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ORIGINAL ARTICLE

BDS-3 SAR service and initial performance

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Abstract

Search and rescue (SAR) service is one of the major services provided by BDS-3 system. Six BDS-3 MEOSAR payloads are optimally distributed on three orbits and work normally. BDS-3 system uniquely adopts the architecture of Regional Up-Link Stations and crosslinks between satellites to provide return link service (RLS) for distressed people worldwide. BDS-3 B2b signal is designed to support the return link message (RLM) broadcasting, positioning, navigation and timing. A variable-length message type of RLM is specially designed to enrich SAR operation information categories and improve SAR operation efficiency. The performance of MEOSAR, RLS and positioning is evaluated through numerical simulation and preliminary in-orbit test. According to the results, the global availability is over 98.79%, with only six BDS MEOSAR payloads. The test indexes of BDS MEOSAR payloads meet the COSPAS-SARSAT MEOSAR space segment commissioning standard requirements. BDS RLS time delay is less than 2 min, which demonstrates the efficiency of BDS RLS architecture. And B2b positioning accuracy is better than 10 m.

Keywords BDS-3 · SAR · RLS · Positioning · COSPAS-SARSAT

Abbreviations

BDS	BeiDou Navigation Satellite System
BOCC	BDS Operation and Control Center
CNMCC	China Mission Control Center
ELTs	Emergency Locator Transmitters
EPIRBs	Emergency Position-Indicating Radio Beacons
GMDSS	Global Maritime Distress and Safety System
LUT	Local User Terminal
MCC	Mission Control Center
MEOSAR	Medium Earth Orbit Search and Rescue
PLBs	Personal Locator Beacons
RCC	Rescue Coordination Center
RLS	Return Link Service
RLM	Return Link Message
RLSP	Return Link Service provider
RULS	Regional Up-Link Station
SAR	Search and Rescue

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Overview

The COSPAS-SARSAT system, established by the United States, Soviet Union, Canada, and France, provides free satellite-aid search and rescue services for users worldwide. Since 1985, COSPAS-SARSAT has saved thousands of lives. Currently, it is the most successful non-profit satellite search and rescue system.

Early COSPAS-SARSAT system mainly utilizes GEO and LEO satellites with SAR payloads to provide alerts with the location of users in distress. However, GEO satellites cannot cover polar areas, and LEO satellites have poor real-time performance. To detect user location anytime anywhere, the COSPAS-SARSAT community gradually developed to use MEO constellation to provide SAR service, which can provide global coverage and quickly determine the location of users in distress (Martin et al. 2018).

In addition, the major MEO satellite system, represented by GNSS, can also support GNSS positioning, which can greatly improve the positioning accuracy of distress alerts. GPS, GLONASS, Galileo, and BDS have

MEOSAR payloads onboard (Xavier et al. 2017; Françoise et al. 2018). BDS has deployed six MEOSAR payloads onboard.

Currently, MEOSAR service can only provide single-direction communication, e.g., from user to satellite. The communication from satellite to user direction in distress is still in need. Also, due to the lack of acknowledgment after the alert is triggered, the false alert rate is very high. Return link service (RLS) provided by BDS MEO navigation satellites can provide distress users with confirmation messages or other rescue information, which can greatly comfort distressed users psychologically and improve search and rescue success rate.

Galileo has carried out the research work on the return link (Europa GSC 2016), and its RLS is put online since 2019 (Sylvain et al. 2019). Galileo deployed RLS on its E1 signal to provide SAR distress acknowledgment messages. Global up-link stations are used to RLM to the distress beacon worldwide. The time delay of RLS is within 15 min (Europa GSC 2020). GLONASS will provide RLS at K-2 satellite (Russian Space Systems 2016).

BDS MEOSAR service with RLS is one of the featured services of BeiDou Navigation Satellite System (Yang et al. 2019; Yuan et al. 2019). BDS uniquely uses crosslinks to broadcast return link messages through satellite constellation globally, which needs just a few RULSs and decreases its operational complexity. Meanwhile, considering COSPAS-SARSAT is part of the global maritime distress and safety system (GMDSS) provider, and GMDSS deeply involves rescue coordination and communication, a variable-length RLM is designed to provide flexible information on B2b signal, which can greatly facilitate search and rescue operations. Besides, BDS-3 B2b signal can support positioning, navigation and timing. The positioning accuracy of B2b signal is at the meter level, which meets the GNSS receiver requirement.

We present BDS SAR service architecture mainly based on crosslinks and regional up-link stations. Then we discuss return link service, including working flow, frame structure, and data format. The performance on key parameters including service coverage, EIRP and bandwidth of BDS MEOSAR payloads, RLS, and B2b positioning are provided. Finally, we summarize our results.

System structure

BDS MEOSAR system shares the same scheme with other MEOSAR systems. BDS RLS adopts a unique architecture of RULS and crosslinks. The system structure composed of the space segment, ground segment, and user segment is shown in Fig. 1.

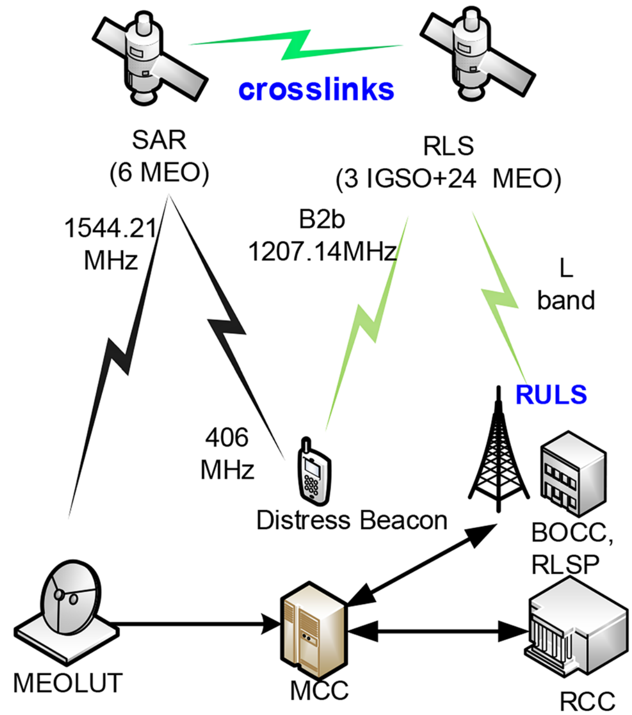

Fig. 1 System Components of BDS SAR and RLS, and information flow when a 406 MHz beacon is activated

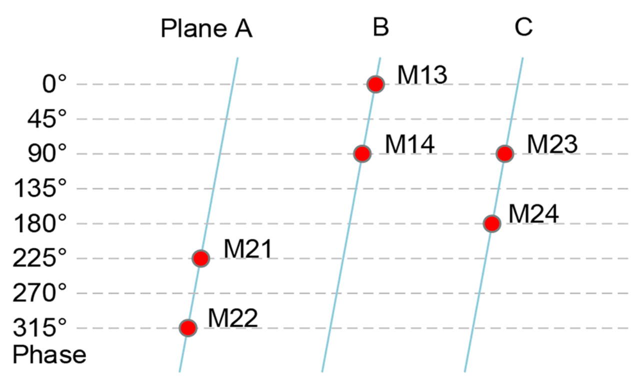

Fig. 2 Distribution of MEOSAR Payload on BDS MEO Constellation

Space segment

BDS MEO satellites are on Walker 24/3/1 constellation slots, orbiting at an altitude of 21,528 km and at an inclination angle of 55°. The distribution of six BDS MEOSAR payloads is optimized for maximum coverage, which is shown in Fig. 2.

The BDS MEOSAR payload is integrated with a bent pipe transponder and transceiver antennas. The bent pipe transponder receives signals in the 406.0 to 406.1 MHz band and retransmits at 1.54421 GHz. The payload is designed in accordance with COSPAS-SARSAT MEOSAR space segment interoperability requirements, ensuring its compatibility and interoperability with other SAR systems.

BDS RLS is provided from 3 IGSO and 24 MEO satellites via B2b signal, which center frequency is 1207.14 MHz. The IGSO satellites operate in orbit at an altitude of 35,786 km and an inclination to the orbital planes of 55 degrees with reference to the equatorial plane. Crosslinks of satellites ensure that one satellite can communicate with any satellite in the constellation.

Ground segment

The ground Segment includes BDS operation and control center (BOCC) with some RULSs, BDS return link service provider (RLSP), china mission control center (CNMCC), the responsible rescue coordination center (RCC), a BDS payload monitor station, and other related COSPAS-SARSAT facilities like MEOSAR local user terminal (MEOLUT).

BOCC is in charge of uploading the return link message to a satellite in sight by RULSs, then the message will be routed among BDS satellite constellation with crosslinks. As crosslinks can deliver RLM to the destination satellite among the constellation, theoretically, just one RULS is needed to upload RLM to a visible satellite, which greatly reduces the number and the operational complexity of up-link stations worldwide. CNMCC is in charge of broadcasting payload status for COSPAS-SARSAT network and processing return link messages with RLSP. RCC is in charge of rescue operations, and the BDS payload monitor station monitors the BDS payload status, such as bandwidth and EIRP. MEOLUT receives SAR request messages and locates the distress beacon.

User segment

Currently, there are three types of COSPAS-SARSAT beacons: emergency position-indicating radio beacons (EPIRBs) used in maritime, emergency locator transmitters (ELTs) used in aviation, and personal locator beacons (PLBs) used for individuals. All beacon types will support BDS RLS and the positioning capability of B2b signal.

Return link service

To enhance the overall effectiveness of SAR operations, existing MEOSAR providers are considering the possibility of advanced capabilities, which are mainly based on the return link. BDS RLS uses different signal and information formats from Galileo, especially with a flexible-length information format.

Working flow

Once BDS RLS-supported 406 MHz beacon sends an RLS request to COSPAS-SARSAT network, as CNMCC receives an RLM request from local LUT or C/S network, the RLM request will be processed by BDS RLSP and be delivered to BOCC. BOCC will choose the proper satellite in sight and upload the RLM by RULSs. Then the RLM will be routed to the destination satellite in the crosslinks network. The navigation payload of the destination satellite will process this RLM and broadcast it. BDS RLS compatible beacon should be equipped with a BDS B2b receiver to decode-related information from BDS B2b signal.

BDS RLSP and BOCC are high-performance, reliable devices with partial and global redundancy. Hence, BDS RLS has 99.95% of system online rate to guarantee 99% successful delivery of RLM.

Frame structure

At present, Inmarsat and Iridium are recognized as mobile satellite communication services providers in GMDSS (Valčić et al. 2019). Mobile satellite communication systems have more traffic capacity to provide a great deal of safety-related information in search and rescue operations.

In order to improve SAR performance in COSPAS-SARSAT, it is necessary to deliver RLM in navigation downlink signals (COSPAS-SARSAT 2019). While navigation satellite systems are dedicated to providing position, navigation, and time services, the information rate is much lower than that of satellite communication systems. It is very reasonable to design RLM as a short and formatted message suitable for various information needs, especially in search and rescue operations.

BDS-3 B2b frame structure is shown in Fig. 3. Each frame is 1000 symbols long and lasts 1 s. More information is provided in BDS SIS B2b ICD (CSNO 2019, 2020).

BDS RLS has its exclusive frame and message type, which is 8, with higher priority to achieve an instant response. RLM frame will use the I component only.

Data format

A single B2b frame contains 436 bits of message data to carry RLM information and could contain multiple RLMs with short and formatted information. Three RLM types are currently designed according to the search and rescue process and different message content. The data format of three RLM types is shown in Table 1. The Service type field is used to identify RLM type. Any RLM type contains a Beacon ID which is a unique beacon identification in COSPAS-SARAST. According to the beacon ID, the distress beacon could judge whether the message is sent to itself or not.

Fig. 3 B2b frame structure

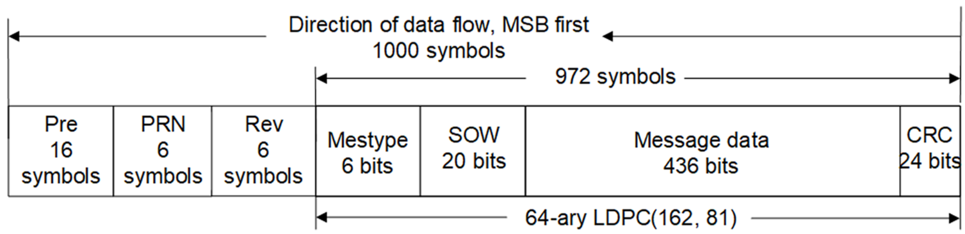

Table 1 Data format of three RLM types

Service type 4 bits	Beacon ID 60 bits	Message data
Short RLM 0001	60 bits	16 bits
Long RLM 0010	60 bits	96 bits
Flexible RLM 0011	60 bits	Message length 6 bits + Flexible message

Flexible RLM especially has a message length field to identify the length of the flexible message.

Short RLM

Short RLM refers to system acknowledgment in COSPAS-SARSAT. After COSPAS-SARSAT ground segment receives the distress information with BDS RLM request, the request will be sent to BDS MEOSAR ground segment (CNMCC, MEOLUT, and RLSP). BDS MEOSAR ground segment automatically and instantly sends the Short RLM to the distress beacon through BOCC.

Long RLM

Long RLM refers to RCC confirmation in COSPAS-SARSAT. In this case, RCC will assess the distress situation and determine appropriate response measures first. Then BDS MEOSAR ground segment will send the Long RLM, which indicates that RCC is processing the alert to the distress beacon through BOCC. Short RLM and long RLM is interoperable with other GNSS's corresponding format.

Flexible RLM

Flexible RLM refers to rescue-related messages of RCC in COSPAS-SARSAT. The actual message field is customized text with flexible length. This message could deliver a small amount of necessary information, such as SAR progress or coordination information. Compare with relative fixed short RLM and long RLM. Flexible RLM is mainly used to send SAR operation-related messages to the distressed user, which could improve the success rate of SAR operation.

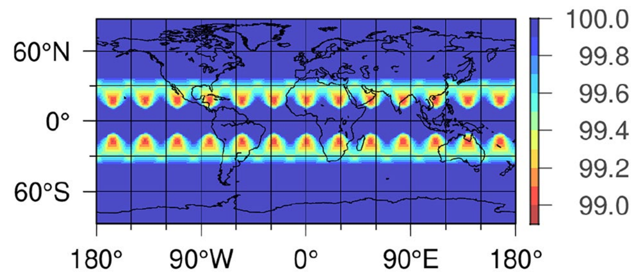

Fig. 4 Simulation result of coverage rate (%)

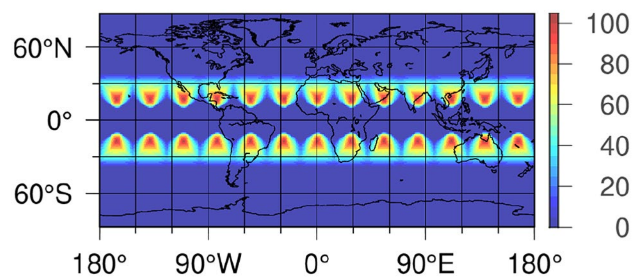

Fig. 5 Simulation result of maximum time gap (min)

Performance analysis

To evaluate the performance of BDS-3 SAR service, the coverage, MEOSAR payload, RLS, and positioning will be analyzed. The coverage analysis is conducted through data simulation, while payload, RLS, and positioning performance analysis are conducted through in-orbit test.

Analysis of SAR coverage

A simulation about earth coverage rate and maximum time gap is demonstrated in Figs. 4 and 5. The MEOSAR payload visibility elevation is above 5 degrees. The results show that the coverage rate can reach 100% in most areas. The minimal coverage rate is 98.79% in partial areas, mainly between 20 and 30 degrees of latitude, and the maximum time gap is about 104.7 min, accordingly, due to the limitation of the number (six) of MEOSAR payloads.

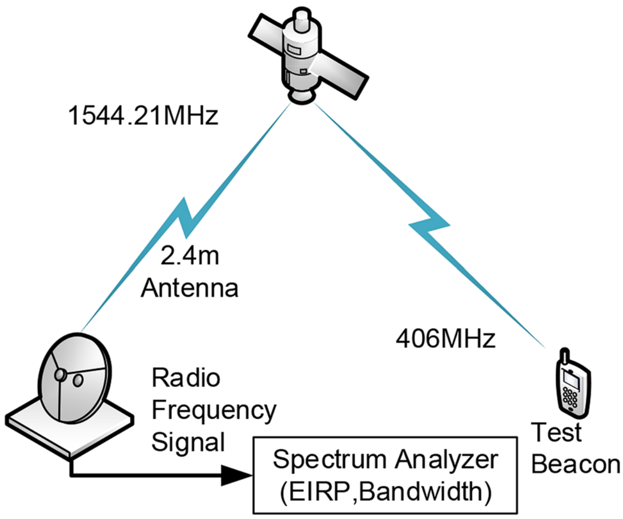

Fig. 6 Major components in BDS MEOSAR payload test facility

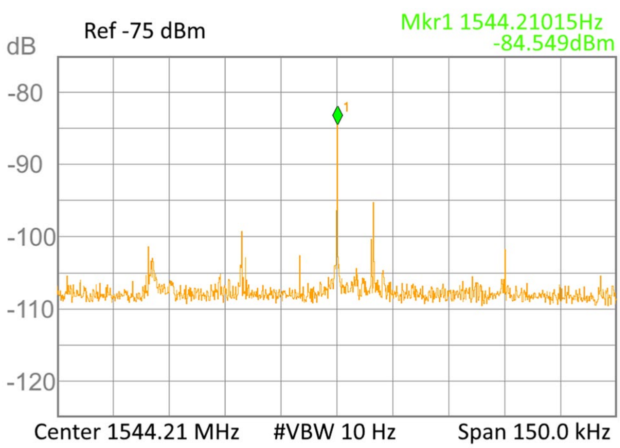

Fig. 7 Payload continuous-wave response in spectrum analyzer

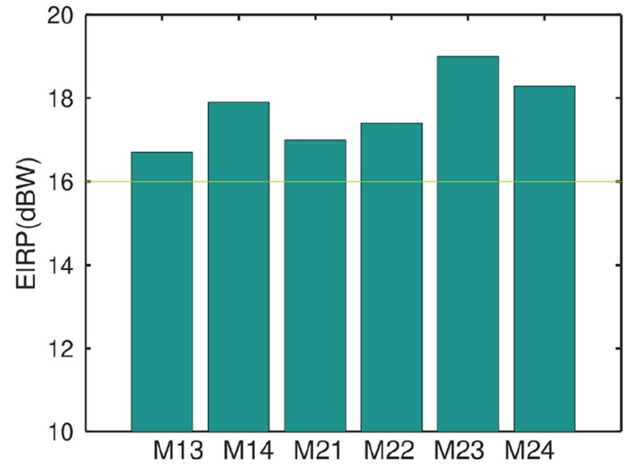

Fig. 8 EIRP of six BDS SAR payloads on-orbit test results, as requirement value is greater than 16 dBW

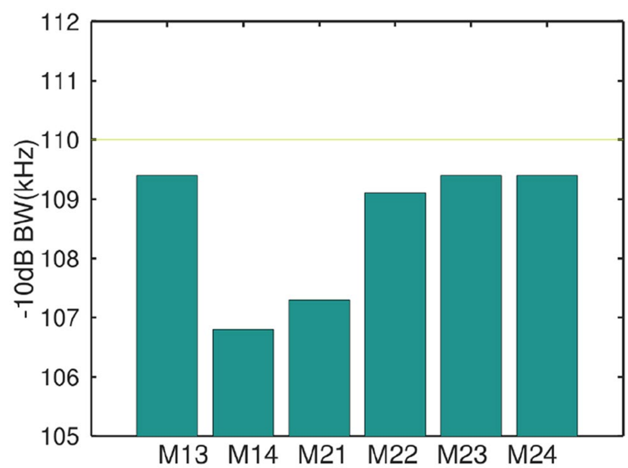

Fig. 9 −10 dB bandwidth of six BDS SAR payloads on-orbit test results, as requirement value is less than 110 kHz

Performance of MEOSAR payload

The following figure shows the components that are used in MEOSAR payload test. The signal generator is used to generate 406 MHz continuous wave signals or beacon signals. Antenna, low noise amplifier, and down converter are used to pick up and enhance the signal that is repeated from a satellite. The signal processor is used to decode 406 MHz beacon signal information, while the spectrum analyzer is used to analyze the signal in the frequency domain (Fig. 6).

The following figure shows the payload continuous-wave response in the spectrum analyzer. The figure also shows the number of beacon signals in the payload band (Fig. 7).

The major BDS MEOSAR payload on-orbit test results, including EIRP (Equivalent isotopically radiated power) and −10 dB bandwidth, are shown in Figs. 8 and 9. On-orbit test results show that BDS MEOSAR payload meets the design requirement and interoperability requirement. The repeater EIRP requirement is better than 16 dBW, and −10 dB bandwidth requirement is less than 110 kHz (COSPAS-SARSAT 2019).

Performance of RLS

The time delay of RLS can be computed as

$$T_{\mathrm{RLS}} = t_{\mathrm{RB}} + t_{\mathrm{BS}} + (N+1) \cdot t_{\mathrm{PRO}} + \sum_{i=0}^{N} t_{\mathrm{ISLi}} + t_{\mathrm{ST}}$$

where t_{RB} is the ground delay from CNMCC to BOCC, t_{BS} is BOCC processing and upload delay, t_{PRO} is the receiving and B2b message generation time delay in a satellite, t_{ISLi} is

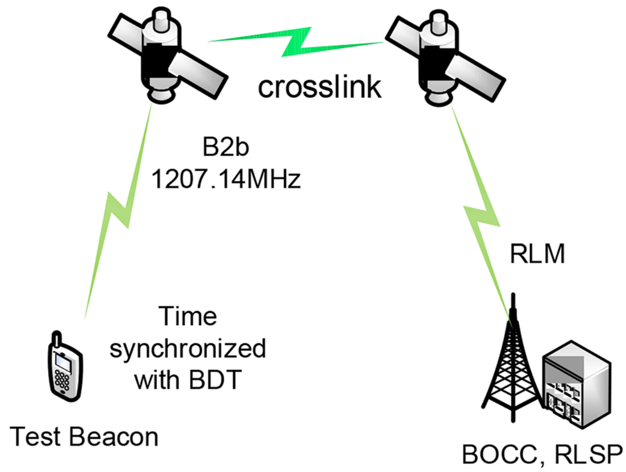

Fig. 10 Test environment configuration

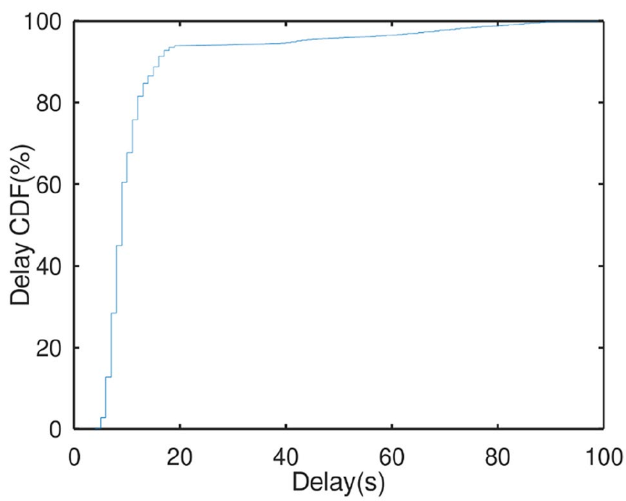

Fig. 11 CDF plot of Delay

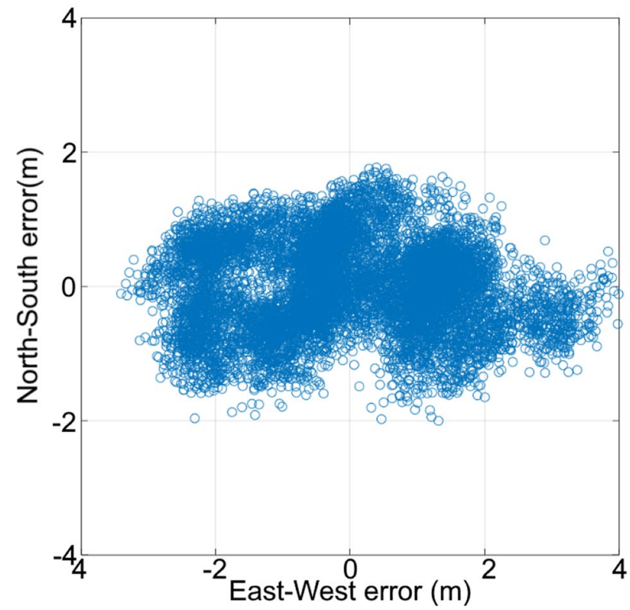

Fig. 12 Horizontal error distribution of B2b positioning

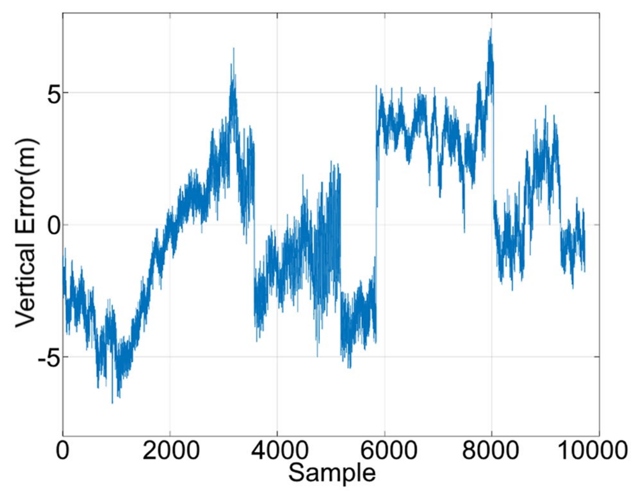

Fig. 13 Vertical error of B2b positioning

a time delay that RLS hops between two satellites, N is the number that RLS routed in crosslinks network, and t_{ST} is the downlink delay. t_{RB}, t_{PRO}, and t_{ST} are in millisecond level, whereas t_{BS} is in the second level. The delay of return link service is usually dominated by the time delay in crosslinks.

RLS preliminary test has been carried out. The configuration of test environment is shown in Fig. 10. BOCC was dispatched to up-link test return link message, and the time delay from BOCC sending to test beacon receiving has been recorded. The receiver time is synchronized with BDS satellite to enhance the accuracy of results.

Cumulated destitution function (CDF) of delay with crosslinks routing is shown in Fig. 11. The results show that 95% of multiple return link messages can be delivered in 42 s, and 99% of return link messages can be delivered in 82 s.

Accuracy of B2b positioning

The accuracy of B2b positioning is evaluated by conducting a preliminary test. A B2b signal receiver is deployed in an open field without block above 5 degrees elevation. More than 9000 samples are collected during the test campaign (Fig. 12). The processed result shows that horizontal accuracy is 2.7 m (95% confidence), vertical accuracy is 4.9 m (95% confidence), which meets the requirement of the GNSS receiver, and is far better than 5 km of SAR locating accuracy (IEC 2020). The following figures show both horizontal and vertical errors (Fig 13).

Conclusion

BDS-3 MEO satellites with SAR payloads have been successfully launched into orbit. The test results of BDS SAR service meet the requirements of COSPAS-SARSAT. BDS MEOSAR payload can work with other MEOSAR systems such as GPS, GLONASS and Galileo systems to enhance the performance of the COSPAS-SARSAT MEOSAR system.

BDS RLS unique architecture of RULSs and crosslinks may give a new method for broadcasting relevant information globally. RLS delay meets the needs of users and can greatly improve search and rescue success rate and efficiency. Also, flexible length RLM could enhance the efficiency of search and rescue operations. BDS team is digging deeper to study the return link compatibility and interoperability with Galileo and other interested satellite navigation systems participants. Besides, the positioning accuracy of BDS B2b signal is better than 10 m. We believe that BDS could provide better search and rescue services for global users.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

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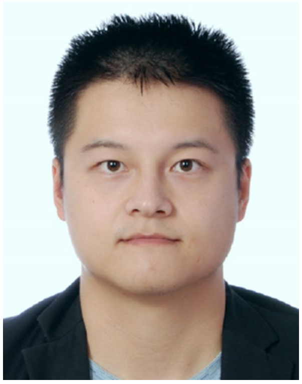

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