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A New Perspective to Integrated Satellite Navigation Systems

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Abstract

In order to further expand and enhance the level of applications of satellite navigation, three new systems are proposed on the basis of successful application of existing satellite navigation systems: a two-way satellite communication and navigation system which is based on a two-way satellite communication transmission link, a satellite-assisted ground mobile communication and navigation system and an air–ground communication cooperation multi-system multi-mode positioning system. Key technologies for achieving breakthroughs and implementation of the three new systems are also described, including deep integration of navigation signals and communication signals, a compared measurement technique, and our method to improve constellation GDOP. Some applications of these new systems, in the fields of high-precision measurement, emergency rescue and equipment real-time monitoring, are introduced.

Keywords: Satellite navigation and communication, two-way, integrated, satellite-assisted, multimode

1. Introduction

The US Global Positioning System (GPS) is a very successful satellite navigation system that marks an important milestone in the history of the thousands of years during which humans have been developing ingenious ways of navigating to remote destinations [1]. GPS has demonstrated a wide range of applications in air and space, at sea and on land, from personal navigation at the accuracy of tens of meters to the determination of spacecraft orbits with uncertainties of a few centimetres. In addition to positioning, GPS is used for timing, velocity and attitude determination, as well as for scientific measurements. Despite these applications, many defects, such as the four outlined below, have also been gradually identified in the existing GPS system.

1. High initial investment and operational costs are the underlying reasons why it has taken so many years for Russia to restore and maintain full operation of the Glonass system.
2. GPS, Glonass and Galileo are all positioning systems based on one-way signals from satellites to receivers. Receivers receive signals only passively, and no one else knows the user locations without additional data links. This feature has been claimed as an advantage of GPS, but in many applications, a centre facility will need to know where their users are.
3. Incoming signals from satellites are very weak, thus suffering from intended interference and jamming. As a result, GPS does not suit indoor positioning.
4. GPS and/or other GNSS systems provide both civilian and military signals services. Often a frequency is allocated solely for military usages, while civilian users are intentionally provided with degraded services.

These defects have affected GPS applications and potentials. Questions arise: is there an alternative solution that can address some or most of these defects? What is the next possible trend in developing new satellite navigation systems?

In fact, a group of scientists in China have carried out significant research efforts since early 2002 to design and demonstrate a different or alternative satellite navigation system based on communication satellites [2]. These scientists successfully established an experimental prototype system, which led to the initial operation of the Chinese Area Positioning System (CAPS) in 2005 [3-5]. They made use of commercial geostationary communication satellites to broadcast navigation information and for transmitting ranging signals [6-12]. In 2009, reporting of broadcasting GPS navigation signals via the Iridium communication satellite constellation [13] showed that other people also began to explore the use of mobile communication satellites for assisted GPS (A-GPS) satellite navigation and positioning. These attempts and their successful initial results have at least shown the potentials for adding navigation functions onto existing communication satellite constellations, or an alternative way to add such functions, thus saving costs for dedicated navigation satellite systems and major maintenance. For communication satellite constellations, adding navigation and positioning values enables more comprehensive utilization of satellites and signal resources.

The overall point is that, while GNSS broadcasting signals are retained to offer positioning services to limitless users with passive receivers, communication links are also reserved in a satellite navigation system for an optional or additional service. In this way, user location information can be made known at the tracking centre, for instance, for vehicle fleet management and monitoring services. Since the system has communication capability, one can allow the achievement of a combination of navigation and communication [14, 15]. A further step is to integrate navigation and communication at the signal structural level, so that a communication satellite link can perform all functions of ranging, positioning, navigation and time service.

This integrated system must possess a special transmission link to meet the high-precision applications. In addition to an outbound positioning channel, another inbound positioning channel is needed [16, 17]. A two-way channel and bi-directional links can be used for two-way comparison [18], closed-loop measurement, data redundancy and two-way communication. At the same time, it is easier for a two-way transmission link to carry out the error measurement, separation and correction in order to achieve high-precision positioning and navigation.

In recent years, it is seen that have included a rapid evolution of land mobile communications, that supporting small size cell phones with powerful functions and huge numbers of users. In the aforementioned A-GPS system, GPS navigation messages are transmitted using the cellular data links, which actually makes up the mobile communication network-assisted GPS system. The satellite-assisted positioning system proposed by Chinese researchers makes use of mobile satellite networks for positioning services, known as Assisted Mobile Positioning System (A-MPS) [19]. In addition, one may take advantage of live television satellites to achieve a high-precision satellite timing service and to improve the base station time synchronization. On the other hand, satellite signals can also be used to enhance mobile phone positioning, and to provide time service for mobile phones directly, so that mobile positioning and timing services can be developed to a new level. Of course, mobile networks can be kept as an auxiliary enhancement of the satellite positioning system, in which the signal integration of devices in the space and on the ground, to creates an integrated ground–space navigation positioning system.

In the rest of the paper, Section 2 of the paper provides an overall design of the bi-directional integrated communication and navigation system. Section 3 describes the key signal structure and measurement technologies. Section 4 explores the new benefits that the integrated communications and navigation system can bring to the community, focusing on the applications that depend on communications. Section 5 is summary which has concluding remarks.

2. The Composition and Design of an Integrated Communication and Navigation System

2.1 Bi-directional integrated communication and navigation system based on two-way satellite communication links

The space constellation of such an integrated system is based on commercial communication satellites, including GEO, MEO and LEO commercial communication or broadcasting satellites. Because the frequency stability onboard communication and broadcasting satellites is not sufficiently high for ranging purposes, the time-frequency reference of the system cannot be accommodated on the satellite. Consequently, the solution is to place the time-frequency reference on the ground-based central station as is done in CAPS [2-5]. Next, the spread-spectrum signals with the time and positioning messages of multiple-code and multiple-frequency are generated at the ground station and transmitted to the satellites, which retransmit these signals and data to the users on the earth. While user number with passive positioning capability is limitless [2-5] just like GPS users, user terminals can also choose to transmit outbound positioning and navigation information via satellite back to the ground stations by inbound link. The satellite inbound transmission link is not only the inbound communication link, but is also the inbound positioning link, with a pseudo-code spread spectrum. It can transmit the location of the ranging test users, and can be used to monitor user status, such as micro-vibrations, baseline changes between users and so on. The inbound positioning communication and outbound positioning devices form a bi-directional positioning communication system, as shown in Fig.1.

Because micro-terminals are applied in this system, both outbound and inbound links are power (signal to noise ratio) limited. As a result, big aperture antenna should be adopted in the communication central station [18, 20].

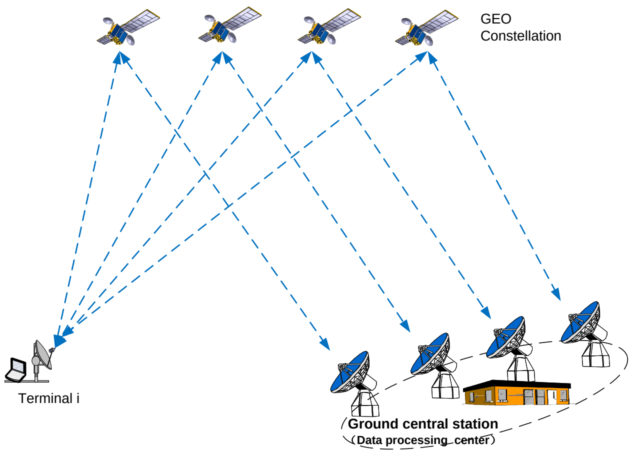

Figure 1: Schematic diagram of a bi-directional navigation and communication integrated system

The combination of positioning and communication gives the system with an ability to perform two-way time comparison, two-way closed-loop pseudo-range measurement, two-way error comparison and correction and so on, so that the transmission delay error can be corrected to get more accurate pseudo-range measurements. In addition, two-way measurement is an additional measurement which can reduce random error and improve reliability. All of these functions enable the user terminals to achieve high-precision positioning and navigation, and to perform the system and center navigation on the basis of the user's individual positioning.

2.2 Scenario of a satellite enhanced mobile positioning system

Land mobile communications have been used widely. The major advantages include small-size cell phones, a huge volume of users, relatively high signal power, bi-directional voice and data communications, and two-way ranging even supporting indoor positioning. However, due to effects of the non-line-of-sight (NLOS) or multi-path signals over ranging measurements in the mobile communication network, the positioning precision is rather poor. We can take use of GPS signals or a mobile TV satellite forwarded signal in which the ranging code and navigation message is embedded to achieve time synchronization. Because the latter satellite effective isotropic radiated power (EIRP) is higher, the transmission link signal to noise ratio is high. As a result, time synchronization accuracy is higher, and pseudorange measurement is more precise. We can make use of the satellite to broadcast the enhancement signal to help finish the time synchronization of the mobile network base-stations, with the pseudo-range precision performed by measuring the time difference. If one or two broadcast satellites with higher EIRP are adopted to retransmit enhancement signals, we can perform direct time service and pseudo-range measurement to mobile phones. When the mobile phones are being positioned and other high-precision pseudo-range measurement values are added from the satellite downlink into the measurement equation, the condition number of the figure matrix of the system positioning measurement equation set can be improved greatly. The value of position dilution of precision PDOP (PDOP) decreases sharply from several thousand to less than ten. With the aid of improvement in arithmetic, high-precision positioning and time service can be achieved, as shown in Fig.2.

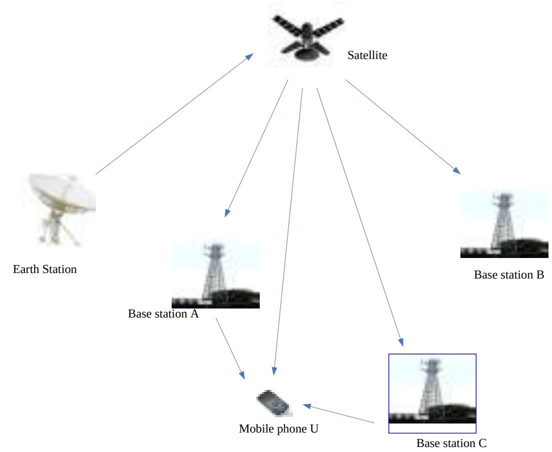

Figure 2: Schematic diagram of A-MPS positioning system enhanced by the satellite signal based on the mobile network

A land broadcasting network can be added on the basis of a ground communication network. Its benefit is to make use of the pilot frame of the China Mobile Multimedia Broadcasting (CMMB) signal to fix the position. That is to say, pseudo-range is measured directly by the spreading code in the pilot frame, and a navigation message is added into the pilot information frame. Such a system does not occupy a communication channel and it is very simple.

In conclusion, the precision of time service and positioning is thus improved greatly via A-MPS for the ground mobile communication network and the mobile broadcast network. If more attention is put into the improvement of NLOS errors in the network, or if data match technology is adopted, this will become a very applicable positioning system.

2.3 Ground-space multi-system multi-mode enhancement system

The satellite navigation system has already been extended with a lot of features, and it can now be developed into an integrated navigation system with GPS as the main body. The concept of a multi-mode integrated satellite positioning system proposed in 2005 takes advantage of multi-systems based on a number of worldwide satellite positioning systems: GPS, GLONASS, Galileo, BeiDou and CAPS. Of course, multi-system integration is not simply additive; nor is it necessarily the more satellites the better. Integration will have to consider compatibility, complementarities and interoperability in order to ensure that such integration will effectively lead to improvement. This is because integration does not come without cost. It will certainly make the receiver design much more complex and will increase hardware and software costs, which could be very negative for user acceptance. The target satellite navigation system after GPS is based on a communication system and a communication capability, is integrated with navigation and time information, and is a comprehensive information system with comprehensive information from space and on the ground.

Five main differences between construction of the integrated system and a typical global satellite navigation system such as GPS are outlined below.

1. The integrated system leverages the existing communication systems and benefits from their advantages, higher data rate, better anti-interference capability, and so on [21].
2. Satellite orbit determination is important for navigation and positioning services. But there is no need to construct a special orbit determination system because there is an inbound link which can work as a monitor so that satellite orbits can be determined by processing these data [17, 18]. Not only is the accuracy high, it is also real time. This will simplify the system and reduce the operational complexity.
3. Differential GPS techniques, including variations such as wide area differential GPS, have been widely used to provide differential corrections to improve user positioning accuracy. The differential base stations or network can on the one hand correct the satellite orbital and clocks errors, and propagation delays, and on the other eliminate the effects of selective availability which are currently "zero", but could be re-introduced any time by the GPS operator. Differential GPS techniques are effective, but users have to deploy and operate ground base stations and networks everywhere. In the new system there is no need for users to set up separate ground stations, as this system can make use of the ground monitoring network.
4. In the composition of the new system, the role of the ground facilities has to be enhanced and fully utilized. The master station would be much more substantially equipped. Several large-aperture antennas (diameter greater than 9 meters) are needed, and ground stations and antennas should possess both transmission and receiving functions. It has not only to uplink navigation and communication message signals, but also to receive the navigation communication message from user terminals. There must be a high stability reference frequency in the ground station as a time measurement basis for the whole system.
5. Miniaturization of user terminals should be emphasized. I use of small antennas and low power transmission power sources will form a new class of low-rate transmission system.

3. Key Technology of New System Applications

3.1 Navigation integrated communication signal format

Navigation and communication integration refers not only to a system where there should be two kinds of links, to implement both navigation and communication functions, but also to a system that needs to achieve integration of navigation and communication functions at a signal structure level [2, 3, 22, 23]. In this stage, four kinds of navigation integrated communication signal format are designed [24].

3.1.1 The first signal structure

The first integrated navigation and communication signal structure is shown in Fig. 3. It is made up of one I slip and one Q slip, which are orthogonal. The signal structure of each slip is composed of consecutive super-frames where each super-frame consists of several sub-frames and each sub-frame contains frame signs, a sub-frame number, an identification number, the main message, check bits and the frame's end. For the I slip, the data rate is low, and its message provides mainly time signal, location information and satellite orbit information. Short code benefits capture and recapture. The Q slip adopts long codes, which have the advantage of longer coherent integration time, higher ranging precision, better security performance and anti-interference ability. It can play an important role in tracking and precise measurement of time delay. The communication message is modulated in the Q slip. In this signal structure, a combination of the I slip and Q slip signals uses the direct sequence spread spectrum (DSSS). The transmission signal can be expressed as:

$$S(t) = A_c C_c(t) D_c(t) \sin(2\pi f_{sc} t + \varphi_c) + A_p P(t) D_p(t) \cos(2\pi f_{sp} t + \varphi_p) \quad (1)$$

where A_c is the amplitude of the communication spread spectrum code; $C_c(t)$ is the spreading code for communication; $D_c(t)$ is communication data; f_{sc} is carrier frequency for the communication information; φ_c is communication carrier phase; A_p is amplitude spreading code for the navigation and positioning; $P(t)$ is spreading code for the navigation and positioning; $D_p(t)$ is the navigation and positioning message; f_{sp} is carrier frequency of navigation and positioning information; φ_p is carrier phase for navigation and positioning.

Because the system can provide continuous and stable ranging and navigation signals as well as communication signals, this signal can provide continuous real-time navigation and positioning like a GPS positioning system.

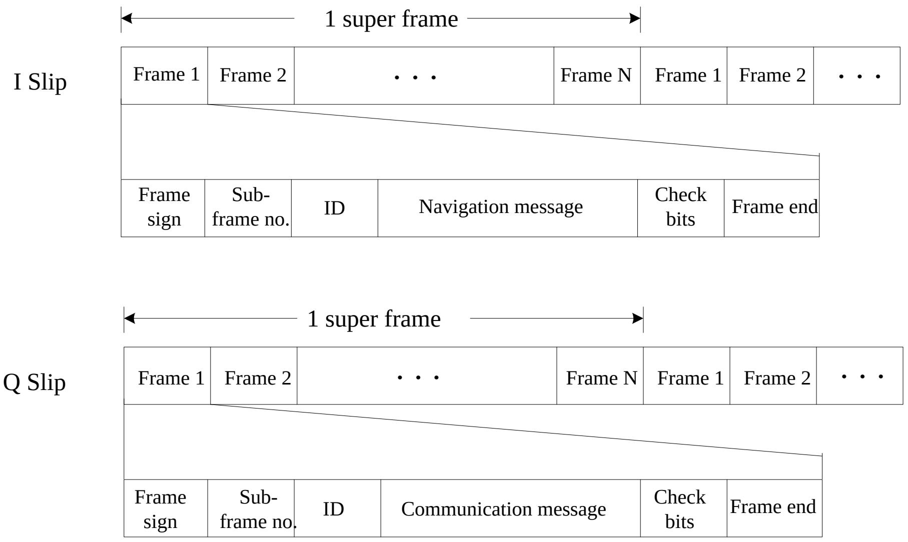

Figure 3: First integrated navigation and communication signal structure

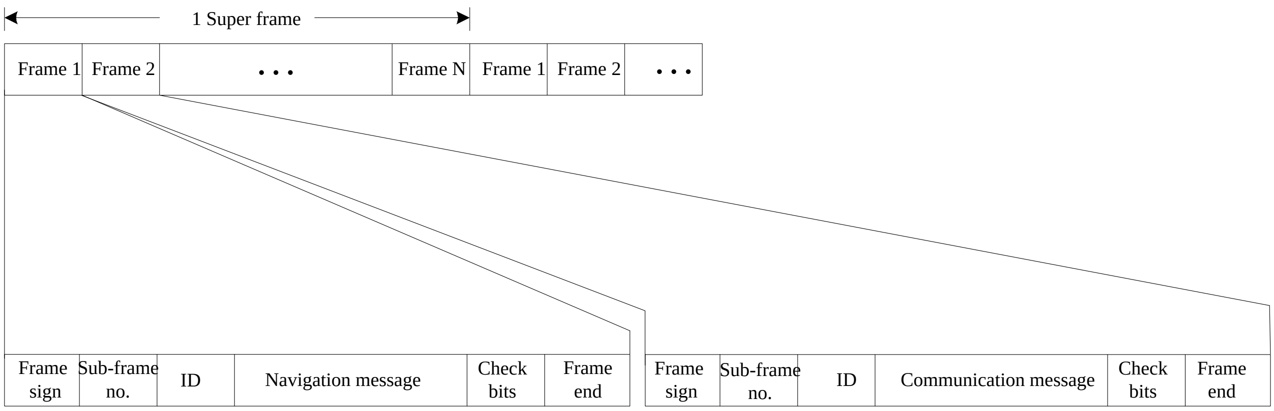

Figure 4: The second integrated navigation and communication signal structure

3.1.2 The second signal structure

The second signal structure is shown in Fig. 4. The former part is the navigation section, and the latter is the communications segment. The two segments are transmitted alternately. The main function of the former part is to capture and transmit navigation-related information, including user ID, message length, time information, and so on. In this capture section, a short code is used for rapid acquisition. The latter, is the track section which is mainly to achieve transmission of information and precision ranging. The communication message is also modulated on the latter part, too. The communication message length can be fixed or variable. Long code is used in the tracking section, which will help improve the measurement accuracy and make it difficult to decipher, and will provide better anti-jamming capability. Capturing of the latter segment is led by the former, or assisted by the preceding paragraph to re-capture.

The message modulated is a combination of an alternating communication and navigation short message. This combination message is modulated onto the ranging PN code, and then modulated to the carrier. It consists of navigation and communication information, so it has a dual function of communication and positioning. The pseudo-code of the navigation section and the communication section can be the same or different. In this signal structure, the signal transmission format is expressed as:

$$S(t) = AP(t)D(t)\sin(2\pi f_s t + \varphi), \quad (2)$$

where A is the spreading code amplitude; $P(t)$ is the spreading code; $D(t)$ is the navigation and communication message; f_s is the carrier frequency; φ is the phase.

3.1.3 The third signal structure

The third signal structure is produced by inserting the navigation message into the pilot frame of the communication signal to achieve the integration of navigation and communication. For example, one can use the CMMB broadcast signals' pilot signal frame directly, as shown in Fig. 5, which is one second per frame. Each frame is divided into 40 time slots, and each slot delay is 25 ms, which includes a beacon sub-frame and 53 OFDM sub-frames. The beacon sub-frame structure is shown in Fig. 6.

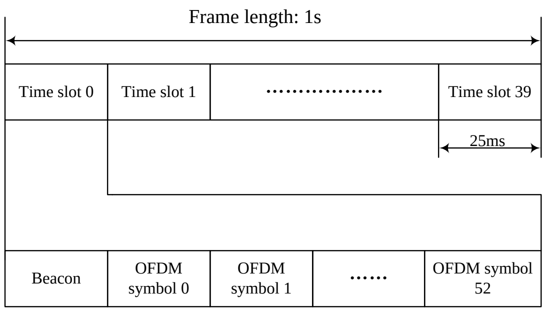

Figure 5: Frame structure diagram

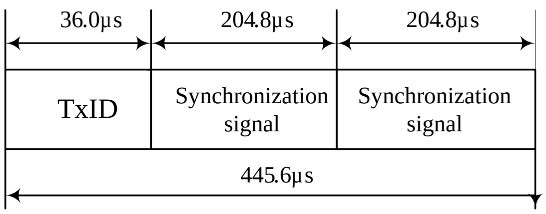

Figure 6: Schematic diagram of the beacon signal sub-frame

As the beacon signal is the band-limited (12.5MHz) part of the pseudo-random spread-spectrum signal, it can be used to achieve accurate ranging. The beacon signal is made up of the transmitter identification (TxID) and two synchronous signals. TxID consists of a cyclic prefix T1 (10.4μs) and data volume T_0 (25.6μs). The data volume can be used to send time information, satellite orbital information and other relevant information so that it can constitute a navigation and time service message. The data length of the spreading code of each beacon is 191, and it can send 1-bit information. Each pilot frame contains 40 slots, so the message content that can be transmitted per second is:

$$1\text{bits} \times 40 = 40\text{bps}.$$

Information which can be transmitted may be slightly less than the GPS navigation data message. However, some information can be reduced, so that 40bps is adequate for the transmission positioning timing message of one satellite (GPS information transmission rate is 50 bps, and the amount of super-frame information transmitted in GPS can be 1500 bits in 30 seconds). The beacon length is 445.6μs, including TxID duration of 36.0μs, which has a 191-bit PN spreading code with the spreading gain of 22.8dB.

3.1.4 The fourth type of signal structure

In the CDMA communication system, one of the communication code channels is selected for navigation purposes, and the other code channels are still used for communication.

Which of these four kinds of signal structures will be used depends on the transmission capability of the system. If system power (or the carrier to noise ratio) is enough to bear both I slip and Q slip transmission, the first kind of signal transmission format is recommended. If the power (or the carrier to noise ratio) is limited and cannot bear the transmission of two slip signals, the second signal transmission format is suggested, transmitting a single slip.

Because the integrated navigation and communication signal needs to complete precise distance measurement, it should adopt a broadband spread-spectrum, or a special wideband spread-spectrum system. In this way, we can get high spreading gain, so that the signal can be buried under the noise background during transmission, and so that the signal transmission has good anti-interference capability. If the system has multiplex capabilities, we can use the fourth signal structure, in which a code channel is used for navigation and positioning, and the other code is still used for communication. In the satellite broadcasting signals, due to the presence of a spread-spectrum pilot frame, we can use the spreading code for ranging. If other empty frames are added with orbit and time parameters, these information can serve as a navigation message. Multiplex transmission is redundant in distance ranging, which can improve the ranging accuracy.

3.2 Contrast measurement technology

Contrast measurement error can be eliminated; eliminating measurement error can help to obtain high-precision distance and positioning measurements. Existing satellite navigation systems have already utilized one-direction contrast measuring techniques by comparing known values of a reference point with base points to get the positioning error with which to correct measurement error of points in the vicinity. However, there are some limitations for one-direction measurement, and there must be a reference station for differential correction. As a result, the operation is relatively cumbersome.

Bi-directional contrast measurement was promoted for satellite orbit measurement in this paper [12, 25, 26]. This is the comparison of points to points, which is called the contrast chain. The principle is shown in Fig. 7.

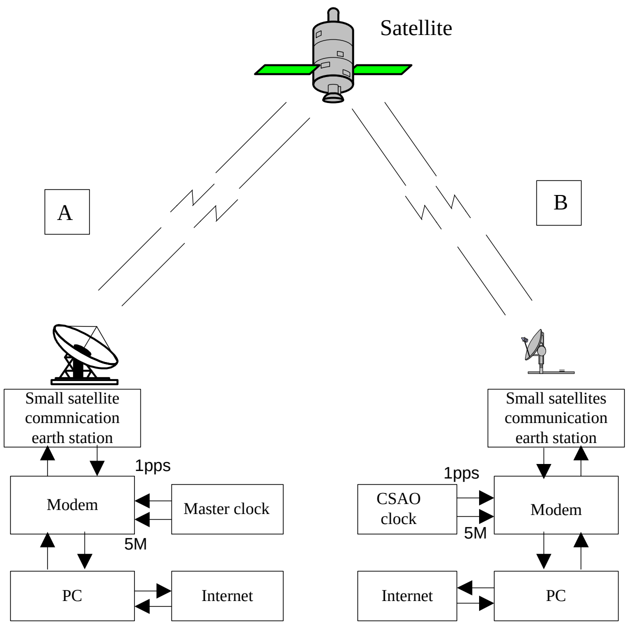

Figure 7: Satellite bi-directional contrast method principle diagram

Bi-directional contrast technology has other variations. For example, earth station A transmits to the satellites and receives the returned signal; or earth station B receives the signal and re-transmits it back to earth station A. Under these two situations, earth station A is the equivalent of station B. Station A time standard of the second pulse (1pps) is modulated by the terminal to IF (70MHz), and sent to the satellite. Then the satellite transponder retransmits the signal to station B, which transforms it to IF (70MHz) and demodulates it to get the local time standard and the time delay difference by the path delay. Therefore, while there is a delay of the path, the time interval counter is not the real time difference between Station A and Station B. Similarly, station B also sends its standard time signal to station A under the same process and gets the delay difference between station A and station B. Their relationship can be expressed as:

$$\begin{cases} R_{ba} = T_b - T_a + t_a^U + t_b^D + \tau_s + \tau_a^T + \tau_b^R \\ R_{ab} = T_a - T_b + t_a^D + t_b^U + \tau_s + \tau_b^T + \tau_a^R \end{cases} \quad (3)$$

where R_{ba} is the station B interval counter reading value (relative to the station A second pulse); the R_{ab} is the station A interval counter reading value (relative to the station B second pulse); T_b is the station B clock-face moment; T_a is the station A clock face moment; t_a^U is the uplink signal time delay from station A to satellite; t_a^D is the downlink signal time delay from satellite to station A; t_b^U is the uplink signal time delay from station B to satellite; t_b^D is the downlink signal time delay from satellite to station B; τ_s is the satellite transponder delay; τ_i^T is the transmission delay of all station equipment; τ_i^R is the receiving delay of all station equipment. Relativistic effects (called the Sagnac effect) are not included in this formula, of which the correct amount is $-2\omega A/c^2$, where C is the speed of light; ω is the earth rotation angular velocity; and A is the projection onto the equator of the area enclosed by the connections between the satellite, the geocentric point and two stations.

Atmosphere ionosphere delay and troposphere delay must be accounted for in the path propagation delay. Troposphere delay may be corrected by a microwave radiometer or meteorological instruments. Special attention must be paid to ionosphere delay, because it is inversely proportional to the square of frequency. For the same path, the uplink and downlink delays are different considering the implications of the different frequencies. For C-band, the ionosphere difference between uplink and downlink is so small that it can be ignored. As a result, C-band clock error determination can be expressed as:

$$T_a - T_b = (R_{ab} - R_{ba})/2 \quad (4)$$

The above statement is a C-band satellite bi-directional contrast formula. In this equation, the time difference between two points is related to the reading values of two interval counters only, and is independent of the path, for example, satellite position, troposphere, or satellite transponder.

Clock error between two stations can be obtained from the original observation equation:

$$R_{ab} - R_{ba} = 2(T_a - T_b) + t_a^D + t_b^U - t_a^U - t_b^D + \tau_a^R + \tau_b^T - \tau_a^T - \tau_b^R \qquad (5)$$

If the instrumental errors and correction of the ionosphere can be obtained, or the ionosphere delay is eliminated by the use of dual-frequency observations, the main clock error can be determined with high precision. For *n* stations, there are C_n^2 observational equations, *n*-1 clock errors can be obtained by least square estimation.

Contrast measurement can also change the condition of two high-stability frequency references in the one-direction measurement, when only one high-stability frequency reference is needed to measure pseudo-range, or when the measurement accuracy is influenced only by one precision frequency reference.

If a closed-loop measurement is formed by receiving the signal from the satellite itself, pseudo-range measurement is expressed as:

$$\rho = \frac{T_2 - T_1 - \Delta t_r}{2} \qquad (6)$$

where, T_1 is the transmission moment of antenna, T_2 is the echo reception moment of antenna, and Δt_r is transponder delay.

If transponder delay, Δt_r, can be measured or calculated, we can obtain a very high accuracy pseudo-range measurement from the formula (6).

This is very meaningful for simultaneous time-frequency reference. For example, clock synchronization of mobile network base stations can be performed by bidirectional contrast, and synchronization accuracy can be better than 0.1ns. Therefore, every possible bidirectional methods must be fully studied to achieve high-precision error correction.

Compared to the phase measurement principle, this measurement method can produce high-precision error elimination and separation, as shown in Fig. 8, Fig. 9 and Fig. 10. Vibration compared measurement of a single point is indicated in Fig. 8, measurement error of closure is indicated in Fig. 9, and relative measurement of changed baselines is indicated in Fig. 10.

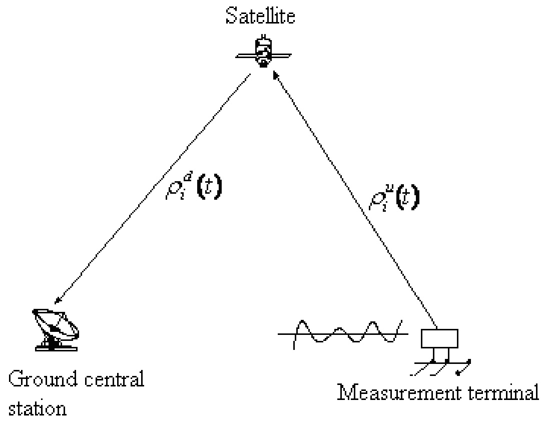

Figure 8: Schematic diagram of single-point vibration measurement

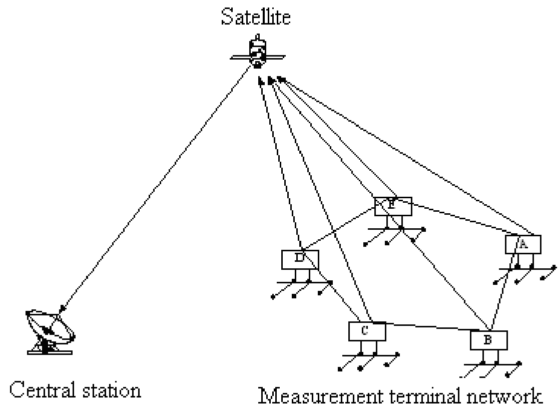

Figure 9: Closed measurement diagram

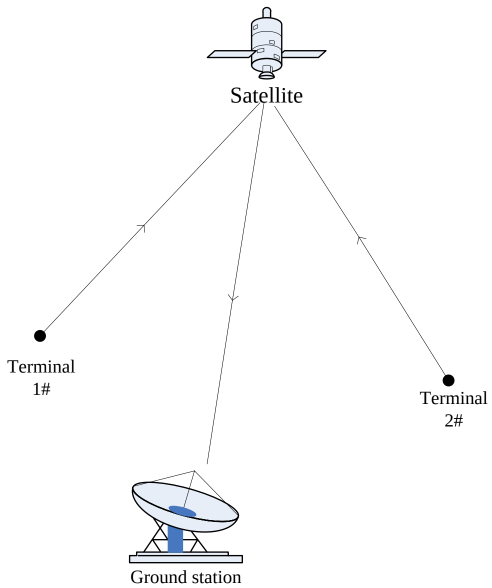

Figure 10: Interferometry basic schematic

3.3 GDOP improving the constellation

Positioning accuracy is an important performance index of a positioning system. Satellite PDOP value can be greatly improved even when only base stations of the terrestrial mobile network are added to the positioning estimation. The distinction between terrestrial mobile network positioning and terrestrial mobile network positioning assisted by satellites is analyzed below.

3.3.1 User range error (URE) by terrestrial mobile network positioning only

Using only o land mobile network for positioning means that the positioning relies solely on the terrestrial mobile network. The accuracy of the time of arrival (TOA) positioning method is analyzed as follows.

Terrestrial mobile network base stations have fixed positions on the ground, so they are not subject to the traditional influence of ephemeris error and atmospheric propagation of error of the satellite navigation system. As a result, the error caused by a clock is directly related to the base station timing accuracy. It is assumed that a land mobile network base station uses GPS timing, with timing accuracy up to 25 ns, which can be transformed into a distance error of 7.5 m.

If the mobile station is used for high precision tracking, and PN code tracking uses DLL (delay locked loop), then the DLL code loop error is expressed as:

$$\sigma = C \times T_c \times \sqrt{\frac{B_{\tau,1} \times d}{2 \times C / N_0}} \quad (7)$$

where C is the light speed; T_c is the chip time and assumed to be 1μs ; $B_{\tau,1}$ is the filter bandwidth with the value of 0.5Hz; *d* is the correlator spacing, taking d = 1; C/N_0 is the carrier to noise ratio, for base stations, which is about-26dB-Hz or so. Then the pseudo-range measurement error is 0.03 m from the above formula. The error caused by multipath is taken from experience as 1 m, while the non-line of sight error is 50 ~ 300 m. It can be obtained that the σ_{URE} is pretty high.

$$\sigma_{URE} = \sqrt{\sigma_{clock}^2 + \sigma_{DLL}^2 + \sigma_{multipath}^2 + \sigma_{NOLS}^2} \quad (8)$$

3.3.2 User range error (URE) by combination of terrestrial mobile networks and satellite positioning method

For the method of combining land mobile networks and satellite positioning, due to effects of the satellite, the satellite URE is influenced by satellite ephemeris error, and the atmospheric propagation model. According to GPS normal data, the error caused by ephemeris parameters temporarily is 1 ~ 3 m. As a result of this timing mode, timing accuracy is up to 10 ns, which is equivalent to a distance error of 3 m; and the atmospheric propagation model error is taken as 3 m; because the CMMB signal transmitted to the ground is about 30dB higher than the GPS signal, pseudo-range error obtained from formula (2) is 0.32 m. With reference to the above analysis, user equivalent error (URE) can be summarized as:

$$\sigma_{URE} = \sqrt{\sigma_{clock}^2 + \sigma_{ephemeris}^2 + \sigma_{DLL}^2 + \sigma_{multipath}^2 + \sigma_{atmospheric-propagation}^2} = 4.9 \text{ m}$$

3.3.3 The geometric dilution of precision (DOP) and the positioning error estimation

The above error analysis is the user range error used in positioning. For the positioning error, because geometric distribution is different for different ground mobile network base station locations, there will be a different error propagation. This has a direct impact on the value of location error.

$$\text{Position error} = \sigma_{URE} \bullet DOP \quad (9)$$

Positioning simulation with the land mobile network only

Simulation conditions follow. There are four base stations, no satellites, and these stations are not in the same horizontal plane but are distributed in different locations, with the mobile station as a reference point in the coordinate system, at a relative height of -50 ~ 100 m, and the relative distance is 2 km. Its 2-D distribution is shown in Fig. 8, with a mobile station in the center and the surrounding points of base stations. Simulation calculated DOP is showed in Table 1.

Table 1: DOP values

GDOP	72.572
PDOP	72.559
HDOP	1.459
VDOP	72.544
TDOP	1.369

The combination simulation of terrestrial mobile networks and satellite positioning

Simulation conditions follow. There are four base stations and a broadcast satellite. This satellite is assumed to be located at the equator with coordinates of 115.5 degrees east longitude, 35796669.769 m altitude. The four base stations are not in the same horizontal plane but are distributed in different locations, with the mobile station as a reference point in the coordinate system, at a relative height of -50 m ~ 100 m, and the relative distance is 2 km. Its 2-D distribution is shown in

Fig. 11, with the mobile station in the center and the surrounding points of the base stations. The calculated DOP values are shown in Table 2.

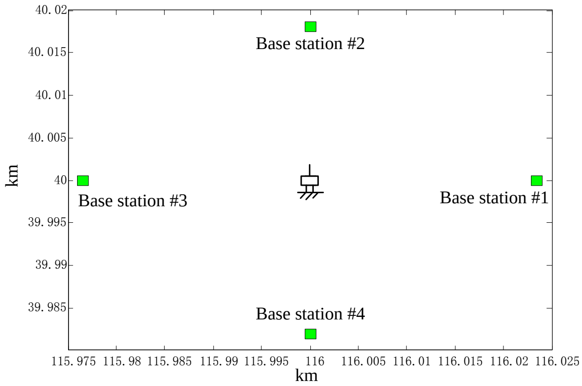

Figure 11: 2-D distribution diagram of the mobile station and base stations

Table 2: DOP values

GDOP	1.59
PDOP	1.51
HDOP	1.22
VDOP	0.90
TDOP	0.51

Simulation conclusions

Substituting into the DOP values the formula (9) can give some clear observations. If a mobile network of only 4 base stations is used to provide positioning, the bad geometry can lead to significant magnification of measurements errors, so solutions are hardly useful. With addition of even just one satellite, DOP values can dramatically improve. Although the overall measurement error is increased with errors from this satellite, the positioning accuracy will still be significantly improved. It is noted that the satellite transmission channel is a constant-reference channel with a higher EIRP. Theoretically it is possible to obtain better pseudo-range measurement accuracy for higher positioning solutions.

On the basis of the existing ground-based mobile positioning method, A-MPS proposes a method of a land mobile network using satellite enhancement to generate high-precision timing and positioning. The simulation proved that this method can greatly improve positioning accuracy.

When the big Wenchuan earthquake occurred on May 12, 2008, experts of the National Time Service Center of Chinese Academy of Sciences in Lintong, Shanxi province, recorded the pseudorange variations data by orbit determination system. And the crust vibration performance caused by earthquake was recorded in Lintong (see Fig. 12).

The measurement results can fully prove that pseudo-range value measured can reflect the state of earthquake shaking (see Fig. 12) and crustal deformation. But there are still three problems. One is measurement accuracy, which is expected to be reached. But careful scrutiny must be done further, especially using a special algorithm. Another is the frequency resolution problem. The measurement data output rate in Lintong is 1Hz, from which the high-frequency components of the earthquake have been removed. Therefore, it is necessary to improve data processing technology to output measurement data at the rate of 50Hz, so that the amount of high-frequency vibration can be measured. The last point is to change the system design. The equipment, measurement mode and number and distribution of measuring points must be changed. For this reason, one kind of micro measurement terminal is promoted, from which the signal is sent out and transmitted via satellite and received by the ground station. This system is called inbound position measurement and two-way relative measurement. Only by this scenario is it possible to better meet the requirements of monitoring crust and network distribution.

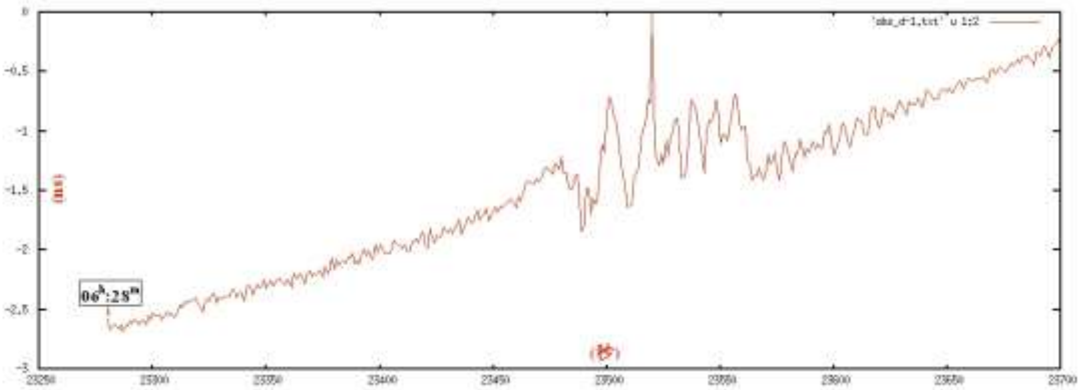

Figure 12: Crust vibration in Lintong caused by Wenchuan earthquake measured by SATRE equipment

In addition to measuring the slow change in plate movement and the vibration and moving of the measuring point on the ground, this method can also achieve other high-precision monitoring: reservoir dam, rivers and lakes water level monitoring; aircraft displacement, attitude and trajectory monitoring; high-rise building vibration and settlement monitoring; railway embankment monitoring; landslide monitoring; measurement of changes in the ionosphere; monitoring of water vapor distribution in the air measurements; and so on. We have applied several patents, including "Method of communication and positioning on the target using satellite" (patent application No.: 200810116829.2) [16], "Millimeter precision displacement measurement of crust in real time" (patent No.: 200810240073.2) [17], "Real-time precise orbital and position measurement of satellites or spacecraft" (patent No.: 20080810226676.7) [20], and "Bi-directional satellite navigation and positioning system" (patent No.: 2010104300.1) [18].

4. Benefits of the Integrated System

4.1 Disaster recovery and emergency services

The integrated communication and navigation system can better serve the needs of disaster monitoring and disaster recovery activities [27]. As the inbound positioning data from a remote user are received and processed by the communication center, there is no need to rely on additional communication links. Disasters such as large scale earthquakes, bushfires, and floods often destroy land communications infrastructure. But locations-based information from the disaster areas is critical for recovery and emergency exercises. With the positioning and communication services offered by the integrated system, the server centre can obtain and maintain data links and contacts with all the disaster team in real time, effectively enhancing the disaster recovery and emergency services. Fig.13 illustrates schematically how a national disaster command centre can coordinate the disaster recovery chain activities via the integrated system.

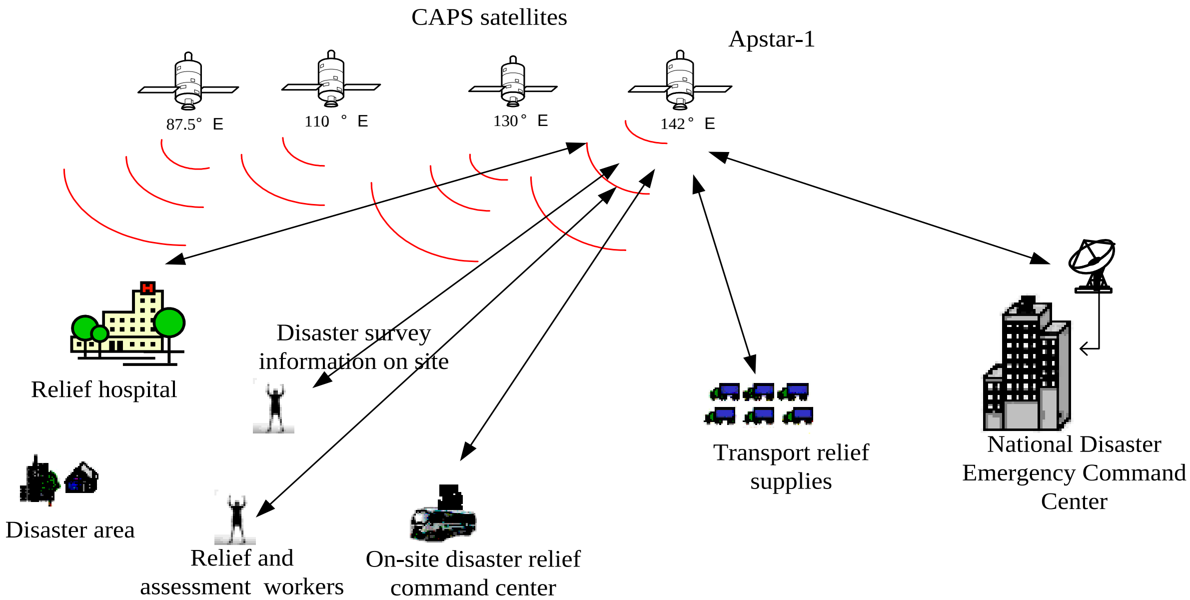

Fig. 13 Schematic diagram of the integrated system for disaster relief

4.2 Contributions of the integrated system to transport safety: road, maritime and aviation

GPS solves only the user states (own positioning, velocity measuring, time and g, and attitude) determination. Because the system does not have a return communication link, users cannot communicate directly with the user service centre without additional data links in time; at the same time, the user center cannot convey the relevant information to users. If the data links are not conveniently available, such as in remote areas, oceans and space, the applications of satellite navigations will be significantly limited. This greatly limits the application and the role of location information. For fishing boats, as an example, the system not only can return the location and other relevant information of the fishing boats in time, allowing the user center to keep abreast of fishing boats situations, but also can update or release weather and sea state information to avoid occurrence of accidents to the fishing boats, and can also broadcast fishing season, fishery product prices and other information to the fishing boats. In this way, it can direct the efficient safe operation of fishing boats, increasing labor productivity and offering economic efficiency.

Similarly, the new system provides a new services model for the automotive business, including monitoring the operation of auto parts to help owners deal with accidents, and also guiding the vehicle to carry out maintenance and repair services and so on. Now the United States, Japan and other countries have formed a new automotive service business model [28, 29]. A vehicle monitoring and controlling system is shown in Fig. 14.

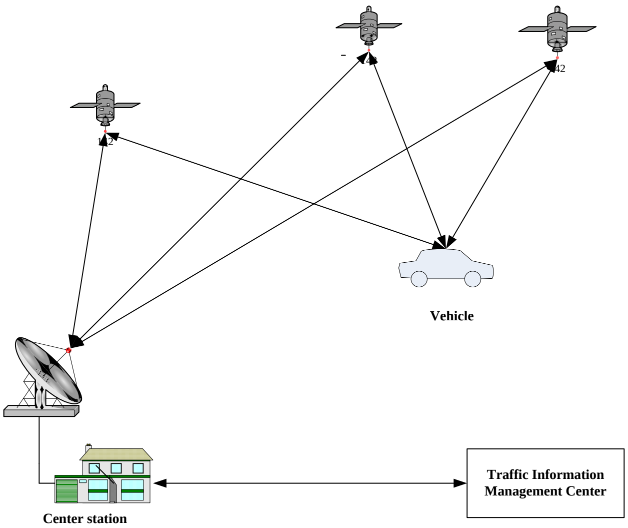

Fig. 14 Vehicle monitoring and controlling system

4.3 The new system can monitor the operation of large equipment

The integrated system has an inbound positioning link and an inbound communication link, so that all of the measurement data of user terminals can be fed to the user center. In this way, the central station can monitor the status of the users. The operation of large equipment can therefore be monitored in real time. Fig. 15 [30] shows the monitoring schematic for the control of marine buoys.

In short, a new age of diversified satellite navigation technology is emerging. In addition to today's classic satellite navigation technology of GPS systems, this new satellite navigation system will have topical application, departmental application and professional applications.

5. Concluding Remarks

Overall, the paper has provided a new perspective for the development trend of navigation technologies and systems: towards bi-directional, multi-frequency, multi-mode, integrated communication and navigation positioning. The integrated satellite navigation system may also be merged with ground mobile communication and broadcasting networks, in order to take full advantage of the various systems and to form a satellite navigation, positioning, timing and communication system with high-precision, high-performance, indoor and outdoor capabilities, aerial and terrestrial applications, and real-time communication.

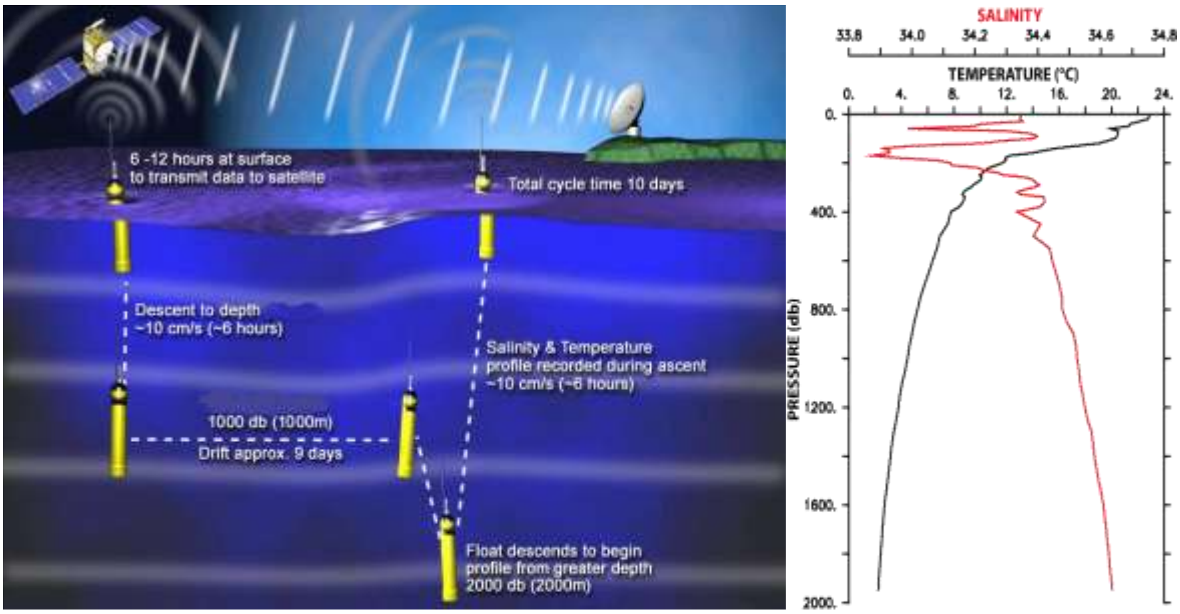

Fig. 15 Schematic diagram of detection and monitoring of marine buoys

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Biography

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