolved.

Some of the major issues are cited below, grouped in these three categories.

DATA MESSAGE CONTENT ISSUES

1. Should latitude/longitude or satellite pseudorange corrections be broadcast?

2. What data elements should be included in the corrections? With what units, resolution, and range?

3. How often should corrections be broadcast?

4. What auxiliary data should be broadcast, and how often?

5. What data should accompany each broadcast segment?

6. Can differential operation maintain high accuracies during a satellite data change, given that different users will generally change over to the new data at different times?

USER/REFERENCE RECEIVER ALGORITHM COMPATIBILITY ISSUES

7. If pseudorange corrections are broadcast, should the corrections include the use of tropospheric models?

8. Similarly, should the corrections include the use of ionospheric models?

9. Similarly, should the corrections include the ephemeris and satellite clock adjustments obtained from the satellite data message?

COMMUNICATIONS TECHNIQUE ISSUES

10. In view of the desirability for some applications of having the differential station operate as a pseudosatellite, or "pseudolite", is it possible to develop a design concept that avoids causing interference to other GPS receivers near the station?

11. Can a pseudolite station be designed to provide an adequate rate for corrections, given that the GPS data is transmitted at 50 bits per second?

12. If pseudolite operation is not used, and an external data link is employed, what interface specification should be used?

13. If an external data link is employed, can it make use of existing facilities such as LORAN-C, DECCA, VHF communications, Air or Marine Radiobeacons, or Mode-S?

Once these issues had been addressed and largely resolved, there would still remain the questions of the generality of any format proposed:

14. Is it possible to create a format that accommodates both pseudolite and external data links?

15. Is it possible to create a format that provides the necessary information and accuracy for airborne, marine, research, vehicle, test ranges, and surveying applications?

16. Is it possible to create a format that can accommodate future research findings and that allows room for future applications such as centralized surveillance and the broadcast of weather information?

Addressing these issues adequately requires thorough consideration of factors of technical feasibility of reference station equipment, knowledge of the NAVSTAR GPS implementation, recognition of user and station costs, compatibility with existing systems, and recognition of institutional limits on the design choices. As further research is performed and as operational experience is gained with NAVSTAR GPS, new capabilities and applications will be found. The format should not constrain the incorporation of new findings.

2. WORKSHOP DELIBERATIONS

The Differential GPS Workshop was held on June 9-10, 1983, at the Department of Transportation's Transportation Systems Center. The purpose of the workshop was to address the technical issues involved in differential operation of NAVSTAR GPS and to formulate a strawman format for the broadcast of differential corrections to users desiring the high-accuracy positioning service. The workshop was sponsored by the DOT Research and Special Programs Administration Office of Management and Programs, the U.S. Coast Guard Office of Research and Development, and the Institute of Navigation Satellite Navigation Division.

The workshop was chaired by Rudolph M. Kalafus of the Transportation Systems Center. There were three technical areas of discussion, headed by the following chairmen:

Data Message Content - A.J. Van Dierendonck,
Stanford Telecommunications, Inc.

User/Reference Station Compatability - Robert P. Denaro, TAU Corp.

Communications Technique - Thomas A. Stansell, Jr.
Magnavox, Corp.

On the first morning the workshop chairman and session chairmen gave presentations defining the focus of the workshop, recommending solutions to the issues, and proposing directions that the format might take. A number of participants also gave presentations making similar recommendations and describing the results of work related to the issues. The presentations are described briefly in Appendix A.

In the afternoon the workshop divided into the three sessions in order to discuss the various issues and attempt to resolve them. The session chairmen and interested participants met again in the evening to review the findings of the sessions and to determine whether there were unresolved issues or conflicting recommendations. In fact, where there were overlapping issues, the different sessions came to quite similar conclusions.

The following morning the results of the sessions were described by the session chairmen and opened up for review and discussion by the whole assembly. There were some issues raised that had not been fully addressed the previous day, and these were resolved.

A number of participants expressed an interest in further defining a format for surveying and geodetic applications. They met after the formal meeting was concluded. This ad hoc group was headed by Ronald Hatch of Magnavox Corporation. They formulated a message format which can accommodate very high relative accuracy applications which involve stationary receivers employing Doppler processing. This message format is included in the workshop recommendations.

The workshop succeeded in formulating a strawman format that, if eventually adopted as a standard, would enable receivers to provide differential capability by the time the NAVSTAR GPS becomes fully operational. The current DOD/DOT Joint Program Office deployment schedule calls for 12-satellite operation by 1987, and 18-satellite operation by 1988. The proposed format is flexible enough to accommodate several communications techniques, and to provide high-accuracy service to a variety of air, marine and land users. It also allows room for future growth and for applications to specialized user groups. Furthermore, it accommodates specialized operations for which it proves to be economically or operationally advantageous to utilize unique formats and data.

Not all the technical questions were definitively answered at the workshop. In particular, a satisfactory design concept for a "pseudolite" was not achieved. (A pseudolite refers to a ground station that uses the NAVSTAR GPS L_1 frequency, modulation scheme and data format, and thus appears to a receiver like an additional satellite. The technique, if feasible, would reduce the costs of differential service to a number of users). This subject will be addressed by a number of participants after the workshop.

Some details have not yet been worked out. While data message elements were reserved for differential station and satellite health, for example, the particular meanings were not specified.

A number of institutional issues also surfaced which need to be addressed before a standard can be finalized. These were identified, and action items were assigned to several participants of the workshop. It is anticipated that the Institute of Navigation Meeting in San Diego in January, 1984, will provide a forum for continuing the process of developing a national and international standard.

3. SUMMARY OF THE RECOMMENDED SIGNAL FORMAT

The proposed data format to be used for the communication of corrections from a differential reference station to nearby users is patterned after the NAVSTAR GPS data format. Subframes consisting of 300 bits are employed, each headed by a preamble and time indication, similar to the GPS TLM and HOW words. The proposed header identifies the start of the message, the differential station identification, station health indication, timing with respect to GPS time, and subframe identification. Figure 1 shows the subframes that were defined at the workshop. Up to 8 different message types are accommodated with the 3-bit subframe ID data element.

Pseudorange corrections are broadcast for each satellite, rather than latitude/longitude corrections. The pseudorange corrections use ephemeris and satellite clock data, but do not use either ionospheric or tropospheric models.

The differential corrections need to be sent out most frequently, while auxiliary data need be broadcast only every minute or so. Accordingly, the Type 1 Message contains the correction data, and consists of one or two subframes. Each subframe contains the pseudorange and pseudorange rate corrections, identities and health indications of up to six different satellites. This enables up to 12 satellites to be handled by a differential station. If 6 satellites or less are in view, only one subframe will be transmitted. The pseudorange corrections have a resolution of 0.1 meters, and the pseudorange rate corrections have a resolution of 0.004 meters per second. The reference time for these polynomial corrections is the Z-count of the subframe contained in the HOW word.

The Type 2 Message is similar to the Type 1 Message, in that 40 bits are sent for each satellite. However, instead of pseudorange and range-rate corrections, Age Of Data (AOD) and "delta corrections" are broadcast. A delta correction for a satellite is equal to the difference between pseudorange corrections utilizing old and new satellite ephemeris and satellite clock data. The AOD data enables the user to determine whether he is using the same satellite data as the reference station or not. If not, he can further correct for the difference between old and new satellite data by subtracting the delta correction. The Type 2 Message is broadcast approximately once for every five Type 1 Messages. It should

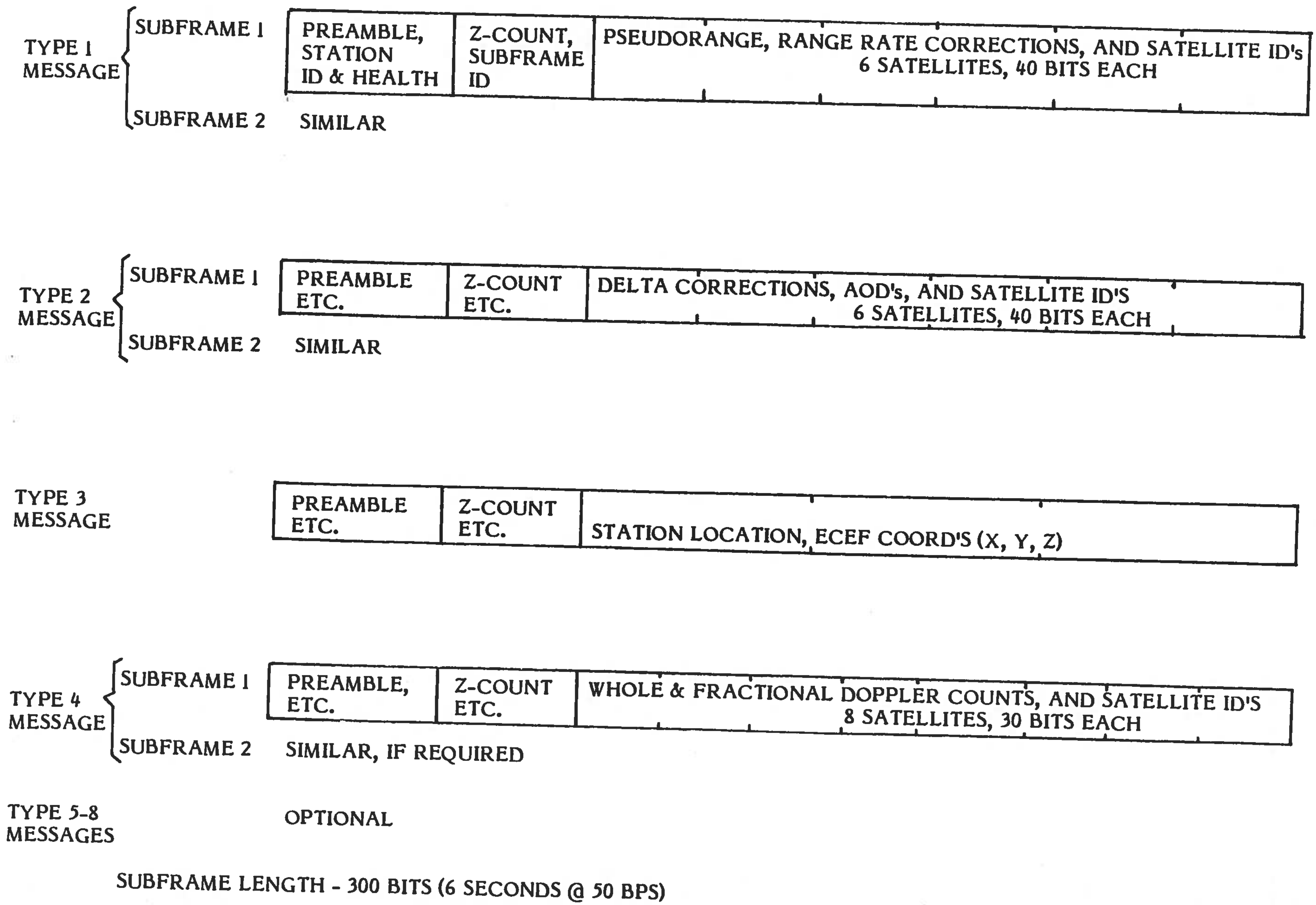

FIGURE 1. PROPOSED DIFFERENTIAL GPS MESSAGES

TABLE 1. DIFFERENTIAL GPS DATA

MESSAGE TYPE	PARAMETER	NUMBER OF BITS	SCALE FACTOR & UNITS	RANGE
ALL (First word)	Preamble	8	(Same as GPS)	
	Station ID	12	1	1-4096
	Station Health	2	-	4 states
	Spare/Parity	2/6	-	-
ALL (Second word)	Z-Count	17	6 seconds	0 - 100,795 s.
	Subframe message type	3	-	1-8
	Spare/Parity	4/6	-	-
TYPE 1 (corrections) Each satellite (6 satellites/ subframe)	Pseudorange Correction	16 (X6)	0.1 meters	± 3276.8 m.
	Range-rate correction	8 (X6)	0.004 m/sec	± .512 m/s
	Satellite ID	5 (X6)	1	1-32
	Satellite Health	3 (X6)	-	8 states
	Spare/Parity (Total)	48	-	-
TYPE 2 (Auxiliary corrections) Each satellite (6 satellites/ subframe)	Delta Correction	16 (X6)	0.1 meters	± 3276.8 m.
	Age of Data	8 (X6)	See ICD-GPS-200	
	Satellite ID	5 (X6)	1	1-32
	Satellite Health	3 (X6)	-	8 states
	Parity (Total)	48	-	-
TYPE 3 (Station Location)	ECEF X-Coordinate	32	.01 meter	$\pm 2.15 \times 10^7$ m
	ECEF Y-Coordinate	32	.01 meter	$\pm 2.15 \times 10^7$ m
	ECEF Z-Coordinate	32	.01 meter	$\pm 2.15 \times 10^7$ m
	Parity	48	-	-
	Spares	96	-	-
TYPE 4 (Surveying) Each Satellite (8 satellites/ subframe)	Delta Doppler Count	8	1	0-255
	Fractional Doppler Phase	8	1/256 wavelength	0-255
	Satellite ID	5	1	1-32
	Satellite Health	3	-	8 states
	Parity	6	-	-
TYPES 5-8	Optional			

be pointed out that the message type mix and relative frequency can be tailored to a particular differential station and does not have to be fixed by the format.

The Type 3 Message contains the earth-centered earth-fixed (ECEF) coordinates of the differential station. The data is contained in one subframe. This message type need only be broadcast once every two or three minutes.

A Type 4 Message was developed to accommodate the extreme precision required by some surveying applications. This message consists of satellite identity, "delta" Doppler cycle counts, and fractional Doppler phase. The "delta" Doppler cycle counts indicate the difference (in whole Doppler cycles) between the measured counts and the number predicted by the ephemerides and the time elapsed since the previous subframe transmission, assuming a perfect oscillator at the reference site. Similarly, the fractional Doppler phase represents the measured phase of the received carrier with respect to the reference site oscillator minus the expected phase computed using the satellite orbit as transmitted, the reference site position and a perfect oscillator. Use of these counts enables relative location accuracies in the centimeter range.

The format can accommodate four more message types, which can be added at a later date. A message for aircraft could contain weather, runway condition dta, runway threshold coordinates, tropospheric refractivity measurements, or instructions to individual aircraft, for example.

If the reference station is a pseudolite, the receiver passes along the data to the processor just as it passes data from the NAVSTAR GPS satellites (i.e., 6-second subframes at 50 bits per second). The processor requires no hardware changes to handle the differential data. Furthermore, the bit phase transitions are or can be synchronized to GPS time, so the pseudorange from user to the station can be measured. In this configuration the reference station acts as an extra satellite, and can be used to improve the accuracy of the position estimate. In this case the Z-count contained in the HOW words is the time of the start of the next subframe.

The data format also accommodates an external data link. The data link itself can be at any of a number of frequencies that might be available or convenient to a particular user group. For example, Mode-S is a planned L-band data link for air-to-ground and ground-to-air communications for civil air users. It may be possible in the future to use some of the data slots for differential corrections. Other possible aircraft bands include VOR broadcasts (108-118 MHz) and VHF communications (118-136 MHz). For marine users, the Radiobeacons (285-325 KHz) may be able to be modulated to provide the differential corrections. These signals can be received over the horizon. VHF marine frequencies (150-174 MHz) may be employed where line-of-sight communications are feasible. It may be possible for vehicles to use unused portions of the FM band to receive differential corrections in the future.

The only requirements placed on the data link are that the data rate be at least 50 bits per second, that it interface with a serial, asynchronous, standard RS-422 port, and that it preferably send the format data to the receiver as ASCII characters (not necessarily implying decimal data). Otherwise, the data may be transmitted as a fast data burst or as a continuous stream and may employ any convenient modulation scheme. In these cases, the transmission of data is not necessarily synchronized to GPS time, and the Z-counts serve only as reference times for the data being transmitted.

The proposed signal format has considerable flexibility and room for growth to accommodate new applications. The resolution values chosen for each of the data elements are fine enough to allow for considerable improvements in accuracy that improved receiver designs and better atmospheric models may provide in the future. As the strawman format continues to be subjected to scrutiny, it is expected that changes will be made. However, the workshop participants considered that the proposed format represents a very satisfactory first effort.

4. RATIONALE

There was considerable discussion on each of the issues as described in Section 1 on the purpose of the workshop, as well as other issues that were raised during the deliberations. While it is impossible to record all the points raised by the participants, this section summarizes the reasons for the major technical choices relating to the differential format. The issues of Section 1 are used here as a framework for citing the rationale employed.

ISSUE 1. Should latitude/longitude or satellite pseudorange corrections be broadcast?

ANSWER - Satellite pseudorange corrections should be broadcast.

DISCUSSION - Several reasons were cited for this choice, most of them relating to the fact that if differential station and user do not employ identical satellites, the accuracy of the solution will suffer. There are several reasons why differential station and user might employ different satellites:

(1) the satellite selection algorithm might be different -- one might use the best-set-of-four while the other used an all-in-view strategy;

(2) different mask angles might be used, which would affect which satellites are used in the navigation solution;

(3) for users distant from the differential station, the geometry could be such that different satellites would be visible, at least temporarily.

Other reasons were cited, relating to the age of the data used by the station and user receivers, which could be different. Also, ionospheric and tropospheric models can't be satisfactorily incorporated into lat/lon corrections.

ISSUE 2. What data elements should be included in the corrections? With what units, resolution and range?

ANSWER - Pseudorange and pseudorange rate should be sent frequently, along with satellite ID and health. Sixteen bits are reserved for pseudorange, so that the message allows for a variation of ± 3277 meters and a resolution of 0.1 meters. With 8 bits for pseudorange rate, the message allows for ± 0.512 meters/second with a resolution of 0.004 meters per second. Eight bits are used for satellite identification and health.

DISCUSSION - Currently both the pseudoranges and pseudorange rates are dominated by the planned Selective Availability characteristics. The current DOD plan is to provide horizontal positioning accuracy of 100 meters (2drms) when the GPS becomes operational. With 16 bits, the message allows for a variation of ± 3.277 kilometers, which allows for unusually high pseudorange offsets to be accommodated. It might be desirable to improve the resolution by a factor of four, for example; this would imply a variation of ± 810 meters, which should still be more than adequate. It may, on the other hand, be preferable to allow for some drift in the station clock.

Pseudorange rate can vary by as much as ± 0.5 meters per second, according to a recent unclassified study of Selective Availability characteristics. This can be accommodated by an 8-bit data element having a resolution of 0.004 meters per second. With a 12-second average update time, projected corrections using pseudorange rate would resolve to 0.05 meters, which is consistent with the pseudorange resolution of 0.1 meters.

If the differential station detected an unusual behavior in the pseudorange measurement, this could be reflected in the three health status bits to give the user a timely warning of a satellite problem. Thus the differential station could perform a GPS monitoring function as well.

The 5 bits reserved for satellite identification will cover all possible satellite ID assignments (32 total).

ISSUE 3. How often should corrections be broadcast?

ANSWER - A 12-second update period is adequate, given that both pseudorange and pseudorange rate are broadcast.

DISCUSSION - Immediately after a correction is made, the accuracy of the user position estimate is very good. As time passes, variations occur in the ionosphere and troposphere path delays as well as in the Selective Availability "waveform". The latter is by far the dominant effect, typically causing pseudorange variations with a standard deviation of about 0.026 meters per second. It was the consensus that the proposed format should try to attain a one meter precision if possible. For this reason it was proposed to measure and broadcast the rate of the change of the satellite signal delay as well. Assuming that a very adequate measure of the rate of change could be made in a few seconds, the combination of pseudorange rate correction and pseudorange correction would add errors of about a meter over a period of 12 seconds.

The 12-second period was driven by the desire of the workshop participants to create a format that would allow use of a pseudolite ground station, which would be constrained by the NAVSTAR GPS data transmission limitation of 50 bits per second. By using the GPS 6-second subframes, corrections for up to 12 satellites could be made every 12 seconds using the proposed format. It should be noted that in the currently planned constellation of 18 satellites plus 3 active spares, as many as 8 satellites could be visible at one time. If future funding permitted, up to 6 additional satellites might be added, in which case up to 11 satellites might be visible. If the ground reference station were a time-synchronized pseudolite, a slot would be used in one subframe to indicate its "clock corrections".

It should also be pointed out that if an external data link were employed, it would not be constrained to 50 bits per second. A higher update rate could be utilized if desired.

ISSUE 4. What auxiliary data should be broadcast, and how often?

ANSWER - Auxiliary data should consist at a minimum of a "delta" correction term, an Age-Of-Data (AOD) word, and an identification code for each satellite, to be sent every half-minute or so. (It is not necessary to specify this update rate.) In addition, the reference station coordinates in meters in Earth-Centered, Earth-Fixed (ECEF) coordinates should be broadcast every minute or so (again, not necessary to specify the update rate).

DISCUSSION - Once an hour each satellite changes its data message to reflect more accurate ephemerides and satellite clock corrections. Each user reads the data asynchronously, so that several minutes may pass before all users are employing current data. While the changes are small, differential service users would experience a discontinuity if the reference station suddenly computed its corrections based on new data while the users were still using old satellite data, especially if the change of data was due to a GPS satellite upload. To get around this problem, the differential station will compute corrections using new data immediately after the data changes, and will also compute the difference between the new and old pseudorange corrections (hence the phrase "delta correction term"). In the auxiliary (Type 2) message this delta correction term is sent for each satellite along with the ID and the Age-Of-Data. The AOD enables the user to determine whether to apply the delta correction term or not, by comparing it to his own AOD.

By broadcasting the station location coordinates in the Type 3 Message the need for a lookup table to relate station ID to location is eliminated. This makes the differential system impervious to changes in station location and the addition of new stations. Code management will still need to be applied in order to remove the possibility of a user receiving two stations with the same code, but there will be no need for frequent updating of a lookup table either manually or by ROM cartridge. The use of ECEF coordinates for station location reflects the most common way that receivers compute the user/satellite line of sight vectors.

Other data such as weather data or refractivity measurements were not considered to be essential for most users at this time. As user groups develop who need other auxiliary information, new message types and subframe formats can be defined. The 96 spare bits available in the Type 3 Message could also be used for these purposes.

ISSUE 5. What data should accompany each broadcast segment?

ANSWER - Each subframe should be accompanied by a preamble identifying the beginning of the subframe (8 bits), station identification (12 bits), station health (2 bits), the Z-count of the next frame (17 bits), and message type (3 bits). In the case of an external data link, the Z-count only represents the reference time for the pseudorange.

DISCUSSION - Following the GPS format, each subframe begins with two 30-bit words. The first word consists of an 8-bit preamble, a 12-bit station identification, and 2 station health bits, leaving 2 spares and 6 bits for parity. The second word consists of a 17-bit time count referenced to the next subframe start time, followed by 3 bits for message type identification, then 4 spares and 6 parity bits.

The station identification actually defines the code for the station, which would be used by a pseudolite transmitter. These codes should to be Gold codes, consistent with the GPS C/A codes, so as not to affect receiver designs. Of course, these codes would have to be known a priori to the users in order for receivers to acquire the pseudolite signal.

The 2 station health bits are not yet fully defined, but since the primary question is "Is the station usable or not?", it was felt that a 4-state answer would be sufficient.

The 17-bit "Z-count" in the second word matches the GPS format, and would be satisfactory for pseudolite transmissions. Operation with an external data link would make it possible to transmit subframes more often than once every 6 seconds. Since the external data link will not necessarily be synchronized to GPS time, the time of the next subframe is meaningless to the user. The data link would have its own protocol based on the design of that link. The Z-count would only represent the reference time for the pseudorange corrections, which could be repeated several times but still have a 6-second resolution.

Finally, the message type identification uses 3 bits, which enables 8 different message types. It should be noted that different subframes within the same message type can use the same IDs.

ISSUE 6. Can differential operation maintain high accuracies during a satellite data change, given that users will generally change over to the new data at different times?

ANSWER - Yes. The Type 2 Messages are specifically designed to provide the "delta corrections" which enable each user to compensate for the possibility that the ephemeris and satellite clock data may be "old".

DISCUSSION - The satellites will receive uploads from the Control Segment at least every 4-6 hours, usually more often. At this time ephemeris coefficients and satellite clock coefficients are altered, so that the corrections sent out on the next hourly update will contain small changes, but changes which would be large enough to be noticed by a differential user. Hourly changes between uploads are smaller, usually insignificant. Also, ephemeris and satellite clock data changes occur at the same time on a given satellite. The Type 2 Message thus enables a user to detect that fact that a data change has occurred and to compensate for it. The differential receiver/processor must be constructed so that it instantly detects a change in data, so that no user can be using new data while the reference station is using old data.

ISSUE 7. Should the pseudorange corrections broadcast by the reference station include the application of a tropospheric model?

ANSWER - A tropospheric model should not be employed by the reference station to compute the pseudorange corrections to be broadcast.

DISCUSSION - By not employing a model, users near the differential station will experience similar tropospheric signal delays from each satellite, so that the effects will cancel. Differences that do occur are due to fluctuations in temperature, humidity and pressure, quantities that do not appear in the models usually employed in GPS receivers. The resulting errors are likely to be negligible near the station, but can become significant at 100 miles away, for example. Also, the elevation angles of user and reference are somewhat different, so that small errors will occur for low-lying satellites. Users wishing to make further corrections can do so by employing models for the station position as well as the user position. These models could also incorporate refractive index data or other information derived from GPS data or other sources.

Thus, by not employing models, users near the station obtain almost perfect cancellation of tropospheric delays, while those users farther away or desiring higher accuracy can further compensate by using models. Furthermore, if better models are developed in the future, or if more information becomes available, they can be accommodated. The alternate choice, i.e., to include the models in the corrections, would constrain the models to the ones currently in use, and not allow for improved future models.

ISSUE 8. Should the pseudorange corrections broadcast by the reference station incorporate ionospheric models?

ANSWER - Ionospheric models should not be employed by the reference station in computing the pseudorange corrections to be broadcast.

DISCUSSION - The same considerations apply for ionospheric models as for tropospheric models. By applying no models to the corrections, users near the station get almost perfect cancellation of ionospheric signal delays. Those users farther out can get some improvement by applying models to their own positions and those of the station. As ionospheric models improve in the future, these further corrections will provide even better results. By not employing models in the pseudorange correction determination, future receivers are not limited by current models.

At this time, it appears unlikely that there would be any benefit to transmitting an additional ionospheric parameter analogous to the tropospheric refractive index. While it would be possible in principle for a two-frequency reference station to accurately determine the ionospheric delay, the information is not useful. There are small differences in transmission times between the L_1 and L_2 frequencies for each satellite. These reduce the accuracy of any correction term that could be measured.

ISSUE 9. Should the differential pseudorange corrections include the ephemeris and satellite time adjustments obtained from the satellite data message?

ANSWER - The differential station should include the ephemeris and satellite clock adjustments, and the users should likewise apply them to the received pseudorange measurements.

DISCUSSION - These adjustments can be quite large, up to hundreds of kilometers, so that a data correction would have to have a large number of bits if the satellite adjustment data were ignored. Ionospheric and tropospheric delays, on the other hand, rarely exceed a hundred meters. Furthermore, the satellite data is not going to change form in the future, so there is little to be gained by bypassing the application of satellite data to the pseudorange measurements.

This does pose a potential problem for the users desiring the highest accuracy, because the satellite data changes every hour or so. Since not all users read the data at the same time, there will be periods of time where the reference station and user are employing different satellite data. This circumstance is obviated by the Type 2 Message, discussed in Issue 4.

ISSUE 10. In view of the desirability for some applications of having the differential station operate as a "pseudolite", is it possible to develop a design concept that avoids causing interference to other GPS receivers near the station?

ANSWER - None of the pseudolite concepts considered at the workshop were considered to be entirely satisfactory, but some participants remained optimistic that such a design concept could be developed. This question will be addressed further by a number of participants.

DISCUSSION - The satellite antenna patterns are tailored to provide a nearly constant signal to a receiver having a uniform antenna pattern, within about 6 db. With expected signal variations user receivers can generally handle about 20 db total signal variation. A ground station transmitting in the GPS band would result in large signal variations, due to the normal power density falloff with distance of the user from the station. A user very close to the station would experience a large signal, which could jam the satellite transmissions and cause false lock indications.

Proposals for pseudolite solutions included frequency-division multiplex schemes, time-division multiplex schemes, and non-Gold code types. None of the proposals clearly solved all the technical challenges. As a result, interested participants plan to develop concepts for consideration. They will meet prior to January to determine whether a feasible concept is possible. This effort will be headed by Thomas A. Stansell, Jr. of Magnavox Corporation, chairman of the Communications Technique Session. If the interference problem can't be solved, it may be necessary to restrict pseudolite operation to remote locations.

Another possible difficulty cited with pseudolite transmissions is the problem of earth-based transmissions at the GPS satellite frequency. It is not clear that ground transmissions would be allowed at L_1.

ISSUE 11. Can a pseudolite station be designed to provide an adequate update rate for pseudorange corrections, given that the GPS data is transmitted at 50 bits per second?

ANSWER - Yes.

DISCUSSION - The format allows for a 12 second update period at 50 bits per second, which appears to offer satisfactory accuracy for the users currently identified.

ISSUE 12. If pseudolite operation is not employed, and an external data link is employed, what interface specification should be used?

ANSWER - A reasonable interface specification would be a serial, asynchronous port such as defined by RS-422. Details such as baud rate, byte format, parity and protocol have not yet been addressed.

DISCUSSION - By defining an interface specification, the format does not limit future users and providers of differential service to a specific frequency or modulation technique. However, the message format for transferring data from the communications link to the receiver needs to be standardized. The same group that attempts to develop a pseudolite approach will recommend a specification before the January meeting.

ISSUE 13. If an external data link is employed, can it make use of existing facilities such as LORAN-C, DECCA, VHF communications, Radiobeacons, satellite communications, FM radio, or Mode-S?

ANSWER - It is apparent that different user groups would favor different frequency bands. Also, making the best use of existing facilities will make differential service more attractive. While the development of standards for specific communications links will probably take several years, credible techniques need to be developed and evaluated in the near term.

DISCUSSION - Some of the advantages and disadvantages of different communications bands and existing broadcast facilities are discussed below:

1. LORAN-C - the 100 KHz band is ideal for broadcasting over-the-horizon signals. Three or four stations could serve the entire easter coast of the U.S., for example. LORAN-C transmitters can and have been modified to transmit data, but it does not appear that this approach is feasible. If a non-LORAN modulation is used, it will interfere with LORAN-C. Using LORAN-C modulation requires a costly data receiver, which is not desirable.

2. DECCA - Some of the DECCA frequencies could be used, but the available data rate does not appear to support a 50 bps channel.

3. VHF Communications - It was agreed that VHF was a likely communication medium for line-of-sight applications. Both air and marine users have assigned bands that could conceivably be used for differential broadcasts. The large number of alternative frequency bands, channel bandwidths, and modulation schemes make it impossible to treat this option, so that this subject should be explored further.

4. Radiobeacons - The LF and MF bands used by air and marine radiobeacons appear ideal for providing over-the-horizon coverage. The

technical problems involved with modulating the radiobeacon transmitters appear to be quite tractable, and the resulting communications receivers would be quite inexpensive. The European community is now preparing a new set of beacon standards to preserve bandwidth and solve a number of existing problems. The results of this effort are to be formalized in 1985 at a meeting of the International Association of Lighthouse Authorities (IALA) at Brighton, United Kingdom. David Scull of DOT/RSPA will attempt to act as liaison with IALA and work with the U.S. Coast Guard to promote coordination with the European efforts. Alan Wheeler of RACAL/DECCA will determine whether and how it might be possible to obtain access to the beacon signals for differential GPS applications. He and Per Enge of RACAL/Megapulse will study the propagation issues of LF/MF transmissions and report their recommendations at the January ION conference.

5. Satellite Communications - Satellite broadcast of differential GPS corrections was concluded to be unlikely for many users due to the weak signal and directional antenna requirements. It was noted that oil exploration companies might implement such a system through INMARSAT for some applications. It was also noted that it might be possible for a country or continent to provide a special satellite to augment GPS coverage while providing differential GPS signals. Other than these special situations there appeared to be no need for a satellite transmission standard.

6. Urban FM Coverage - It was reported that there is a move in Europe to adopt a standard for providing digital data transmission by audio subcarrier on either side of the 19 KHz pilot tone accompanying FM broadcasts. The data rate is expected to be 600 bits per second. Thomas Stansell will work through the N.V. Philips Company, Netherlands, to determine whether differential GPS data might be included in the transmissions. He will also explore the possibility of a similar standard in the U.S.

7. Mode-S - The Mode-S transponder system for airborne air traffic control use incorporates a data link. The specifications for this data link are now being developed. It is expected that most aircraft will have these transponders in the early 1990's. It would be convenient to have the data link message from the ground include differential GPS corrections. Keith McDonald of the FAA will explore this possibility and determine what steps would be required to establish this capability.

In summary, the external data link can be implemented in a variety of ways using any of several different frequencies. The problems lie in selecting the best implementation techniques and obtaining the necessary institutional acceptance.

ISSUE 14. Is it possible to create a format that accommodates both pseudolite and external data link?

ANSWER - Yes. The proposed format achieves this capability.

DISCUSSION - While the format is designed around a pseudolite data link, it is quite compatible with an external data link as well. In addition to the parity bits incorporated in the format, an external data link might add its own parity and divide up the message in any way desirable.

ISSUE 15. Is it possible to create a format that provides the necessary information and accuracy for airborne, marine, research, vehicle, test range, and surveying applications?

ANSWER - Yes. The proposed format appears to achieve this capability.

DISCUSSION - The format, as embodied in Type 1, 2, and 3 Messages appears to provide adequate accuracy for airborne, marine, vehicle, and many test range applications. Research and surveying applications making use of stationary receivers can get higher accuracies by receiving the Type 4 Messages as well. The high accuracy is achieved by the transmission of the number of delta Doppler cycles counted since the previous transmission of that satellite's correction (see the discussion of Type 4 messages, page 10). This measurement is taken off the carrier. The format even allows for an estimate of the corresponding fractional phase change. This estimate is the 8 bit fractional count. Thus the precision of the measurement is a little over one degree of phase. The transmission of this information would be delayed for a minute or so to foil any real-time use of this information.

ISSUE 16. Is it possible to create a format that can accommodate future research findings and that allows room for future application such as centralized surveillance and the broadcast of weather information?

ANSWER - Yes. The proposed format allows for additional message types to be added in the future to meet such needs.

DISCUSSION - There are four undefined message types, which can be used for a number of purposes. For example, weather and runway condition data could be broadcast, which would assist in aircraft landing applications. Similar data could help mariners decide whether to proceed into a harbor area.

A centralized surveillance scheme for marine or air applications could use one of the available message subframes for selective addressing of vessels or aircraft, and for transmission of ground-derived position information. The downlink format would not be involved with GPS. Similar applications for vehicle tracking can be accommodated if the need arises in the future.

5. FOLLOW-UP EFFORTS

A number of participants, primarily from companies that design and manufacture receivers, have agreed to meet to address the problems of pseudolite feasibility (Issue 10) and the external data link interface definition (Issue 12). This group will be headed up by Thomas A. Stansell, Jr. It will meet once or twice between now and January. The results will be reported at the January, 1984, meeting of the Institute of Navigation.

The meaning of the station and satellite health bits has not yet been worked out. Two and three bits have been reserved for each of these functions, respectively, allowing at least four states to be defined: satisfactory, unsatisfactory, and two (or six) intermediate indications. The intermediate indications need to be defined at least to the extent that the user receiver's responses to them are specified.

A number of action items involving individual participants were assigned on the questions of the possibility of using particular frequency bands and existing facilities. These are discussed under Issue 13. The status of these questions will be reported at the January ION meeting.

An important question is the course of action that needs to be taken after the January meeting takes place. Assuming that the outstanding questions are answered to the extent though necessary at the time, the tentative plan is for the Satellite Navigation Division of the Institute of Navigation to formally approach a number of groups that formulate standards, asking them to develop a set of standards around the proposed format for differential NAVSTAR GPS operation. The Radio Technical Commissions for Aeronautics and Maritime Services (RTCA and RTCM) are natural organizations for this kind of activity. They could be asked to set up Special Committee to draft such standards. International organizations such as the International Maritime Organization (IMO), the International Association of Lighthouse Authorities (IALA), and the International Civil Aviation Organization (ICAO) should be approached for the purpose of coordination world-wide. Other organizations will eventually be involved if vehicle use becomes imminent.

APPENDIX A. PRESENTATIONS BY PARTICIPANTS

PRESENTATIONS BY SESSION CHAIRMEN

1. Van Dierendonck, A.J., "Comments on Differential GPS" - Recommendations on the elements of the proposed signal format.

2. Denaro, Robert P., "Differential GPS Filter Implementation Tradeoff Analysis" - a discussion of a simulation program that computes the navigational errors experienced by a helicopter employing NAVSTAR GPS in a differential mode, including results.

3. Stansell, Thomas A. Jr., Untitled - A discussion of a number of user's requirements for differential GPS, with format recommendations.

PRESENTATIONS BY OTHER PARTICIPANTS

1. Delikaraoglou, Demitris, "Differential GPS Models" - Computations of differential accuracy degradation of pseudorange at a number of receiver stations.

2. Edwards, Fred, "NASA/Ames Civil Helicopter Satellite Navigation" - A description of the NASA program to evaluate GPS for helicopter guidance; includes simulations, hardware development, and field tests.

3. Enge, Per, and Alan Wheeler, "The Transmission of Differential NAVSTAR GPS Corrections Using Low Frequencies" - An examination of the possibiity of using LORAN-C and/or DECCA frequencies for the transmission of GPS differential corrections.

4. Fickas, Ernest, and Tom MacDonald, Untitled - A description of test range applications of GPS, including differential GPS, as well as some preliminary results.

5. Mertikas, Stelios, "Evaluation of Some Parameters Affecting the Performance of Differential GPS Navigation" - A study of accuracy degradation of differential GPS from a number of different error sources, as a function of distance from a reference station.

6. Murphy, Jack, "Considerations Related to the Use of Pseudolite for Differential GPS" - A description of the problems and implications of pseudolite operation.

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