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Development trends of the national secure PNT system based on BDS

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Abstract Satellite navigation systems are vulnerable. To guarantee the positioning, navigation and timing (PNT) safety of core infrastructure, it is necessary to establish a secure PNT system with hybrid physical principles. In this paper, the augmentations of the BeiDou satellite system (BDS) itself are analysed, namely augmentations through the BDS inter-satellite link, BDS geostationary orbit (GEO) and inclined geostationary orbit (IGSO) satellites, and BDS PNT services supported by low earth orbit (LEO) satellites. Then, taking BDS as the core component, the comprehensive PNT infrastructure seamlessly covering deep space and deep ocean is described, consisting of the deep space PNT constellation, the sea-floor PNT sonar beacon network, and the ground-based low frequency and very low frequency (VLF) long wave radio stations. Moreover, the key technologies of resilient PNT application matching comprehensive PNT and various autonomous perception PNT information are discussed, such as resilient PNT sensor integration, the resilient PNT functional model and the resilient stochastic model. As a future development direction, the key factors of intelligent PNT services are analysed, including the intelligent perception of PNT application scenes, the intelligent optimization of PNT functional and stochastic models and the intelligent fusion of multisource PNT information.

Keywords Secure PNT system, Comprehensive PNT infrastructure, Resilient PNT application, Intelligent PNT application

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1. Introduction

The accomplishment and provision of the BeiDou Global Satellite Navigation System (BDS) indicate that significant progress has been made in national space-based positioning, navigation and timing (PNT) service infrastructure, and independent and controllable PNT information can be provided to major national infrastructure operations and economic construction (Yang Y F et al., 2020, 2021). However, similar to other Global Navigation Satellite Systems (GNSS), there is inherent vulnerability in the services provided by the BDS. Due to the low landing power and poor penetrating ability, the signal of the Radio Navigation Satellite System (RNSS) cannot serve users in nonexposed spaces (e.g., underground, underwater, and indoors). Even the obstruction of tall buildings, trees, and the interference of other electronic devices might lead to the invalidation of space-based PNT services. In addition, the service performance of GNSS in the North and South Poles is relatively poor due to the limitation of the GNSS constellation (Yang and Xu, 2016).

U.S. policy-makers regard PNT as the cornerstone and significant infrastructure concerning the U.S. national economy and national defence security and worry about the vulnerability and security of GPS. Thus, changing the PNT application rules is advocated, as well as the construction of new PNT infrastructures (Mcneff, 2010). The U.S. Department of Defense and Department of Transportation origin-

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ally proposed constructing a new national PNT system in 2010, planned to be accomplished by 2025 (U.S. Department of Transportation and Department of Defense, 2010). The U. S. Defense Advanced Research Projects Agency initiated the micro-PNT project in 2010, emphasizing the development of micro-PNT components with micromachinery devices, and the micro-PNT terminals featuring small size, low power consumption and better performance (Dalal, 2012). Professor Bradford Parkinson proposed the concept of Protect, Toughen and Augment (PTA) for GPS applications (Parkinson, 2015, 2017). The U.S. government issued multiple acts concerning national resilience and secure PNT from 2015 to 2018, emphasizing the reconstruction of the ground-based PNT system as the backup and complement of GPS (U. S. Senate, 2015, 2017, 2018).

Before the completion of BDS-3, Chinese scholars realized the structural risks in a single satellite navigation system, and started exploring the development direction of the Chinese PNT system. In 2016, the concept of comprehensive PNT was proposed by designing a seamless PNT source system from deep space to deep ocean with different physical principles (Yang, 2016). However, the comprehensive PNT only provides multiple PNT information sources, while the fusion of multiple pieces of information should also be realized to support the safe operation of major infrastructures and the users with high continuity requirements. In 2018, the resilient PNT conceptual framework was proposed to realize the resilient integration of multisource PNT sensors, the resilient modification of functional models and stochastic models, and the resilient data fusion of multiple PNT information sources in diverse environments, and guarantee the high continuity and availability of PNT service (Yang, 2018).

The proposal of a resilient PNT conceptual framework gave rise to research on resilient PNT theory and technology. In 2020, President Trump signed the Executive Order on Strengthening National Resilience Through Responsible Use of Positioning, Navigation and Timing Services, aiming to protect national infrastructure from the interruption of PNT service through the responsible use of PNT services by both the government and local organizations (Executive Office of the President, 2020). Many other scholars have also characterized resilient PNT systems from a macro perspective (Aresta, 2017; Scholz, 2020).

As we know, the normal operation of almost all major national infrastructures, such as transportation, finance, power and communication, have high demands for PNT service. As the GNSS cannot always provide continuous, reliable or stable PNT service, a high security PNT system should be constructed from the following four aspects. First, the GNSS constellation should be augmented to improve the PNT performance, and reduce the service interruption caused by system failure. Second, a comprehensive PNT infrastructure with hybrid physical principles should be constructed to tap complementary PNT information source, and expand the service coverage from deep space to deep ocean and from the outdoors to indoors. Third, resilient PNT terminals should be developed with multisource awareness, enabling the autonomous perception and selection of available PNT sources in complex environments and ensuring the continuity and reliability of PNT services. Last, an intelligent PNT application system should be developed to intelligently integrate reliable and available PNT sources according to different scenes, and realize intelligent fusion of multiple PNT sources.

This paper describes the secure PNT system architecture from the aspects of space-based PNT augmentation, comprehensive infrastructure augmentation and user terminal resilient augmentation, analyses the related key technologies and predicts the future development.

2. Space-based PNT augmentation

Spaced-based PNT remains the core infrastructure of global PNT services. The GNSS constellations are generally deployed at 27000 km altitude, and the Geostationary Orbit (GEO) satellites and Inclined Geosynchronous Orbit (IGSO) satellites of BDS are operated at 36000 km altitude. According to World Radio Communication Conference Resolution 609, the landing power flux density (PFD) of the RNSS signal in the 1164–1215 MHz band transmitted by any single satellite should be lower than -129 dBW m^{-2} MHz^{-1}, and the aggregate equivalent power flux density (AEPFD) produced by all space stations of all RNSS systems should be below -121.5 dBW m^{-2} MHz^{-1}. With such a low landing power, the GNSS signal is easily sheltered, interfered with and spoofed, regardless of whether it is encrypted or not. In addition, ground tracking and operational control systems are indispensable for GNSS to update parameters such as satellite orbits and clock errors. Thus, to improve the performance of space-based PNT services, BDS could be augmented with the inter-satellite links (ISLs), high earth orbit satellites and Low Earth Orbit (LEO) satellites (as shown in Figure 1).

2.1 Inter-satellite link augmentation

The roles of the ISLs may be enlarged. The distances provided by the Ka-band phased array ISL and laser ISL of BDS are important measurements to improve the global PNT performance of the BDS. First, the ISLs establish the communication channel between satellites, making it possible to transfer information from BDS Global Short Message Communication Service (GSMCS) and BDS Medium Earth Orbit Search and Rescue (MEOSAR) within the constella-

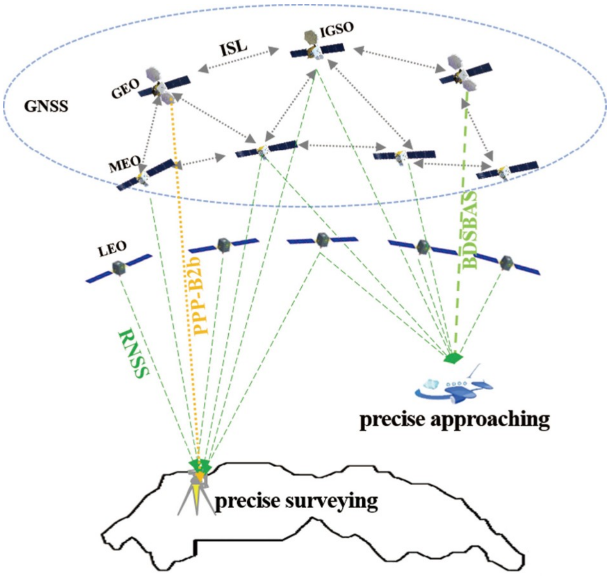

Figure 1 Space-based PNT augmentation.

tion. Second, the ISLs help to realize ranging and time synchronization between satellites to autonomously maintain orbit determination within a short time (Yang and Ren, 2018; Ren et al., 2017, 2019; Yang Y F et al., 2021). Third, ISL measurements can better constrain the constellation geometry and achieve precise orbit determination of the whole arc with only partial ground tracking observations (Yang et al., 2018; Yang Y F et al., 2020, 2021). In addition, with stable and precise Hydrogen Maser clocks mounted on some of the BeiDou satellites, the ISLs may help to maintain the unified time system of the satellite constellation by using the quasi-stable adjustment among the satellite clocks to improve the time keeping accuracy (Yang Y X et al., 2021a; Yang Y F et al., 2021).

2.2 BDS high orbit constellation augmentation

The IGSO satellites may help GEO satellites provide similar featured services. GEO satellites are important for performance improvement and service function expansion of the BDS (Yang Y X et al., 2020b, 2021a). On the one hand, GEO satellites provide uninterrupted signals for users in the Asia-Pacific region to improve the availability of regional PNT services. Even if only one Medium Earth Orbit (MEO) satellite is visible, the standard PNT service is still available with the support of the three GEOs. On the other hand, GEO satellites provide BeiDou Satellite-Based Augmentation System (BDSBAS) and BDS-3 Precise Point Positioning (PPP-B2b) services for users in China and the surrounding areas by transmitting precise satellite orbit and satellite clock offset correction parameters. The featured services of Regional Short Message Communication Service (RSMCS) and Two-Way Satellite Time and Frequency Transfer (TWSTFT) service, which were developed at BDS-1 and BDS-2, are still retained.

The BDS IGSO satellites are significant information sources of the augmented regional PNT service, and can reduce the 'South Wall' impact of the GEO satellites, which means that the IGSO satellites could replace the GEOs to provide the same services if the GEOs in the south are invisible to the users. On the one hand, the combination of the IGSOs can increase the number of visible satellites and decrease the value of Position Dilution of Precision (PDOP). On the other hand, IGSOs can provide an RSMCS with onboard RSMC devices, and join the services of BDSBAS and PPP-B2b, if parameters such as SBAS parameters, precise ephemeris and Differential Code Bias (DCB) are uploaded (Yang Y X et al., 2020b, 2022). Actually, the Japanese QZSS has realized regional PPP service.

2.3 LEO constellation augmentation

The LEO constellation is an important means to augment GNSS services. With a relatively shorter transmission distance, the LEO signals usually have larger landing power, better penetrability and anti-interference capability compared with those of the BDS-3 satellites, and the signal power is easier to enhance. The orbit determination (OD) accuracy of BDS-3 satellites can be improved by combined OD with LEOs, indirectly augmenting the BDS PNT performance (Zhao et al., 2017; Yang Y F et al., 2020). In addition, with a higher speed of the satellites relative to the ground users, the Doppler effect of LEOs is much more remarkable, and a better velocity measurement accuracy can be achieved. Similarly, with a quickly changing geometry structure, the correlation between the LEO constellation measurements of each epoch is relatively low, which can improve the resolution of PNT parameters and reduce the convergence time of carrier-phase ambiguity parameter estimation (Zhang and Ma, 2019).

The LEOs could contribute to the PPP service. On the one hand, with the constellation consisting of LEOs and BDS satellites, the number of available satellites for PNT service is increased, the DOP value is reduced, and the PNT performance is improved. Even without extra ground-tracking stations, the point positioning performance can be improved as well. On the other hand, the LEOs can broadcast the precise orbits and clock error parameters of BDS-3 globally, and extend the current service scope of BDS PPP-B2b with the support of a global tracking system.

3. Comprehensive PNT infrastructure

A comprehensive PNT system is the integration of various PNT information sources based on various physical principles (Yang, 2016), including the comprehensive PNT infrastructure and comprehensive PNT application system. The comprehensive PNT infrastructure refers to the large-scale PNT information sources built artificially, such as the Lagrange point navigation satellite constellation, medium and high earth orbit satellite constellations, LEO augmentation constellations, ground-based augmentation station nets, indoor positioning beacon networks, sea surface positioning buoy networks, and seafloor sonar beacon networks. The comprehensive PNT application system is the integration of available PNT sensors, including natural PNT information sensors such as Pulsar signals, gravity field and magnetic field, and traditional sensors such as inertial navigation systems (INSs) and atomic clocks. A comprehensive PNT system features the diversity of PNT physical principles, the ubiquity of PNT sources and the unity of space-time datum. The comprehensive PNT system has superiority in overcoming the limited coverage of a single PNT information source and improving the availability of PNT service seamlessly covering from deep space to deep ocean; reducing the interruption risk caused by the breakdown of a single PNT system, especially the interference and deception of the GNSS and realizing the continuity of PNT service in complex situations; compensating for the possible systematic errors and improving the accuracy of PNT results; fusing multisource PNT information and improving the reliability and security of PNT services. The infrastructures of the comprehensive PNT system are mainly described in Figure 2.

3.1 The deep space PNT infrastructure

The deep space PNT infrastructure mainly consists of a satellite navigation constellation in deep space. The location and time information are indispensable to secure navigation for environment detection and scientific research in deep space. The PNT service in deep space mainly relies on astronomy navigation, ground-based very long baseline interferometry (VLBI), and pulsar navigation which may be available in the future (Shuai et al., 2006; Mao et al., 2009). A pulsar is a compact object outside the Milky Way, with a radius of approximately 10 km and a mass 1.44 to 3.2 times heavier than that of the sun, exhibiting the second largest density after a black hole. A pulsar has better period stability which can be used to measure the time difference and the range between the two points. However, a pulsar is not an infrastructure. To construct a controllable infrastructure in deep space, navigation satellite constellations at the Earth-Moon Lagrange points and Sun-Moon Lagrange points should be taken into consideration. The deep space constellation should adopt the same signal frequency and modulation as those of the BDS or be designed as having a compatible and interoperable signal with the BDS. In addition, to realize an integrated service together with the BDS, the Earth-Moon and Sun-Moon Lagrange point navigation constellations should be equipped with downwards antenna broadcasting BDS navigation messages to provide better PNT service for near-Earth users, and upwards antennas providing PNT service for deep space users together with the BDS sidelobe signals.

3.2 The deep sea PNT infrastructure

The deep sea infrastructure is mainly composed of seafloor control stations, namely, seafloor sonar beacon networks. The construction of sonar beacon networks involves the development of seafloor shelters, the selection of beacon locations, the precise positioning strategy of the beacons, and acoustic observation models and data processing strategies in different ocean environments (Yang et al., 2017; Yang Y X et al., 2020a; Yang and Qin, 2021; Qin et al., 2022, 2023). In recent years, Chinese scholars have made great contributions to underwater PNT research, and deployed a seafloor acoustic positioning network at depths over 3000 m in the South China Sea. The precision of the seafloor station is about 0.3 m by combining circular and cross observation configurations (Yang Y X et al., 2020a; Zeng et al., 2021). A centimeter-level positioning precision is achieved by using the ocean sound speed model and equivalent sound speed model supported by a neural network learning algorithm (Xin et al., 2018; Wang et al., 2020a). Resilient acoustic observation models considering ocean environments have been established (Yang and Qin, 2021; Qin et al., 2022). Stochastic models of acoustic observations have also been built, and a series of underwater navigation and positioning algorithms have been developed, such as the robust adaptive Unscented Kalman filter (UKF) (Wang et al., 2020b; Qin et al., 2023), and the differential positioning algorithm for deep ocean control stations with depth difference constraints and horizontal distance constraints (Sun et al., 2019). To achieve meter level or 10 m level calibration of the INS accumulated error of underwater carriers, the relayed seafloor acoustic networks should be built in the future, that is, a set of sonar beacon networks should be built every hundred nautical miles to control the accumulated errors of INS, improving the precise PNT capability for long-term sailing.

3.3 The ground-based PNT infrastructure

As an important component of the national comprehensive PNT system, the ground-based radio PNT infrastructure should be strengthened. The ground-based radio PNT infrastructure refers to the long-range radio navigation system and the thriving 5G ground-based communication base station network, other than the ground-based augmentation system (GBAS). The reason is that the GBAS only improves

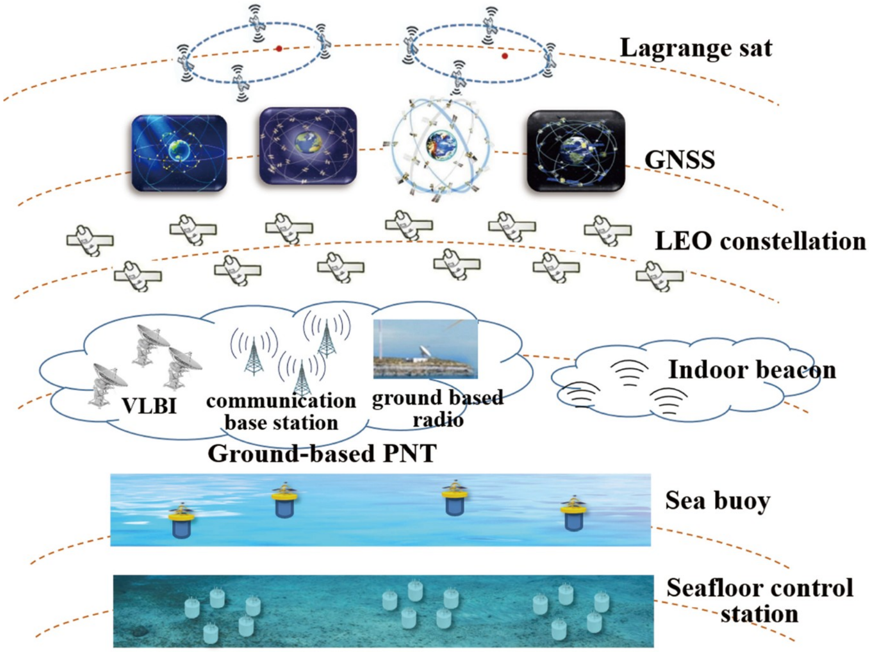

Figure 2 Comprehensive PNT infrastructures.

the service precision within the coverage of the ground monitoring stations. It cannot strengthen the observation geometry or the signal power, not to mention replacing the GNSS.

Compared with space-based PNT, the ground-based low and very low frequency PNT signals have better anti-inference and anti-deception capabilities. In the middle of the last century, long-range radio navigation (Loran) technology was substantially developed and widely used. The U.S. initiated research on long-range navigation technology and formed a complete ground-based navigation system with global coverage. Many similar ground-based radio navigation systems in the low and very low frequency bands have been established, such as Omega, Chayka and Alpha (Fuentes, 1987; Hu, 2018). Loran-C and Chayka transmit pulse signals at low frequencies and provide regional land-based remote radio PNT services within a radius of 2000 km. Omega and Alpha transmit pulse signals at very low frequencies and provide global PNT service with a radius larger than 5000 km. The ground-based PNT system at low and very low frequencies strongly supported global navigation and aviation at that time. With the development of GNSS, the ground-based radio PNT has gradually lost its superiority, leading to the shutdown of most systems. Being aware of the vulnerability of GNSS, developed countries have rebuilt their ground-based radio PNT systems and taken them as the backup of GNSS. The U.S. restarted Loran-C, and Russia used Scorpius to replace Chayka. Scorpius has better coverage and can control the whole network with only one control station. In addition, it has advantages in the auto maintenance of transmit signal parameters and restraint of the residual radio pulses. Compared with the systems in the middle of the last century, the rebuilt or modified ground-based radio PNT infrastructure greatly advanced the coverage and performance and can meet the PNT requirement of major infrastructure operation as well as flight route navigation, terminal area navigation, nonprecision approaching, ship navigation and secure entry into the harbor under low visibility.

China has built several low frequency navigation stations, namely the “Changhe” system (Wang et al., 2011). In addition to the modification of existing longwave navigation stations, new low and very low frequency station networks with better distributions should be built in the future to form a radio PNT system complementary to the BDS with almost global coverage. However, more efforts should be made to miniaturize and minimize the power consumption of the low-frequency and very low frequency PNT terminals.

The ground-based cellular radio communication (especially 5G) base station network could be used as an important national PNT infrastructure. The cellular radio base station network could provide PNT services for users within the coverage (Liu et al., 2020; Zhang et al., 2022), and at least can be an important compensation for major domestic PNT infrastructures.

4. Resilient PNT application mode

Resilient PNT is the key to the flexible integration and usage of PNT information. Although comprehensive PNT provides multisource PNT information, it is necessary to formulate resilient PNT using strategy, develop resilient PNT terminals and form the resilient PNT application mode to realize the secure and reliable use of PNT. Resilient PNT is similar to Flexible PNT, and adaptive PNT (Yang et al., 2001; Yang and Gao, 2006). The early adaptive PNT focuses on the stochastic model of multiple kinds of PNT information to optimally balance their contributions optimally. Resilient PNT includes the resilient integration of PNT sensors and the resilient modification of observation models and dynamic models, and finally realizes the resilient fusion of PNT information (Yang and Gao, 2004).

4.1 Resilient PNT integration

Resilient PNT integration is the basis of multisource PNT information application. Aiming to realize the mutual information compensation, support and replacement, resilient PNT needs redundant PNT signal sources; otherwise, the resilient selection is impossible. Obviously, comprehensive PNT is the basis of the resilient PNT. In the circumstances without any interference, deception or shelter, users in deep space, near space and on the ground could preferentially integrate radio PNT signals, including the GNSS signals, space-based and ground-based GNSS augmentation signals and Lagrange point constellation PNT signals and ground-based low and very low frequency radio PNT signals as well as cellular signals. When the radio signals are blocked, interfered with or deceived, autonomous PNT information such as inertial navigation information (Li et al., 2004), astronomy navigation information (including pulsar signals), optical navigation information and quantum perception information (Zou, 2014) can be used as resilient PNT information sources.

Different integration strategies should be used in different application scenes (as shown in Figure 3). For example, deep space users can integrate astronomy navigation information (including pulsar information), VLBI and GNSS sidelobe signals. Underwater users can use the sonar information provided by acoustic networks on the seafloor or buoys floating on the ocean surface and matching navigation information such as the Earth's gravitational field, magnetic field and the seabed terrain. Indoor users can use GNSS pseudolite signals, the ultra-wideband (UWB) signals (Pang et al., 2005), WiFi, Bluetooth (Wang et al., 2011), acoustic, optical, radar and visual information (El-Sheim and Li, 2021), etc.

In addition, the velocity and acceleration information measured by inertial navigation sensors (Li et al., 2004; El-Sheim and Youssef, 2020), quantum perception information (including quantum clock information, physical field information from quantum sensors, and quantum inertial information), and micro clocks are all available information for resilient PNT.

Obviously, the resilient PNT information integration includes the information provided by the comprehensive PNT infrastructure and sensed by various sensors in the nature. Resilient PNT integration emphasizes microminiaturization, low power consumption, availability and reliability. Thus, micro-PNT is the development direction of resilient PNT (Yang and Li, 2017).

4.2 Resilient PNT function model

A resilient functional model is the basis of resilient PNT information fusion. In complex environment, the sensitivity of PNT information is different in different backgrounds. Resilient functional model modification focuses on the autonomous compensation of various systematic errors through PNT observation models (Yang, 2018). Usually, the observation model for a certain kind of PNT observation is fixed and the correction for systematic error (if there is any) is applied to simplify the observation model. However, the resilient PNT functional model modification attaches resilient correction items to the frequently-used observation models with parameters estimated together with the PNT parameters while fusing multisource information or with the support of a priori information. Certainly, the non-PNT estimated parameters could be eliminated through the reduction method.

The core of resilient functional model modification is systematic error compensation. It is known that any observation model or dynamic model is approximate, and there is basically no completely accurate functional model. Either the linearization of the nonlinear model or the reduction of the dynamic model will result in residual model errors. In complex urban environments, mountain areas, deep space, deep sea, and indoor and underground areas, certain systematic errors exist in all kinds of PNT information that vary with time. The fusion of multisource PNT information supports the study of observation systematic errors, because the sensitivity of observations based on different physical principles to the environment is different, as are the error characteristics. These errors could be compensatory, and as long as appropriate resilient error correction items are set in the functional model, the systematic error terms can be obtained according to the data fusion criterion. The deep sea resilient acoustic observation model is a meaningful experiment (Yang and Qin, 2021; Qin et al., 2022).

4.3 Resilient PNT stochastic model

The resilient stochastic model refers to the measurement model of the uncertainty evaluation of each kind of PNT observation. The uncertainties of various PNT sources are

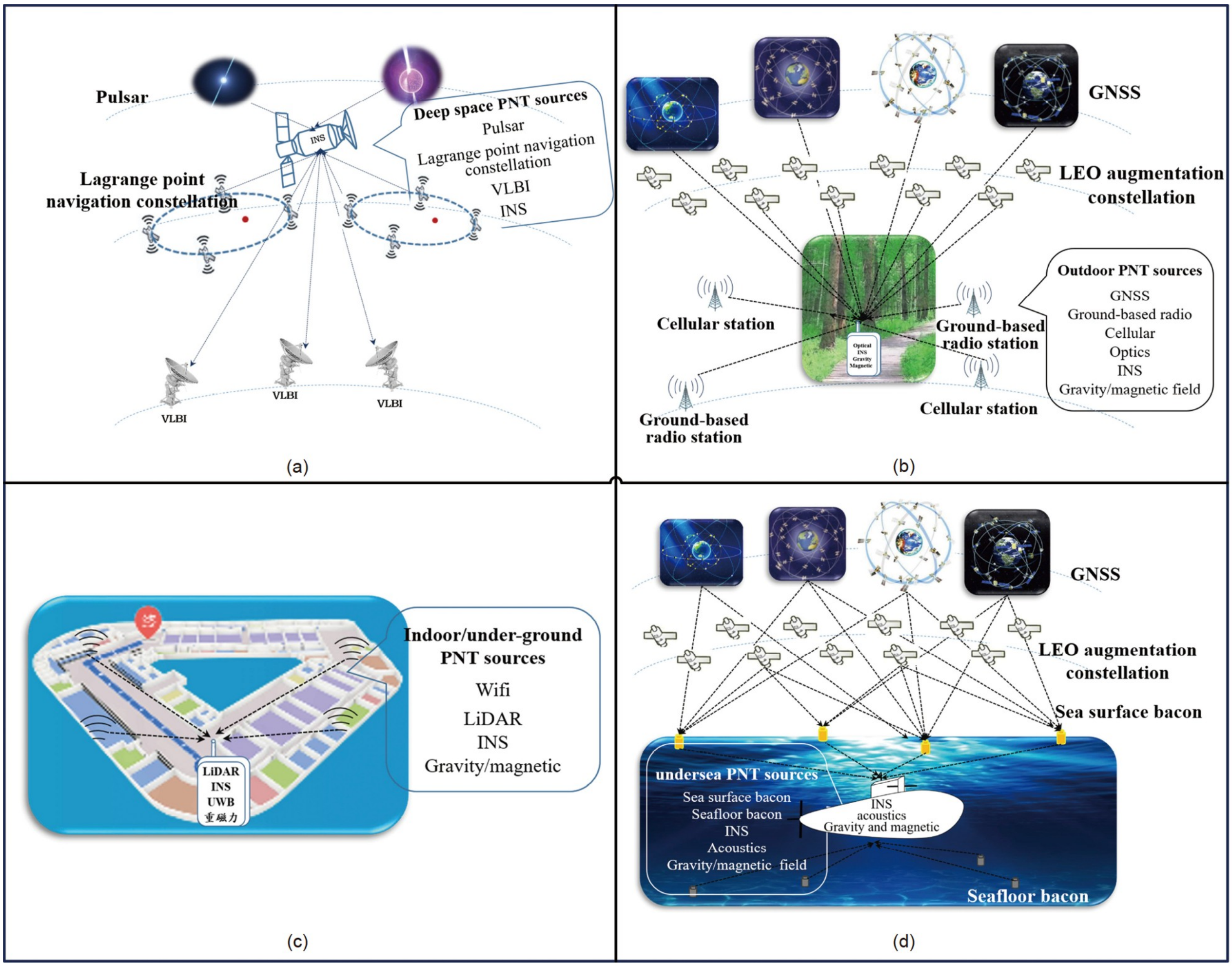

Figure 3 Resilient information integration for typical scenes.

different, especially in different environments. The resilient PNT stochastic model focuses on the self-adaptiveness of the actual uncertainty between the stochastic models and the corresponding observations. Significant achievements have been made in resilient stochastic models, among which covariance estimation is a widely used adjusting algorithm (Yang and Xu, 2003). Factually the adaptive factors in adaptive Kalman filtering (Yang et al., 2001; Yang and Gao, 2006) are mainly used to adjust the stochastic models of different PNT information.

The resilient stochastic model is mainly based on the reliable functional model. Any bias or outlier in the functional model will affect the stochastic model, and thus the overall modification of the functional model and stochastic model must be solved. To control the effect of outliers on stochastic models, the stochastic model modification based on the robust estimation should be a focus in the resilient stochastic model studies.

The purpose of resilient PNT information integration, resilient PNT function model modification and resilient stochastic model adjustment is to realize resilient PNT information fusion. The study of resilient PNT has just started, and further research should be conducted on the theory, algorithm and mode.

5. Intelligent PNT application mode

Intelligent PNT includes intelligent PNT systems and intelligent PNT applications. In this section, only the intelligent PNT application mode is discussed. For both comprehensive PNT and resilient PNT, the core is to guarantee the security, continuity, accuracy and reliability of PNT service. Due to the ever-changing PNT application environment, the resilient PNT application mode should be intelligent. Therefore, an intelligent PNT application mode should be developed (Yang Y X et al., 2021c). Intelligent PNT application includes the intelligent perception of users, intelligent multisource information integration and intelligent modification of the functional model and stochastic model (as shown in Figure 4).

Figure 4 Key factors of intelligent PNT.

5.1 Intelligent perception of PNT users and intelligent multisource information integration

Intelligent perception of users is the premise of intelligent PNT applications. In certain environments, the availability, reliability and accuracy of PNT information sources are different. Meanwhile, users have particular requirements for the efficiency, security and precision of PNT information. Thus, intelligent PNT application should initially distinguish the environment and understand the requirements of the users, then intelligently select and integrate the PNT information sources, and finally provide the PNT service matching the user requirements and environment. For example, GNSS signals are unavailable to underwater users, and information integration should be intelligently switched to INS navigation, acoustic positioning, or magnetic, gravity or terrain matching navigation modes. Once the user vehicle surfaces, the ground-based radio navigation/GNSS/INS mode is a reasonable choice.

It should be noted that intelligent PNT must be resilient and integrated, while resilient integration may not be intelligent. Therefore, resilient integration does not necessarily contain PNT intelligence. In addition, resilient PNT should obtain a priori user requirements and background information in advance. If the intelligent recognition, perception and mining of user requirements and the environment are included in the resilient PNT integration, the resilient PNT information integration can be regarded as intelligent.

5.2 PNT functional model and intelligent modification of the stochastic model

An intelligent PNT model is the basis for improving the intelligence of PNT applications. Intelligent learning could modify the PNT observation model and stochastic model in real-time or near real-time, making the observation model and stochastic model adapt to the observation environment and the observation uncertainty, respectively. Any model improvement with a priori information belongs to supervised learning, and that without a priori information belongs to unsupervised learning. For example, the determination of GNSS multipath signals and non-line-of-sight signals based on the supervised learning method can improve GNSS observation models and control the effect of multipath errors (Zhu et al., 2021). Model improvement is an intelligent learning belongs to the intelligent PNT model modification. It is noted that the intelligent modification of functional model includes the resilient modification of the functional model, but the resilient modification does not have to be intelligent. Similarly, the intelligent adjustment of the stochastic model includes the resilient adjustment of stochastic model, but the resilient adjustment does not have to be intelligent. Intelligent modification will be achieved if intelligent elements are integrated into the resilient modification of the function model and stochastic model.

Intelligent PNT model modification is the basis of the intelligent fusion of multisource PNT information. Multisource PNT fusion is not a simple weighted average, but intelligent fusion comprehensively balances the reliability (including continuity), accuracy, and uncertainty of each kind of PNT information. Without intelligent learning and determination of the PNT observation model errors, a reliable and modified observation model cannot be built; without intelligent tracking and evaluation of the uncertainty of the PNT information, the intelligent adjustment of PNT stochastic model cannot be realized; without an intelligent PNT functional model and stochastic model, intelligent fusion of multiple PNT sources will not be achieved, not to mention the intelligent PNT applications. In most PNT applications, the systematic biases of PNT observation models can be obtained through intelligent learning and then compensated by the intelligent functional model. Similarly, the suitability and biases of each kind of PNT stochastic model can be sensed to support the optimization of PNT stochastic model (Yang Y X et al., 2021c).

6. Conclusion

Now and in the future, GNSS is the core of PNT systems with unparalleled coverage, performance, popularity and flexibility. However, PNT signals are vulnerable in terms of the signal intensity, signal penetration, anti-interference and anti-spoofing capbility. To improve the security, robustness and coverage, a seamless PNT system covering from deep space to deep ocean, that is, a comprehensive PNT infrastructure should be built first, and then the corresponding resilient and intelligent PNT application modes must be followed.

(1) As the core of the PNT service system, the BDS ISLs must be used to improve the capability of space-time datum maintenance based on the BDS. Furthermore, the BDS GEOs and IGSOs should be fully used to improve the BDS satellite-based augmentation and satellite-based precise point positioning. Meanwhile, the LEO constellation should be constructed to improve the anti-inference and anti-deception of BDS PNT service.

(2) As the core of the secure operation of major infrastructures, a national PNT system with powerful functions and rich information sources must be constructed. A deep space navigation constellation and deep ocean acoustic network should be constructed to provide PNT services for deep space and deep sea users, respectively. Ground-based low and very low frequency longwave PNT stations should be constructed as important backups of the BDS. Ground-based 5G stations could be used as a backup PNT system for major domestic infrastructures.

(3) With the support of the comprehensive PNT infrastructure and other autonomous PNT perception information, a resilient PNT application mode adaptive to various complex environments should be constructed, as well as a PNT application system with solid theoretical basis, high availability, high continuity, high stability, high reliability and high security from the aspects of resilient PNT sensor integration, resilient functional model, resilient stochastic model and resilient data fusion.

(4) The intelligent perception of PNT users, intelligent modification of the functional model and stochastic model and intelligent data fusion are the preconditions for intelligent PNT applications. It is certain that the intelligent PNT service system and application mode will be an important development direction in the near future.

(5) With the BDS as the core, the secure PNT system is the inevitable development trend of the PNT system, and comprehensive PNT, resilient PNT and intelligent PNT are important ways to realize secure PNT. Comprehensive PNT provides all-domain, seamless and multiple information sources, resilient PNT provides the resilient application mode for users, and intelligent PNT is the further whose core is to apply knowledge learning, intelligent perception and intelligent modification to every step of PNT application.

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