Analysis on the One-Way Communication Capability of GPS Satellites in Orbit Transmitting Non-navigational Information

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***Abstract*—The GPS system is capable of the one-way communication (OWC) transmitting non-navigational information if the reserved bits of L1C Nav message and the newly-added CNav message types for L2C signal are utilized. Excluding the potential communication protocol overheads, a single frequency with one satellite transmits data at 0.5B/s; with the dual frequency transmission by using L1C and L2C frequencies and the parallel transmission of multiple satellites, the transmission rate can be increased to approximately 4B/s. The one-way communication of GPS is covert due to the covertness of communication channels, the occasionality of one-way communication, the disorderly distribution of information and the difficulty in recognizing and understanding communication data when the communication protocol is unknown. This paper discusses the problems of satellite rise-and-fall, data packetization and data dropout and gives solutions for them. A design paradigm for the format of newly-added L2C CNav message types is given. The GPS one-way communication has the advantages of global coverage, day-and-night and all-weather operation, as well as low cost, thus it can meet the needs for special purposes, such as civilian emergency broadcast communication, military submarine command system and command of intelligence collection.**

Keywords- GPS; one-way communication (OWC); covert communication; emergency communication; submarine communication;Navigation Message; Reserved Bits.

I. INTRODUCTION

At present, the GNSSs (Global Navigation Satellite Systems) [1] that have been fully operational or under development consist of USA's GPS, Russia's GLONASS, Europe's GALILEO and China's Beidou, among which, the last one is not only able to fix positions, but also capable of two-way communication. In the GPS Modernization program, the L5 frequency [2] is proposed for use as a civilian safety-of-life signal, which has the capability of two-way communication, but until now orbiting satellites can't provide this service yet. Through the in-depth analysis, the GPS system is found with the one-way communication (OWC) capability, which is unexpectedly useful in many fields. The study of this capability is valuable for both academic study and practical application.

Communication is generally two-way, but the OWC is used in a wide range of application fields, which include: submarine communication, satellite television, broadcast communication (radio), communication between GPS satellites and receivers, other wireless broadcast communications etc. The height of satellites makes the GPS OWC advantageous over many traditional means of communication. The mobile communication system of cell phone is limited by the coverage of base stations, thus being unable to communicate in deserts, open seas, mountains and the Arctic area; voice broadcasting system suffers the same problem; satellite television has high technical requirements for antennas and receivers. GPS receivers have the advantages of widespread use, small size and low requirement for power, all of which provide a practical basis for the OWC of GPS; for GPS users, what they need to do is only to add a software module to their receivers. Therefore, the OWC of GPS is feasible and easily realizable.

Up to now, no reports on the study of the OWC capability and application for the GPS system have been seen both at home and abroad. It implies that this potential function of the GPS system hasn't been explored yet. Accordingly, this paper conducts systematical study on the GPS system's OWC capability and its applications.

II. RELATED WORK

During the design of navigation message format [3][4] in the early stage of developing the Global Positioning System (GPS), in order to leave room for further improvement, a number of bits are reserved in the navigation message. However, when IS-GPS-200D [5] was released in 2004, there were still a lot of reserved bits that haven't been defined. From the perspective of navigation fix, it is a waste of resources. In view of this, the new L2C civilian signal proposes a new type of CNav navigation message [6]. However, the reserved bits of L1C navigation message support information transmission for non-navigational uses, thus GPS has the capabilities of both navigation fix and OWC.

Data communication rate of OWC is usually slow, such as submarine communication [7], VLF communication [8] and ELF communication [9], whose communication rates are terribly low. In practice, the techniques, like information coding and data compression, are applied to improve the communication efficiency[8][11][12]. As for secret communication, the information is always transmitted after encryption [13]. Apart from increasing the efficiency of communication and keeping confidential by applying the above-mentioned techniques, after the in-depth study of the GPS system, it is found that quite a few traits of the GPS system itself provide approaches to acquire the covertness of the one-way communication and increase its efficiency. As regards the one-way communication capability of GPS orbital satellites transmitting non-navigational information, this paper conducts the systematical study on the feasibility of the one-way communication, the applications of the GPS one-way communication and its covertness, communication efficiency and methods to improve

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the efficiency, as well as the major problems with these methods.

III. FEASIBILITY ANALYSIS OF GPS OWC

3.1 Feasibility Analysis of GPS L1C Signal used for OWC

When the GPS system is used for OWC, the information transmitted should be unrelated to GPS navigation fix and it won't disrupt or interfere with original functions of GPS [14], that is to say, it shouldn't produce any interference to the position fixing of GPS receivers in use. After the deep-going study of the GPS navigation message, it is found that reserved bits in it [5] can carry additional OWC information.

The GPS navigation message mainly contains: the satellite's ephemeris, satellite clock (bias) correction parameters, ionospheric delay correction, the satellite's status, P code acquisition by C/A code translation (HOW) and so on. The navigation message consists of 25 mainframes, which make up a complete navigation message packet, also called a superframe. A mainframe is divided into five subframes of 300 bits (each subframe is divided into 10 words of 30 bits each) each and transmitted at 50 bits/s. Each subframe takes 6 seconds, each mainframe 30 seconds, and the entire set of 25 mainframes takes 750 seconds (12.5 minutes) to complete. See Table 1 for the mainframe format of GPS navigation message.

TABLE 1. MAINFRAME FORMAT OF GPS NAVIGATON MESSAGE

Subframe	10 words (30 bits each) for a subframe		
1	TLM	HOW	Data block I —clock correction parameters
2	TLM	HOW	Data block II—ephemeris
3	TLM	HOW	Data block II—ephemeris (continued)
4	TLM	HOW	Data block III—satellite almanac and others
5	TLM	HOW	Data block III—satellite almanac and others

The reserved bits in each subframe are analyzed as follows.

(1) Location and capacity of reserved bits in subframes 1, 2 and 3.

As shown in Table 2, subframes 1, 2 and 3 of a mainframe carry 93 reserved bits, then in a superframe containing 25 mainframes, in 12.5 minutes, it totally carries $25\times93=2325$ reserved bits in all of the subframes 1, 2 and 3.

(2) Reserved bits in subframes 4 and 5

As shown in Table 3, there are 2354 reserved bits in total in subframes 4 and 5, that is to say, in 12.5 minutes, a superframe carries 2354 reserved bits in subframes 4 and 5.

(3) As stated above, a superframe carries 2354 + 2325 = 4679 reserved bits in 12.5 minutes. Therefore, we can employ these bits to transmit other information for non-navigation uses, and the mechanism of GPS itself decides that it is a kind of OWC.

TABLE 2. RESERVED BITS IN SUBFRAMES 1, 2 AND 3

Subframe	Word	Location in the word	Bits
1	1	23 – 24	2
1	4	2 – 24	23
1	5	1 – 24	24
1	6	1 – 24	24
1	7	1 – 16	16
2	1	23 – 24	2
3	1	23 – 24	2

TABLE 3. RESERVED BITS IN SUBFRAMES 4 AND 5

Subframe	Page	Word	Bits	Location in the word
5	1~25	1	50	23 – 24
5	25	10	22	1– 22
4	1~25	1	50	23 – 24
4	1,6,11,12, 14~17, 19~24	3	224	10 – 25
4		4~9	1680	1 – 24
4		10	308	1 – 22
4	18	10	14	9 – 22
4	25	8	2	7-8
4	25	10	4	7-10

3.2 Analysis on Communication Efficiency of GPS L1C OWC

Theoretically speaking, GPS receivers calculate positions only after receiving 30s data of at least four satellites. As a result, when the GPS system is used for OWC, it had better take minute as the granularity for calculating the communication rate. The GPS navigation message carries 4679 reserved bits in a 12.5-minute superframe, thus we have 4679bits / 12.5min = 374.32bits/min. 374.32bits are equal to 46.79Bytes. Considering the bandwidth allocated to communication protocol, even if 30% of bandwidth is allocated, the actual data transmission rate still can reach more than 30B/min, namely 0.5b/s. This rate exceeds the communication rate of all countries' land-based long wave submarine communication in use. As a standby, when land-based long wave and short wave communication facilities are damaged, the GPS system can provide an emergency communication channel. As the means of emergency communication for civilian use, the communication rate of 0.5B/s determines that it can only be used for broadcasting short message.

The discrete and disorderly distribution of reserved bits will have significant impacts on the design of the protocol for the GPS one-way communication and its efficiency, as detailed in the following. See Fig. 1 for the average information capacity of OWC by each subframe in GPS mainframes. The information capacities of subframes 1, 2 and 3 are evenly distributed, in other words, the actual information capacity of subframes 1, 2 or 3 in a mainframe is completely equal to what in any mainframe respectively. Subframe 5 is a little badly distributed in mainframes and it has 22 reserved bits in the 25th mainframe of a superframe, as shown in Fig. 2. The distribution of subframe 4 is the most complicated, as shown in Fig. 3. So, the capacity distribution of reserved bits in the mainframes within a superframe is complicated too, as shown in Fig. 4.

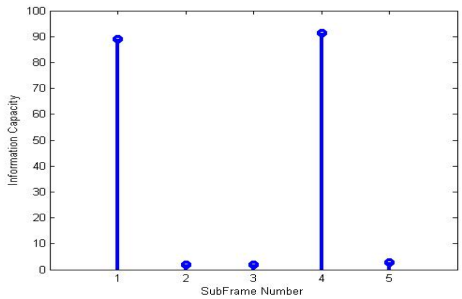

Fig. 1 The Average Information Capacity of OWC by Each Subframe in GPS Mainframes

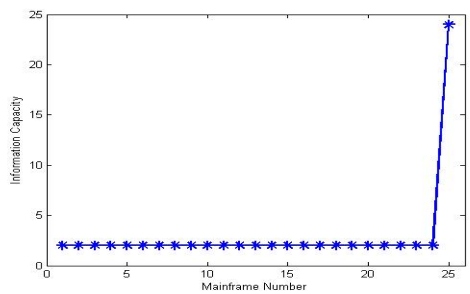

Fig. 2 The Distribution of Subframe 5 in Mainframes

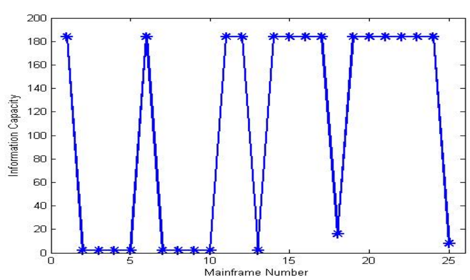

Fig. 3 The Distribution of Subframe 4 in Mainframes

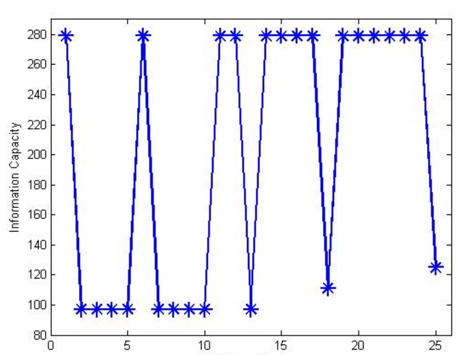

Fig. 4 The Distribution of Mainframes in a Superframe

It can be observed from Fig. 1 and Fig. 4 that, though the average OWC capacity of a mainframe is 187.16bits, half of mainframes in the superframe have a capacity of 100bits or so. In view of this, when mainframe is taken as the basic unit of the information transmission of OWC, the communication rate will surely be influenced by the distribution of information capacity of subframe 4 in mainframes. But if a superframe is taken as the basic unit of OWC, there isn't such problem. Obviously, from Fig. 1 we find that it is completely unsuitable to have subframe be the basic measuring unit for the time domain of the OWC, for the reason that some subframes can't carry any non-navigation information at all.

3.3 Feasibility Analysis of New Civilian L2 Signal Used for OWC

Some satellites currently in orbit are broadcasting L2C signals [5][6]. The civilian signal L2C allows direct comparison of L1 and L2 frequencies for ionospheric propagation delay correction. To separate civilian and military frequency bands and for utilizing new receiver technology, USA redesigns the structure of L2C signal, which is quite different from L1C signal.

From IS-GPS-200D [5], it is found that the navigation message of L2C signals can be Nav or CNav, of which the former is the navigation message for L1C and the latter is an improved navigation message format with higher efficiency and less waste of resources. Which kind of navigation message is carried by L2C is controlled by the ground upload station, thus the message structure of L2C is very flexible.

(1) When L2C modulates Nav message, due to the fact that L2C has the same capability of navigation message transmission with L1C, it can also support an OWC rate of 46.79Bytes/min (or an effective data communication rate of 30B/min).

(2) When L2C modulates CNav message, the CNav format, instead of using the superframe / frame / subframe architecture of Nav, features a new pseudo-packetized format, transmitting message in the form of data packets, where there are only a few reserved bits, so the information is more compact and the efficiency is higher. Obviously, it is impractical to make OWC by use of the reserved bits in CNav navigation message. CNav allows for a wide variety of packets (64 types) to be transmitted, but only a small fraction of the available packet types (15 types) have been defined. This enables it to grow and incorporate advances.

By virtue of the extensibility and flexibility of CNav, the special data packet types for OWC can be designed, which excels the OWC with L1C. The transmission rate of CNav message is 25bps, and the 300-bit message packet take 12s. Generally, a cycle of CNav is 48s; in a cycle it can transmit 4 packets, 3 of which (36s) are: two packets (type 10 and type 11) are ephemeris data and at least one packet (type 30) will include clock data and ionospheric correction. The remaining 12s can transmit only one packet, which is dependent on the actual needs. If it is used for one-way communication, the communication rate will be 300bits/48s=6.25bits/s = 46.87Bytes/min. This rate is equivalent to L1C OWC, but with better time balance, for it can transmit 300bit packets for OWC in every 48s. The communication rate of L1C OWC has bigger time jump and worse balance.

As stated above, no matter Nav or CNav navigation messages are modulated, L2C has the same OWC capability. And the combined use of L1C and L2C can double the capability of the GPS OWC.

3.4 Approaches to Increase the Efficiency of OWC

As analyzed above, when the GPS system is in use for OWC, the effective data communication rate can reach 0.5B/s only, which is very low and can do nothing but transmit short message. Therefore, in the actual application of the GPS OWC, several approaches and techniques can be adopted to increase the communication efficiency. The data compression techniques are the methods in common use for improving the communication efficiency and now they have already matured, needless of further elaboration. Based on the actual situation of the GPS system, this paper proposes a parallel transmission technique with multiple satellites to increase the efficiency of the GPS one-way communication.

The GPS satellite constellation is designed in such a manner as to guarantee that at least 4 satellites are visible from any place on earth at any moment in time. Many commercial GPS receivers can receive and process signals from 10~12 satellites at most. Based on the satellite orbits, we can accurately get to know the number of satellites which are visible at any place on earth at any moment in time. Accordingly, as to a specific region for OWC, several visible satellites in this region at this moment can be in parallel to transmit OWC data, and thus expanding the bandwidth at least 4 times (4 satellites in parallel). With the widespread use of GPS software receiver techniques, the capability for users to receive GPS satellite signals is gradually raised, so this kind of parallel transmission with multiple satellites is completely feasible. The parallel transmission needs adding the sequence number of data packet in the OWC data of visible satellites, so that receivers can reorganize the original information. This is analogous to the transmission of internet data packets in fragments.

IV. ANALYSIS ON APPLICATION AND COVERTNESS OF GPS OWC

4.1 Application of GPS OWC

The OWC capability of GPS can be used for military purposes, disseminating intelligence or transmitting operation commands for allied nations at war without being aware of by enemies. It can also be used as a standby mode for submarine communication of USA or its allies. For the land-submarine communication [7], submarines, especially the strategic nuclear submarines, when under water, rely on the one-way reception of ultra long wave commands sent by land-based posts; when above water, they mainly depend on the two-way short wave communication with the land-based posts. The long wave communication facilities are so tremendous that they are easily destroyed, so are the short wave communication facilities. The long wave communications, especially the ELF and VLF communications [8] [9], transit a small amount of information in a unit-time and the rate is very slow. As was proved by experiments made abroad, sending 20 English letters need tens of minutes. Therefore, it can only send some predefined simple symbols to nuclear submarines, such as the command to launch nuclear bombs. The communication rate of the GPS OWC can sufficiently meet the needs for the land-submarine communication, thus GPS can be an emergency standby for submarine communication.

The OWC capability of GPS is able to take command of the intelligence collection by intelligence agents, such as task-assignment, giving notice of the development of events. There is no way for us to know whether USA has already applied the GPS OWC for intelligence collection, but our study shows that GPS possesses of this capability. The most outstanding trait is that it is covert. Although with the need for decrypting the secret information in the navigation message, this kind of special GPS receivers carried by intelligence agents are similar to ordinary civilian receivers in appearance, thus they are covert and difficult to be detected by other countries. The commonly-used monitoring and detection methods for intelligence collection are ineffectual for them. If GPS military receivers are captured by other countries, the security of GPS codes for military use might be threaten, so USA is unlikely to assign tasks or to send commands or important information through the military channels of GPS.

The OWC capability of GPS can be used to meet the public emergency needs. For example, for common user receivers, China's Beidou navigation system [10] provides the two-way communication, which played a critical role in the disaster relief after the Wenchuan Earthquake happened [15]. With Beidou receivers, the disaster area fixed positions for over 70,000 times and sent more than 30,000 short messages per day, rendering support for the scientific decision-making and arrangement of disaster relief by Chinese governments and providing information channels for Wenchuan people who were working in other cities when the earthquake occurred, to know the situations of their relatives. In the early stage, the GPS hasn't been designed for meeting public emergency needs. In the GPS Modernization (the GPS III program), it is planned to implement a civilian-use signal, broadcast on the L5 frequency, for the Safety of Life purpose, but to date it hasn't been implemented yet. In this paper, the study shows that the OWC capability of GPS in orbit can play a significant part in the civilian emergency communication of big disasters. In recent years, big natural disasters came in succession and the issue of public safety caused by disasters became a focal point of governments of all countries. When earthquake, tsunami and tornado occurred, the GPS can be used to release the progress of emergencies to people in specific regions, and tell them how to meet the emergencies. Thus, besides fixing position, GPS can be used as an effective OWC means to give commands and guide common people in case of emergencies.

4.2 Covertness of GPS OWC

The good covertness of the GPS OWC is embodied as follows:

(1) The covertness of communication channels. It is claimed that the reserved bits in subframes of GPS navigation message were not used, belonging to redundant information, which is ignored when a GPS receiver calculates its position. Considering this, the communication by using reserved bits itself is highly covert, in other words, GPS provides a natural covert channel[16] [17] for the OWC, which can have unexpected effects if it is used for military [18] and commercial purposes. For example, USA can use this to transmit operation commands for its allied nations at war.

(2) Occasionality of OWC. Only when necessary, the reserved bits in the GPS navigation message are in use for OWC. It is discrete, short-term and temporary in time domain, so it is difficult for a third party to know when the OWC starts and when it ends.

(3) Disorderly distribution of information. Reserved bits carrying OWC information are disorderly distributed in the GPS navigation message, which significantly enhance the covertness of OWC.

(4) Difficulty in recognizing and understanding communication data. The one-way communication data carried are disorderly distributed in reserved bits of navigation message. The communication protocol is not released to the outside, so it is difficult for any third party to correctly organize the binary information and get the right communication data. Even if the communication data are obtained, how to understand them is still a problem. Therefore, it is difficult to recognize and understand the GPS OWC data.

In summary, the satisfactory covertness of the GPS OWC enables it to be used as a standby mode for the submarine communication. In the wartime, in the event that the conventional submarine communication mode fails, the GPS OWC is a good standby. Although a drawback of this mode is that submarines must come to the surface to receive GPS signals, it is still acceptable as a standby mode.

V. THE DISCUSSION OF PROBLEMS

5.1 Problems Existing in the Parallel Transmission with Multiple Satellites

Without multiple satellites transmitting in parallel, the identical one-way communication information can be transmitted simultaneously in all the satellites visible to users, and the substantial increase of redundancy enhances the reliability of one-way communication. With the parallel transmission of multiple satellites, the efficiency of the GPS one-way communication can be increased greatly, but the reliability of the one-way communication will be significantly reduced by the complexity of the parallel transmission. Accordingly, various new situations and new problems that might be emerged in the parallel transmission of multiple satellites must be taken seriously.

(1) The problem of rise-and-fall of satellites must be solved during the parallel transmission of multiple satellites. The GPS satellites orbit at an altitude of 20200km. For a fixed point on earth, the rise-and-fall of GPS satellites above the horizon will not only change the number of satellites visible at this point, but also causing GPS receivers to lose satellite lock and / or to recapture and retrack. Therefore, when a satellite is about to fall below the horizon, the satellite should be excluded from the parallel one-way communication, that is to say, a time threshold or a threshold for the GPS satellite elevation angle should be set up. By the same token, a time threshold or a threshold for elevation angle should be set up for any satellite rising above the horizon, so as to make sure that GPS receivers can complete the capturing and tracking before the threshold and then lock. In addition, the data packets of one-way communication must contain the satellite availability predicting information and the status of satellites for the parallel transmission, both of which are the important component parts of the one-way communication protocol.

(2) The problem of data packetization among multiple satellites. Since multiple satellites synchronously support the one-way communication, how to packetize the data to be transmitted and allocate the data packets to each satellite is another problem that must be solved. The different configurations and performances of various GPS receivers cause differences in the maximum number of satellites that can be locked by them, thus it is necessary to take account of the receiving capability of receivers. For a GPS receiver to return a position fix, at least four satellite signals are required, so it is recommended to choose four satellites from the visible ones for the parallel transmission. The number of satellites visible to users is generally more than four, but don't waste other visible satellites on this. The redundant transmission is used to choose another visible satellite as a standby to transmit data packets which are allocated to the four satellites for the parallel transmission. In this way, the reliability of the one-way communication is improved. The data packets for one-way communication should contain the information about the standby satellites, with the purpose of providing necessary support for the reliable one-way communication to GPS receivers.

(3) The problem of data dropout and the countermeasure. The said redundant transmission can moderate the problem of data dropout in the parallel transmission with multiple satellites to a certain extent, but this is not enough. Each data packet should be repeatedly transmitted by each of the multiple satellites for the parallel transmission. By reason that the GPS one-way communication is commonly used under specific circumstances, it requires little for the communication rate and the data can be repeatedly transmitted. Though the communication rate descends to some extent, the reliability is improved. So, the performance of transmitting in parallel with multiple satellites is obviously better than that of transmitting through only single satellite.

5.2 CNav Message Types for the One-Way Communication

In the fall of 2009, for the first time, CNav civil navigation message will be broadcasted on the GPS L2 civil signal (L2C) by orbiting satellites. When CNav is used for the one-way communication, specific message types must be designed, which also are important components of the one-way communication protocol. The CNav structure, as defined in IS-GPS-200D [10], allows up to 64 different message types, of which 15 types have already been defined, being the message types 0 (default message), 10~15 and 30~37. CNav has its basic format for message types; based on this, the paper presents the new type 63, whose code is 111111, specific for the transmission of non-GPS information. The format is as shown in Table 4.

TABLE 4. DEFINITION OF THE NEW MESSAGE TYPE SPECIFIC FOR TRANSMITTING NON-GPS INFORMATION

8bits	6bits	6bits	17bits	1bit	238bits	24bits
Preamble 10001011	SV PRN	Type 111111	Gps Time	Alert Flag	Non-Gps Info	CRC

In Table 4, Preamble is appended at the beginning of each data packet, occupying 8 binary bits with the fixed value being 10001011. SV PRN (satellite's pseudo-random noise) takes up 6 binary bits. Type is a message type code and the code for newly-added type is 111111. GPS Time is the time for transmitting data, denoted by GPS time of week (TOW) count. TOW, when multiplied by 6, gives the time in seconds for the next 12s CNav data transmitted. When Alert Flag, a warning sign, equals to 1, it indicates that the actual situation is worse than the data given and it's the users who will decide whether these data to be used. The 24-bit CRC stores the cyclic redundancy check values. Non-Gps Info takes up 238 bits, for storing the non-GPS navigational information to be transmitted.

5.3 Design of GPS Receivers for OWC

For receiving the one-way communication information, GPS receivers must be capable of unscrambling the reserved bits of L1C Nav message and understanding the newly-added L2C CNav message types. For this end, new GPS receivers must be developed not only with the function of position fix, but also with the capability of receiving the one-way communication information sent by GPS. It is easy to develop GPS receivers specific for the land-submarine communication and the command of intelligence collection, but when the GPS one-way communication is in use for the public emergency communication, it should enable quite a number of GPS receivers to receive broadcast messages of disaster emergency response. Naturally, a unified protocol for the GPS public emergency communication is needed by the world. With this protocol, GPS receiver manufacturers will develop new receivers that can receive the disaster emergency response information and make it a standard function of GPS receivers.

VI. CONCLUSION

When the GPS system is used for transmitting the non-navigational information, a single frequency with one satellite can transmit data at 0.5B/s; with the dual frequency transmission by using L1C and L2C frequencies and the parallel transmission of multiple satellites, the effective data communication rate can be increased to at least 4B/s, which is much higher than the rate of ELF submarine communication and even higher than the rates of VLF and LF submarine communications. The non-navigational information transmission by the GPS is covert, and with encryption techniques, it can meet the needs for special purposes, such as emergency submarine communication, command of intelligence collection, as well as civilian emergency broadcast communication.

The study of this paper is of merits for China's development of Beidou 2 system. It is recommended that: (1) under specific circumstances, the navigation message of Beidou 2 satellites in certain region is to be replaced by communication message, further to increase the communication efficiency; (2) the extensibility and flexibility of CNav message of L2C is referential, so that we can extend the functions of Beidou Navigation System and give full play to its advantages. The next step we'll take is to make research on: (1) algorithms with high compression ratio of short message; (2) the allocation and combination of OWC data during the parallel transmission with multiple satellites; (3) the allocation and combination of OWC data during the dual frequency transmission.

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