COSPAS-SARSAT MEOLUT PERFORMANCE SPECIFICATION AND DESIGN GUIDELINES

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COSPAS-SARSAT MEOLUT PERFORMANCE SPECIFICATION AND DESIGN GUIDELINES

HISTORY

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1. INTRODUCTION

1.1 Overview

The purpose of the Cospas-Sarsat System is to provide distress alert and location data for search and rescue (SAR), using spacecraft and ground facilities to detect and locate the signals of Cospas-Sarsat distress radiobeacons operating on 406 MHz. An earth receiving station that tracks medium earth orbiting (MEO) satellites in the Cospas-Sarsat System (the Cospas-Sarsat MEOSAR system) is called a MEOSAR Local User Terminal (MEOLUT). The MEOLUT transmits alert and location data to its associated Cospas-Sarsat Mission Control Centre (MCC) for subsequent distribution to SAR authorities.

For acceptance as part of the Cospas-Sarsat System, a MEOLUT shall be commissioned as defined in document C/S T.020, Cospas-Sarsat MEOLUT Commissioning Standard, to verify compliance of its performance with this specification.

1.2 Scope

This specification describes the minimal operational capabilities and performance requirements of a Cospas-Sarsat MEOLUT. The specifications in this document apply to data transmitted by a MEOLUT for distribution in the Cospas-Sarsat MCC network, and to data exchanged between Cospas-Sarsat MEOLUTs.

1.3 Document Organization

A brief description of a MEOLUT is provided in section 2. Operational requirements are provided in section 3, section 4 defines the functional and processing requirements, and section 5 contains specific performance requirements for a MEOLUT.

The Annexes to this document contain information about the MEOSAR Link Budget, the Beacon Message Processing, the MEOLUT Network Architecture, and MEOLUT Coverage Area.

1.4 Reference Documents

Reference	Title
C/S T.001	Specification for Cospas-Sarsat 406 MHz Distress Beacons
C/S T.015	Cospas-Sarsat Specification and Type Approval Standard for 406 MHz Ship Security Alert (SSAS) Beacons
C/S T.016	Description of the Cospas-Sarsat MEOSAR Space Segment
C/S T.017	Cospas-Sarsat MEOSAR Space Segment Commissioning Standard
C/S T.020	Cospas-Sarsat MEOLUT Commissioning Standard
C/S A.001	Cospas-Sarsat Data Distribution Plan
C/S A.002	Cospas-Sarsat MCC Standard Interface Description
C/S A.003	Cospas-Sarsat Monitoring and Reporting
C/S A.005	Cospas-Sarsat Mission Control Centre (MCC) Performance Specification and Design Guidelines

- END OF SECTION 1 -

2. COSPAS-SARSAT MEOLUT DESCRIPTION

The MEOLUT is a ground receiving station in the Cospas-Sarsat MEOSAR system that detects, characterizes and locates emergency beacons, and forwards the appropriate information to an MCC. The MEOLUT shall receive and process beacon signals received through downlinks from GPS, Galileo and GLONASS MEOSAR satellites to obtain beacon data. The MEOLUT shall use this beacon data to meet all the operational, functional, processing, and performance requirements contained in this document.

The MEOLUT shall measure the frequency of arrival (FOA) and time of arrival (TOA) of detected beacon message bursts on each satellite channel and use the results to locate the beacon. The MEOLUT shall calculate an unambiguous location for the beacon if the message is received from at least three MEOSAR satellites for a given burst. This method of beacon location will be referred to in this document as Frequency Difference of Arrival/Time Difference of Arrival (FDOA/TDOA) location. The MEOLUT shall be capable of improving the location accuracy of the beacon over the first burst by combining data from subsequent bursts as it is received.

A MEOLUT consists of at least the following basic components and appropriate interfaces:

a) antenna(s) and radio frequency subsystems,
b) one or more processor(s),
c) a time and/or frequency reference subsystem,
d) a satellite tracking subsystem, and
e) an MCC interface.

Figure 2.1 contains a functional block diagram of a typical MEOLUT system.

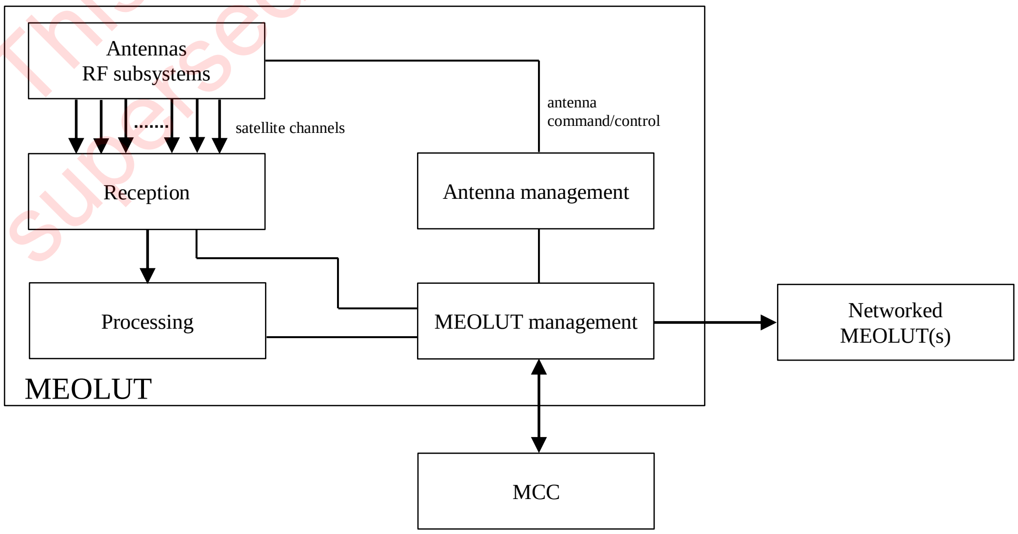

Figure 2.1: Functional Block Diagram of a Typical Cospas-Sarsat MEOLUT System

The MEOLUT shall meet the operational, functional, processing, and performance requirements contained in this document without relying upon TOA/FOA data received from other MEOLUTs. In addition, the MEOLUT shall be capable of exchanging data with other MEOLUTs, according to specifications in Annex C. Sharing of MEOSAR TOA/FOA data is optional, determined by national requirements and arranged on a bilateral basis between MEOLUT operators. The intent of MEOLUT data exchange is to enhance the Cospas-Sarsat System performance and support redundancy within the Cospas-Sarsat Ground Segment.

The SAR instruments on Cospas-Sarsat MEOSAR satellites receive up-link signals from distress beacons, test beacons and system beacons such as orbitography beacons. These up-link signals, along with unwanted interfering signals, are frequency translated and retransmitted to the ground upon a downlink carrier for reception by a MEOLUT. Cospas-Sarsat MEOLUTs may also process the downlinks to characterize and locate interferers.

The operational, functional and performance requirements for these processing channels are described in the following sections of this document. They are intended to ensure that:

a) the MEOLUT is available and capable of receiving and processing:

    i. signals from C/S T.001-compliant beacons that are received through MEOSAR satellite downlinks; and
    ii. 406 MHz beacon data from other MEOLUTs, if MEOLUT data exchange processing is implemented.

b) the MEOLUT provides timely reliable alerts and accurate position data by:

    i. detecting valid and invalid 406 MHz beacon messages and processing them in accordance with this specification;
    ii. verifying whenever possible that the beacon identification and encoded position information are valid;
    iii. properly selecting the data points used to calculate beacon locations;
    iv. providing updated position information to the MCC, as appropriate;
    v. validating calculated beacon locations; and
    vi. maintaining an accurate time reference.

- END OF SECTION 2 -

3. OPERATIONAL REQUIREMENTS

The basic operational objective of a MEOLUT is to process data from as many satellites as possible and to send the resultant alert data to its associated MCC, according to the specifications contained in this document. Once a MEOLUT has been commissioned and connected to the Cospas-Sarsat network through an MCC, it shall continue to meet the specifications of this document.

3.1 MEOLUT Data Availability

A MEOLUT commissioned for operation within the Cospas-Sarsat System shall provide data to the associated MCC twenty-four (24) hours a day, seven (7) days a week with less than five (5) percent downtime calculated over a year.

A MEOLUT should be designed to maximise data availability (including beacon detections, alerts and location solutions, and data to be exchanged among MEOLUTs) in the event that not all MEOLUT performance requirements are being met.

3.2 Data Requirements

The MEOLUT shall provide all data necessary for the MCC to distribute relevant alert data to the appropriate Search and Rescue Point-of-Contact (SPOC), according to document C/S A.002, Cospas-Sarsat MCC Standard Interface Description.

Optionally, the MEOLUT may provide 406 MHz beacon data to other MEOLUTs according to the specifications contained in Annex C.

3.3 Data Channels

3.3.1 Satellite Data Channels

The MEOLUT shall receive and process beacon signals received through downlinks from MEOSAR satellites to obtain beacon data. The MEOLUT shall use this beacon data to meet all the operational, functional, processing, and performance requirements contained in this document. The MEOLUT shall be able to process beacon messages relayed from any combination of commissioned MEOSAR satellites as described in C/S T.016 and C/S T.017.

The MEOLUT may also receive and process beacon signals received through downlinks from non-MEOSAR, Cospas-Sarsat commissioned satellites to obtain beacon data. However, the MEOLUT shall meet all the operational, functional, processing, and performance requirements contained in this document without relying upon TOA/FOA data from non-MEOSAR satellites.

3.3.2 MEOLUT Data Exchange

Optionally, the MEOLUT may exchange data with other MEOLUTs, according to the specifications contained in Annex C, to enhance system performance and support redundancy of the Cospas-Sarsat Ground System. However, this beacon data cannot be relied upon to meet the operational, functional, processing, and performance requirements contained in this document.

3.4 Satellite Tracking and Visibility

The MEOLUT shall be capable of simultaneously tracking as many visible MEOSAR satellites as the MEOLUT has antenna beams.

The MEOLUT should be located to give the widest possible horizon because it is desirable to be able to track satellites down to the horizontal plane for all azimuth angles. The MEOLUT shall be capable of continuously receiving and processing all satellite data for all portions of a satellite pass above its minimum declared elevation angle, except where prevented by local obstructions, without any data degradation or loss.

3.5 Status and Alarm

The MEOLUT shall provide all data necessary for the MCC to identify degradation of its operational capability in accordance with the specifications described in this document at a minimum.

3.6 RF Radiation and Emissions

The MEOLUT shall not radiate or emit any radio frequency (RF) signals that will interfere with the functioning of the Cospas-Sarsat system.

3.7 Data Archiving

At a minimum, the MEOLUT shall store the following data for a period of at least 90 days:

a) the 36 hexadecimal character representation of each beacon message;

b) the frequency and time measurement of each beacon burst;

c) the C/No ratio for each beacon burst on each satellite channel;

d) the beacon locations and related solution data calculated by the MEOLUT;

e) the solution data for all 406 MHz interferers detected;

f) the log files that capture the status of the MEOLUT during the time period; and

g) the satellite orbit vectors for each satellite data channel and each beacon transmission.

3.8 Cospas-Sarsat Quality Management System (QMS) Continuous Monitoring and Objective Assessment

The MEOLUT shall support requirements provided in document C/S A.003.

- END OF SECTION 3 -

4. FUNCTIONAL AND PROCESSING REQUIREMENTS

4.1 Summary of Requirements

The basic functional and processing requirements for the MEOLUT are to:

a) maintain and update satellite ephemeris;
b) acquire, track and receive the downlink signal from Cospas-Sarsat MEOSAR satellites;
c) maintain and update the required time and frequency references;
d) demodulate the satellite data channels;
e) process satellite data channels as described in section 4.2;
f) calculate beacon positions whenever enough reliable data is available;
g) optionally use network data from other MEOLUTs to enhance the computed beacon position estimate;
h) maintain and update a database of relevant information pertaining to each detected beacon and associated location processing;
i) provide interfaces for command and data access both locally and remotely; and
j) provide the resultant data to the associated MCC, as necessary, to support the requirements of document C/S A.002, Cospas-Sarsat MCCs Standard Interface Description.

4.1.1 Antenna and RF Subsystem

The MEOLUT shall have antenna beams and RF subsystems that are able to acquire, track and receive the downlink signal from any Cospas-Sarsat MEOSAR satellite as described in document C/S T.016[1].

4.1.2 Time and Frequency Reference Subsystem

The MEOLUT shall maintain system time and frequency references with sufficient accuracy to ensure that the beacon location accuracy specifications are met.

4.1.3 Satellite Tracking Subsystem

The MEOLUT shall maintain accurate satellite orbital elements and tracking schedules for all MEOSAR satellites. In addition, the MEOLUT shall have the capability to implement MCC provided orbital elements. The MEOLUT may receive orbital elements from the MEOLUT operator or the GNSS satellites hosting the MEOSAR payloads.

[1] This may include use of satellites with an S-band downlink.

The MEOLUT shall be capable of generating its own satellite pass tracking schedule but may also be capable of accepting a satellite pass tracking schedule from an external source, such as its host MCC, and be configurable to follow either satellite pass tracking schedule.

The MEOLUT shall be able to generate a tracking schedule based on configuration at the MEOLUT. The tracking schedule algorithm should be configurable locally or remotely.

The MEOLUT shall be able to optimize its tracking schedule to maximize performance over its designated coverage area.

4.1.4 MCC Interface

The MEOLUT must provide timely information of the level of quality and detail required by documents C/S A.002 and C/S A.005.

4.2 Processing 406 MHz Beacon Message Data

4.2.1 General Processing Requirements

The MEOLUT shall process 406 MHz beacon message data based on the formats described in document C/S T.001 (Specification for Cospas-Sarsat 406 MHz Distress Beacons). The processing consists of the following sequence:

a) message recovery,

b) bit verification,

c) message validation,

d) message processing,

e) FDOA/TDOA location processing, and

f) transmission of resultant alert data to the MCC.

These processing requirements apply to all satellite data channels. If implemented, MEOLUT data exchange channels will meet the requirements specified in section 4.2.6.

4.2.2 Beacon Message Recovery

Normal mode beacon messages have a perfect match of bits 16 to 24 with the 9-bit frame synchronization pattern described in document C/S T.001 (beacon specification). The MEOLUT shall process all normal mode beacon messages and transmit them to the MCC based on specifications in this document. Beacon messages that are not in normal mode shall not be processed operationally.

The MEOLUT may include the capability to integrate different messages, received from the same transmission through different satellite channels, to determine the contents of the beacon message. Successive bursts of the same transmitting beacon may also be integrated until a valid message is produced.

The MEOLUT shall be capable of recording “self-test” mode beacon messages that have an inverted frame synchronization pattern. However, such data shall not be used in the processing of operational alerts.

“Self-test” mode beacon messages may be forwarded to the MCC for other uses, such as the verification of beacon registration, system test support or message traffic analysis. If this capability is provided, the transmission of “self-test” mode beacon messages shall be configurable.

4.2.3 Bit Verification

The MEOLUT shall detect and correct bit errors in the 406 MHz beacon messages received through the satellite data channels, as follows.

1) The digital message transmitted by 406 MHz beacons includes a 21-bit BCH error correcting code, and, in the long message format, an additional 12-bit BCH error correcting code (except for the orbitography protocol as noted below). The MEOLUT shall use these BCH codes to verify and correct as necessary the received data. All beacon messages include the following fields:

    a) first protected data field (PDF-1, bits 25 to 85) which contains the beacon identification and can include position data; and
    b) first BCH error correcting field (BCH-1, bits 86 to 106) which contains the 21-bit BCH error correcting code that protects the 82 bits of PDF-1 and BCH-1.

    The 82 bits of PDF-1 and BCH-1 are also referred to as the first protected field.

2) The long message format may also include:

    a) the second protected data field (PDF-2, bits 107 to 132) which contains position and supplementary data; and
    b) the second BCH error correcting field (BCH-2, bits 133 to 144) which contains the 12-bit BCH error correcting code that protects the 38 bits of PDF-2 and BCH-2.

    The 38 bits of PDF-2 and BCH-2 are also referred to as the second protected field.

3) The MEOLUT shall use BCH-1 to correct all messages that have a maximum of three bit errors in the first protected field, and detect the existence of more than three (3) errors with a probability of 95%. The MEOLUT shall use BCH-2 to correct any messages that have one bit error in the second protected field of the long message format and to detect the existence of two or more bit errors. When the MEOLUT determines there are 2 or more bit errors in the second protected field, bits 113 to 144 shall all be replaced with “1”. For short format beacon messages, the MEOLUT shall set bits 113 to 144 to all “0” values.

4) The MEOLUT shall process the orbitography protocol beacon messages with the short message portion (bits 25-106) error corrected by BCH-1; the data in bits 107 to 144 is sent without error detection and correction.

4.2.4 Beacon Message Validation

- A 406 MHz first generation beacon message produced by a MEOLUT is valid when:

  - the first protected field (PDF-1 + BCH-1) has 2 or less corrected bit errors and the fixed bits of Standard and National location protocols that start at bit 107 contain no errors; or
  - the first protected field (PDF-1 + BCH-1) has 3 corrected bit errors and is confirmed by an identical match with another valid message from the same beacon ID detected within ± 20 minutes and the fixed bits of Standard and National location protocols that start at bit 107 contain no errors.

- A 406 MHz first generation beacon message produced by a MEOLUT is complete when it consists of:
  - the first protected field (PDF-1+BCH-1) of a valid short message; or
  - the first and second protected fields (PDF-1+BCH-1+PDF-2+BCH-2) of a valid long message where the second protected field contains less than 2 corrected bit errors.

Bits 113 to 144 of the second protected field of a valid long message shall all be set to "1" if this field contains 2 or more bit errors. The message is then declared incomplete.

If a long message is valid but not complete, for any protocol other than the orbitography protocol, bits 113 to 144 of the second protected field shall all be set to "1" by the MEOLUT.

A confirmed beacon message may be a confirmed valid message or a confirmed complete message. The message confirmation process requires that two independent burst processing results produce identical valid or complete messages.

The confirmation can be obtained from successive transmitted burst processing or, in the case of multi-channel MEOLUT processing, from the result of the processing of the same transmitted burst via two or more satellites provided each received burst is processed independently to produce a beacon message and both messages produced are identical.

4.2.5 Beacon Message Processing

Beacon messages shall only be treated as being from the "same burst" when the associated times are within 2.5 seconds (i.e., 5% of the nominal beacon repetition rate). If the associated times for two beacon messages exceeds this threshold, then the messages should be treated as being from separate bursts. If the beacon type (e.g., orbitography or operational) is not known, then the repetition rate for operational beacons shall be used.

In order to provide updated beacon messages and to generate TDOA/FDOA locations, it is necessary to associate 406 MHz beacon messages received from different satellites and at different times for the "same" beacon. This section specifies the rules for associating independent packets for the same beacon.

Two 406 MHz beacon messages are associated when the fixed bits of the first protected field (PDF-1 + BCH-1) of the two beacon messages are identical. Since the encoded position data in 406 MHz beacon messages using location protocols may change over time (in accordance with document C/S T.001), only fixed bits in a beacon message can be used for matching. Beacon messages shall be matched based on the fixed bits in accordance with Protocol type, as follows:

Table 4.1

Protocol	Fixed Bits
User	25 to 85 (61 bits)
Standard Location	25 to 64 (40 bits)
National Location	25 to 58 (34 bits)
Undefined	25 to 106 (82 bits)

If a beacon message is not valid, then its Protocol is "undefined" and matching shall be based on bits 25 to 106, as specified above.

In addition, two beacon messages are associated when the first protected field (PDF-1 + BCH-1) of one beacon message has 3 corrected bit errors and its PDF-1 is identical to the PDF-1 of a valid beacon message that was received by a MEOLUT within 20 minutes. In this case, the MEOLUT shall use the valid beacon message in subsequent processing.

4.2.6 MEOLUT Data Exchange

If implemented, the MEOLUT shall provide data to, and retrieve data from other MEOLUTs according to the MEOLUT data exchange specifications contained in Annex C.

4.2.7 Time and Frequency Requirements

The MEOLUT shall measure the time and frequency to the accuracy required to satisfy the location accuracy requirements specified in section 5.

4.2.8 Independent Location Processing

The MEOLUT shall measure the FOA and TOA of each beacon message received. When the same burst is received from the same beacon through three or more satellites, the MEOLUT shall use these measurements to calculate FDOA/TDOA 2D locations.

It is noted that a MEOLUT may produce a 2D location with data from fewer than three satellites.

The MEOLUT shall be capable of identifying and filtering beacon messages with low quality measurements that degrade location accuracy. The MEOLUT shall use all available FOA/TOA data to calculate FDOA/TDOA locations, except when the FOA/TOA data is identified as low quality. The MEOLUT shall not produce a located solution if the location is outside the footprint of any satellite for which data was used to compute the location at the time of the associated burst data.

4.2.9 Transmitting Data to the MCC

Upon initial detection and processing of a beacon message for a given 406 MHz beacon:

a) if an independent location is available, the MEOLUT shall send an alert with the independent location to the associated MCC immediately;

b) if an independent location is not available but the beacon message is valid, the MEOLUT shall send an alert solution without independent location to the associated MCC as soon as the beacon message is confirmed (with an indication that the beacon message is confirmed), or after 3 minutes if the beacon message remains unconfirmed.

After the initial alert has been sent by the MEOLUT to the associated MCC for a given beacon, the MEOLUT shall send a new alert solution (i.e., an alert with data not previously sent) to the associated MCC immediately if any of the following conditions is met:

a) an independent location is first available;

b) a better quality independent location than all previously sent for that beacon is available;

c) an encoded position is first available;

d) the encoded position has changed;

e) a confirmed beacon message is available for the first time; or

f) five (5) minutes has transpired with no other alert being sent and data has been received since the previous alert was sent, then the MEOLUT shall send a single new alert to the associated MCC including the valid beacon message with the most recent detect time and the independent location with the most recent detect time (if a new independent location is available).

No more than six (6) alerts shall be sent to the MCC during any five (5) minute period.

When the MEOLUT has not received any new data from a beacon for a period of ten (10) minutes it shall treat the beacon activation as ceased. If data is received for a beacon after its activation status is ceased, then the MEOLUT shall return to the initial processing procedure described above and ignore all data received prior to the time the activation status was deemed ceased in subsequent processing of alerts for that beacon.

The MEOLUT shall have the capability of suppressing all orbitography and calibration beacon messages and passing them to the MCC only on request.

The MEOLUT shall transmit all the necessary data to enable the associated MCC to satisfy the requirements of documents C/S A.002 and C/S A.005.

The MEOLUT shall transmit data to its associated MCC as required by the QMS continuous monitoring and objective assessment process described in document C/S A.003.

The MEOLUT may filter or send additional alerts to the MCC as defined by national administrations.

- END OF SECTION 4 -

5. PERFORMANCE REQUIREMENTS

The performance requirements defined in the following sections establish measurable performance criteria that a MEOLUT must meet before it can be integrated into the Cospas-Sarsat System and be commissioned by the Cospas-Sarsat Council. This specification applies to C/S T.001 compliant beacons using the MEOSAR space segment as defined in document C/S T.016.

The Minimum Performance Area (MPA) of the MEOLUT is defined as the minimum area over which the MEOLUT can expect to receive sufficient data to meet all of the performance requirements of this MEOLUT Specification and Design Guidelines. The Minimum Performance Area is an area equivalent to the area of a circle with a radius of at least 1,000 km from a reference location (e.g., the geographical centre of associated antenna(s)).

MEOLUT performance is expected to extend over a coverage area beyond the Minimum Performance Area. Refer to Annex D for a discussion of the achievable MEOLUT coverage area and the factors that affect it.

5.1 RF Signal Margin

The MEOLUT shall be designed to maintain a positive link margin from MEOSAR satellites (refer to the MEOSAR link budget contained in Annex A).

5.2 Sensitivity

The signal sensitivity threshold is the C/No level at which the MEOLUT will produce valid messages for at least 90% of individual beacon messages, where C/No is the ratio of the unmodulated carrier power to noise power density in dB-Hz.

The MEOLUT signal sensitivity shall be better than 34.8 dB-Hz.

5.3 Beacon Detection Probability

The probability of detecting the transmission of a 406 MHz beacon and recovering a valid beacon message at the MEOLUT, within 10 minutes from the first beacon message transmission shall be a minimum of 99%.

5.4 Probability of FDOA/TDOA Location

The probability of obtaining a 2D location (latitude/longitude), independently of any encoded position data at the MEOLUT in the 406 MHz beacon message, using a single burst transmission, within two minutes of the single burst transmission, shall be 90%.

The probability of obtaining a 2D location (Latitude/Longitude), independently of any encoded position data at the MEOLUT in the 406 MHz beacon message, within 10 minutes from the first beacon message transmission, shall be 98%.

5.5 Capacity

The MEOLUT must be able to detect and process at least 100 beacons active.

5.6 Location Accuracy

Independent locations, using a single burst transmission, shall meet the following accuracy requirement:

M/N shall be greater than or equal to 0.90 where:

M = number of locations within 5 km

N = number of locations

An independent location provided within 10 minutes from the first beacon message transmission shall meet the following accuracy requirement:

M/N shall be greater than or equal to 0.95 where:

M = number of locations within 5 km

N = number of locations

M/N shall be greater than or equal to 0.98 where:

M = number of locations within 10 km

N = number of locations

5.7 Processing Bandwidth

At a minimum, the MEOLUT shall be capable of processing the signals of the 406 MHz beacons defined in document C/S T.001. Processing the 406.01 MHz to 406.09 MHz bandwidth (i.e., 80 kHz) is required.

5.8 MEOLUT Data Exchange

5.8.1 TOA/FOA Measurement Accuracy

This specification applies to data obtained from a beacon that is visible to a satellite being tracked by the MEOLUT.

If the MEOLUT provides data for use by other MEOLUTS, the accuracy of the TOA and FOA data shall be as follows:

- The TOA measurement accuracy for beacon transmissions received with a C/N_0 between 34.8 dB-Hz and 37.8 dB-Hz shall be better than the standard deviation of 25 microseconds. The bias of the mean of the measurement errors from the actual TOA of the beacon transmission shall be less than 2.5 microseconds.
- The FOA measurement accuracy for beacon transmissions received with a C/N_0 between 34.8 dB-Hz and 37.8 dB-Hz shall be better than the standard deviation of 0.20 Hz. The bias of the mean of the measurement errors from the actual FOA of the beacon transmission shall be less than 0.02 Hertz.

It is expected that TOA and FOA measurements accuracy quoted above will also allow the MEOLUT to meet its expected location accuracy requirement.

5.8.2 External Data Processing

The MEOLUT may process 406 MHz beacon data retrieved from other commissioned MEOLUTs, according to the specifications contained in Annex C, to enhance system performance and support redundancy of the Cospas-Sarsat Ground System. However, this beacon data cannot be relied upon to meet the operational, functional, processing, and performance requirements contained in this document. Furthermore, the performance of the MEOLUT shall still be compliant with the performance requirements of sections 5 and 4.2.9, despite the processing of data retrieved from other commissioned MEOLUTs.

5.9 Processing Combined with non-MEOSAR Satellites (optional capability)

If the MEOLUT does use data from non-MEOSAR satellites as described in section 3.3.1, the MEOLUT shall meet all the operational, functional, processing, and performance requirements contained in this document without relying upon TOA/FOA data from non-MEOSAR satellites and the MEOLUT's capability to meet the performance requirements contained in this document shall not be impaired.

5.10 Expected Horizontal Error / Quality Factor

The MEOLUT shall produce an Expected Horizontal Error for every independent location. The Expected Horizontal Error is the radius of the circle that is centred on the estimated location and contains the true location with a probability of 95 ± 2 %.

The MEOLUT shall produce a Quality Factor (QF) derived from the Expected Horizontal Error as per Table 2, which also provides the mapping with a Confidence Factor (CF) for information.

Table 5.1: Quality Factor

Quality Factor (QF)	Expected Horizontal Error		Confidence Factor (CF)	CF Radius
11	xx ≤ 0.05 NM		5	1 NM
10	0.05 NM < xx ≤ 0.1 NM			
9	0.1 NM < xx ≤ 0.25 NM			
8	0.25 NM < xx ≤ 0.5 NM			
7	0.5 NM < xx ≤ 1 NM			
6	1 NM < xx ≤ 2.7 NM		4	5 NM
5	2.7 NM < xx ≤ 5 NM			
4	5 NM < xx ≤ 10 NM		3	20 NM
3	10 NM < xx ≤ 20 NM			
2	20 NM < xx ≤ 50 NM		2	50 NM
1	xx > 50 NM		1	> 50 NM

As an example, the Expected Horizontal Error can be calculated from the horizontal JDOP model. A JDOP definition is provided at Annex J or can also be derived from the general formula presented below:

$$JDOP = \sqrt{Tr\big(G(1,1) + G(2,2)\big)}$$

With the matrix G defined as:

$$G = M^T.(H^T.R^{-1}.H)^{-1}.M$$

With:

- M: transformation matrix between the ECEF global frame and the ENU (East North Up) local frame,
- H: the matrix of partial derivatives of the measurement equations with respect to the position coordinates in ECEF coordinate system.
- R: the weighting matrix normalized with σ_{TOA}, $R = \begin{bmatrix} 1 & 0 & \cdots & \cdots & \cdots & 0 \\ 0 & 1 & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \frac{\sigma_{FOA}}{\sigma_{TOA}} & 0 \\ 0 & \cdots & \cdots & \cdots & 0 & \frac{\sigma_{FOA}}{\sigma_{TOA}} \end{bmatrix}$

Finally, the Expected Horizontal Error with a 95% probability can be defined by:

$$Expected\ Horizontal\ Error = 2 \times JDOP \times \sigma_{TOA}$$

With σ_{TOA} expressed in NM.

5.11 Processing Anomaly Rate

A processing anomaly is an alert message produced by the MEOLUT, which should not have been generated, or which provided incorrect information. The ratio of MEOLUT processing anomalies to actual alerts shall not exceed 1×10^{-4}.

- END OF SECTION 5 -

ANNEX A

DESIGN GUIDELINES FOR DETERMINING THE LINK POWER BUDGET FOR MEOSAR SYSTEMS

A.1 Introduction

Administrations intending to acquire a Local User Terminal (LUT) to be used in the Cospas-Sarsat MEOSAR system should ensure that the station's antenna and RF subsystems will meet the Cospas-Sarsat performance standards defined in documents C/S T.019 (MEOLUT Performance Specification and Design Guidelines) and C/S T.020 (MEOLUT Commissioning Standard). MEOLUTs will need to be able to receive the downlink signal from any Cospas-Sarsat MEOSAR satellite as described in document C/S T.016 (Description of the 406 MHz Payload Used in the Cospas-Sarsat MEOSAR System). As such, a link budget analysis is necessary. In this annex an uplink and downlink budget is provided. This annex provides guidance for making these calculations for all MEOSAR satellites.

A.2 Explanation of the Uplink Link Budget

When doing a link budget of a satellite communication system, one needs to ensure that the signal originating from the ground can reach and be relayed by the satellite. For beacons, the accepted antenna designs and beacon specifications as per document C/S T.001 should be used in this calculation. As well, the provided receiver properties as per document C/S T.016 should be used at the satellite receive side. Administrations should consider the following when calculating a 406 MHz beacon signal up link budget:

propagation (free space) loss	=
ionoshperic fading loss	=
rain fall / atmospheric attenuation	=
antenna polarization mismatch	=
beacon antenna pointing loss	=
other localised losses	=
TOTAL LOSSES (L_o)	=

The uplink budget is used in the calculation of the overall system (C/N_o) which is the actual energy the MEOLUT will detect and use to process the messages. If the actual overall C/N_o is larger than the required C/N_o, which is derived from the E_b/N_o requirements, then there is a positive link margin, which gives a very good probability for a beacon signal to be properly decoded.

It should be noted that, at various times during a satellite pass, transient signal activity in the uplink channels, including interference from all ground sources such as radars, can cause the satellite repeaters to supress their gain (so the receive Low Noise Amplifier is not saturated) signals up to 30 dB for periods of 10s to 100s of milliseconds, increasing bit errors within the message and/or deteriorating beacon signal detection rates.

A.3 Explanation of the Downlink Budget Calculation

In contrast with LEOSAR, the MEOSAR repeaters do not perform any type of decoding or baseband manipulation of the received signals. It simply receives all signals within the individual constellation satellites passband (approximately 90 kHz, see details for each constellation in document C/S T.016). It then down converts and conditions the signal to reduce intermodulation products, and then finally up converts to a downlink signal (centre frequencies for each constellation are provided in document C/S T.016) for transmission back to the Earth. Therefore the onus of demodulation falls on the MEOLUT to demodulate what is a very close approximation, as repeated by the MEOSAR satellite, of the original beacon signal as described in document C/S T.001.

The Cospas-Sarsat signal is designed to provide reliable performance if the "bit error rate" (BER) received at the MEOLUT is better than $5x10^{-5}$. To ensure reliable reception of the downlink signal, an analysis should be made on the antenna and RF subsystems and the probable "bit error rate" computed. Such an analysis should include:

- the satellite transmit parameters (EIRP, antenna gain, etc.),
- power sharing losses,
- the geometry between the moving satellite and the MEOLUT, the MEOLUT location, local environment (e.g., site conditions, meteorological and ionospheric effects, noise and interference sources, etc.),
- the MEOLUT receive and processing characteristics (e.g., antenna, radome, RF system, receiver, bit synchronizer, modem implementation and data modulation losses, etc.).

Administrations should also consider the following atmospheric and design dependent losses and determine appropriate values for their MEOLUT design and specific site location.

propagation (free space) loss	=
atmospheric absorption	=
ionospheric fading loss	=
excess rain fall attenuation	=
antenna polarization mismatch	=
terminal antenna pointing loss	=
other localised losses	=
TOTAL LOSSES (L_o)	=

A.5 Calculations

Table A.1 is a detailed link budget analysis that looks at the energy-per-bit-to-noise-density ratio (E_b/N_0) of an individual beacon message (i.e., the primary factor governing the BER of the data) received by the MEOLUT via the satellite. It also provides indicative values for some of the parameters described in sections A2 and A3 for calculating the system link power budget and link margin.

E_b/N_0 can be calculated using the following equation[2]:

$$(E_b/N_0)_c = (EIRP) - (FSL) - (L_f + L_o) + (G/T) - (k) - (r) + (CG) \text{ dB}$$

where:

- EIRP Equivalent Isotropic Radiated Power
- FSL Free Space Loss
- Lf: Fading and other ionospheric losses
- Lo: Other LUT local losses (atmospheric/weather/noise), including modem, modulation processing implementation and modulation index losses
- k: Boltzmann constant
- r: data rate of message
- CG: Coding gain at LUT

Theoretically, a value of $(E_b/N_0)_{th}$ = 8.8 dB is necessary to achieve the required BER value of 5×10^{-5} in for a BPSK type signal*.

Solving the initial equation using values from Table A.1 shows that the difference between the calculated value $(E_b/N_0)_c$ and the theoretically required value $(E_b/N_0)_{th}$ is the link margin:

$$\text{Link Margin} = (E_b/N_0)_c - (E_b/N_0)_{th} = G/T - Lo + X_G$$

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2 For coherent detection of a biphase-phase-shift-keyed (BPSK) signal in a Gaussian noise channel, as defined in communications textbooks, such as Spilker, J.J., "Digital Communications by Satellite", Prentice-Hall Inc., New Jersey, USA, 1977, pp 31-32, (ISBN 0-13-214155-8), and Roger L. Freeman, “Telecommunication Transmission Handbook” "Principles of Coherent Communication", A Wiley Interscience Publication, New York, USA, 1991, pp. 430 and 434 (ISBN0-471-51816-6).

where X_G is the individual constellation difference value, which is different mostly due to path loss difference of different orbits, and repeater design.

However, to meet this link margin, one needs to calculate the overall carrier to noise ratio of the entire system from end to end ($(C/N_o)_{sys}$) since the MEOSAR satellites are analogue repeaters. As such[3]:

$(C/N_o)_{sys} = 1/ [(C/N_o)_{up}^{-1} + (C/N_o)_{dn}^{-1} + (C/N_o)_{im}^{-1}]$ (dB.Hz) where:

$(C/N_o)_{up}$: uplink carrier to noise ratio

$(C/N_o)_{dn}$: downlink carrier to noise ratio

$(C/N_o)_{im}$: intermodulation products carrier to noise ratio (or IM noise)

If the $(C/N_o)_{sys}$ is greater than the required C/N_o, which is derived from the calculated E_b/N_o and the data rate of the beacon signal, then the link margin is positive and the beacon message can be decoded with a high percentage of availability. This percentage of availability can range from 99 to 99.99% depending on the atmospheric, excess rain, and other local attenuation values (antenna elevation) chosen. Such values can be found in tabular format in various satellite and telecommunications text books[4].

A.6 Summary

From sections A2 to A4, administrations have two parameters that they can modify to ensure they can achieve a positive link margin: the LUT G/T (Antenna gain) and the local losses at the LUT (Lo). Administrations should ensure that their MEOLUT antenna G/T values, when combined with the other losses, will provide a positive value link margin. The excel sheets allow for such analysis for various values of losses that could be locally seen for all three MEOSAR constellations.

[3] Roger L. Freeman, “Telecommunication Transmission Handbook” "Principles of Coherent Communication", A Wiley Interscience Publication, New York, USA, 1991, sections 6.4.8 (pp. 383-388) and 6.8 (pp. 441-443) (ISBN0-471-51816-6).

[4] Roger L. Freeman, “Telecommunication Transmission Handbook” "Principles of Coherent Communication", A Wiley Interscience Publication, New York, USA, 1991, pp. 494-537 (ISBN0-471-51816-6).

Table A.1: Example of Downlink Power Budget Parameters for MEOSAR

Parameter	**Units**	**Galileo**	**Glonass**	**GPS**	**GPS /DASS**	**Source**
	Nominal					
Carrier frequency	(MHz)	1544.1	1544.9	1544.9	2226.3	C/S T.016
Polarization (circular)	(n/a)	LHCP	LHCP	RHCP	LHCP	C/S T.016
Minimum Elevation angle	(degrees)	5	5	5	5	C/S T.019
Satellite altitude	(km)	23620	19100	20200	20200	C/S T.016
Satellite transmit EIRP	(dB_W)	17.0	17.0	17.0	7.5	C/S T.016 / C/S T.017
Power sharing loss****	(dB)	10	10	10	10	C/S R.012
Beacon Satellite EIRP*	(dB_W)	7.0	7.0	7.0	-2.5	
Slant range (SR)@ 5 degrees	(km)	28760	24120	25250	25250	from geometry
Free-space path loss (FSL) @ SR	(dB)	185.4	183.9	184.3	187.4	standard formula
Fading loss (L_f)	(dB)	2.5	2.5	2.5	2.5	between -20 dB, and -0.5 dB
Other local to/and LUT losses (L_o)**	(dB)	L_o**	L_o**	L_o**	L_o**	LUT design/site dependent
Antenna (G/T)***	(dBK^{-1})	G/T	G/T	G/T	G/T	LUT design dependent
Boltzmann constant (k)	($dB_WK^{-1}Hz^{-1}$)	-228.6	-228.6	-228.6	-228.6	physical constant
Data rate factor @ 400bps (r)	(dBHz)	26.0	26.0	26.0	26.0	C/S T.001
Coding Gain (CG)	(dB)	2.0	2.0	2.0	2.0	BPSK BCH C/S T.001
Calculated $(E_b/N_0)_c$	(dB)	G/T-L_o+ 23.7	G/T-L_o+ 25.2	G/T-L_o+ 24.8	G/T-Lo+ 12.2	from above parameters
Desired maximum Bit Error Rate	(BER)	$5x10^{-5}$	$5x10^{-5}$	$5x10^{-5}$	$5x10^{-5}$	BPSK Signal
Theoretical $(E_b/N_0)_{th}$	(dB)	8.8	8.8	8.8	8.8	for desired maximum BER
Link Margin	(dB)	G/T-L_o+ 14.9	G/T-L_o+ 16.4	G/T-L_o+ 16.0	G/T-L_o+ 3.4	see text in section A.3

____

* Equivalent Isotropic Radiated Power per beacon signal, must include antenna gain and power sharing loss

** See factors in previous list (page A-3)

*** Antenna Gain-to-Noise Temperature Ratio, to include radome, if applicable, and cable losses

**** Power sharing loss assuming 8 total signals + 1 dB for noise.

END OF ANNEX A-

ANNEX B

BEACON MESSAGE PROCESSING INFORMATION

[Data to be provided]

- END OF ANNEX B -

ANNEX C

MEOLUT NETWORK ARCHITECTURE

This Annex illustrates the architectural concept for MEOLUT networking for the exchange of TOA/FOA data packets.

C.1 MEOLUT Network Topology

Network topology refers to the physical connectivity between MEOLUT sites: examples include mesh, star and ring configurations. The primary approach for exchanging data is a partial mesh topology, involving point-to-point connections between MEOLUTs, as necessary to provide connections to neighbouring MEOLUTs. Two optional approaches are also described.

C.1.1 Primary Partial Mesh Topology

The primary approach for exchanging data is a partial mesh topology, involving point-to-point connections between MEOLUTs, as necessary to provide connections to neighbouring MEOLUTs. Each MEOLUT providing TOA/FOA data using this approach will only provide its own local data to the receiving MEOLUT. This topology is illustrated in Figure C.1.

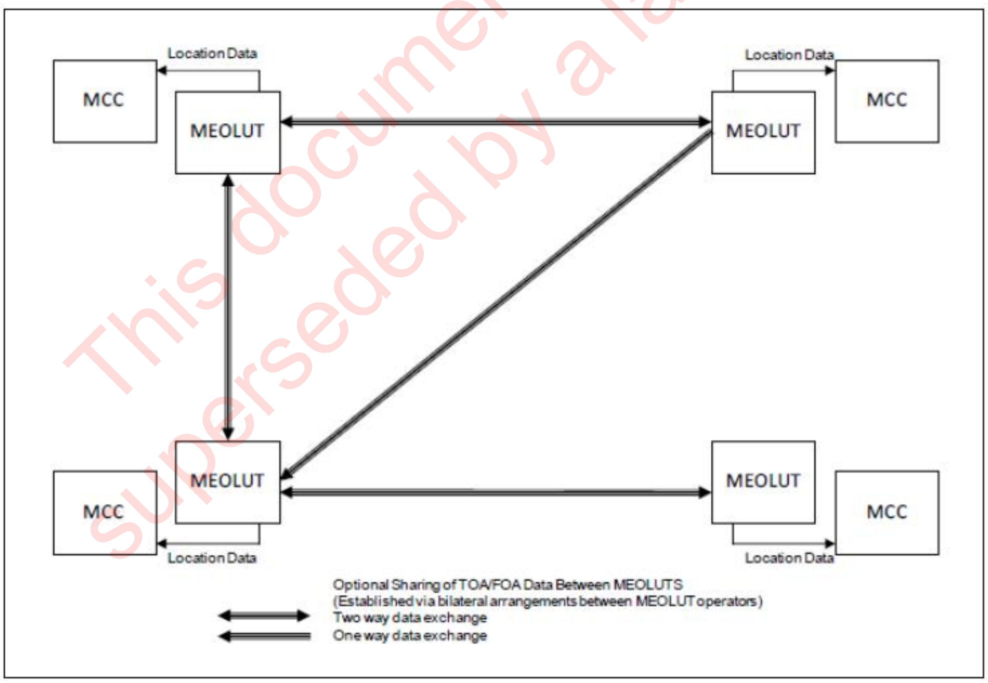


Figure C.1: Primary Topology for a MEOLUT Network: a Partial Mesh

C.1.2 Optional Data Forwarding Topology

As an option, some MEOLUT providers may want to share measurement data with all participating MEOLUTs while limiting the number of point to point connections. An example of this is a node forwarding methodology, in which the forwarding of data received from other MEOLUTs requires the preliminary step of the concatenation of the local MEOLUT data with all data coming from other MEOLUTs. Forwarded MEOLUT TOA/FOA data shall not be modified by the transit nodes. This topology is illustrated in Figure C.2.

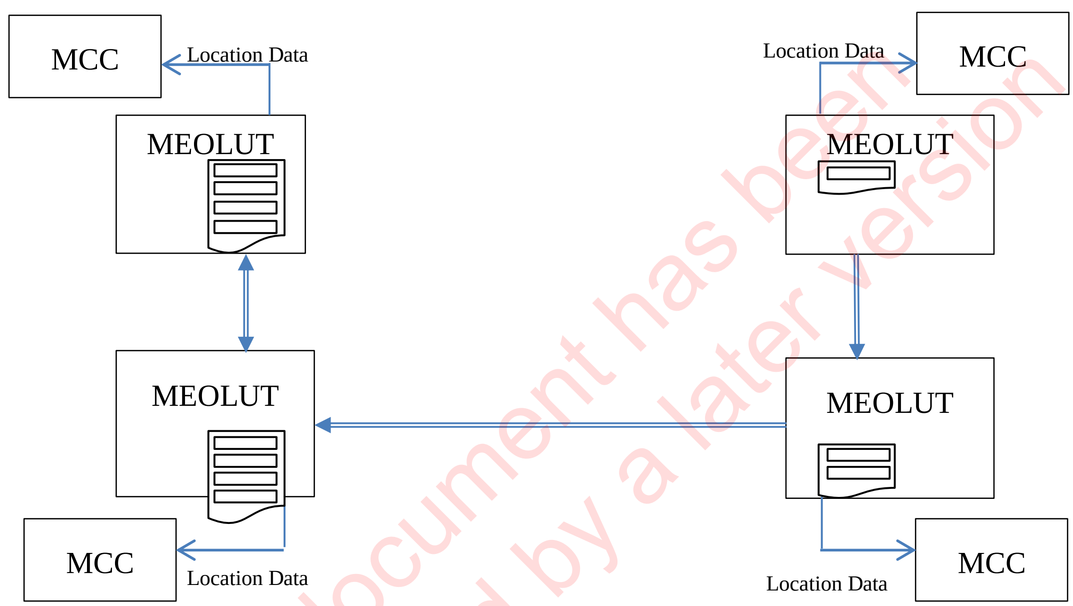


Figure C.2: Optional Node Forwarding Topology

C.1.3 Optional Central Data Server Node Topology

An optional MEOLUT Central Data Server could be implemented within the primary partial mesh topology of the MEOLUT network. MEOLUTs could store their data on the Central Data Server. MEOLUTs could then obtain data from the central data server as desired, as illustrated in Figure C.3.

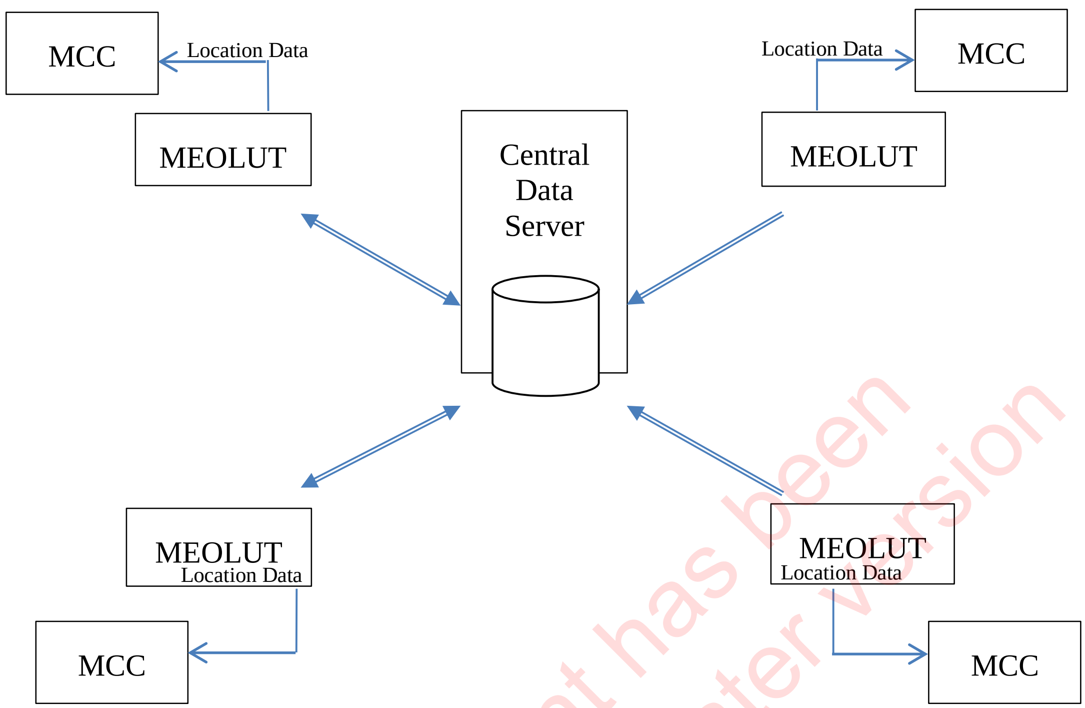


Figure C.3: Optional Central Data Server Topology

C.2 MEOLUT TOA/FOA Data Exchange

Sharing of MEOSAR TOA/FOA data is optional, determined by national requirements and arranged on a bilateral basis between MEOLUT operators. All TOA/FOA data shall include data content and be transferred in the data format specified in document C/S [A.002]. Data transfer shall use a secure form of FTP as per the specifications found in document C/S [A.002]. Using shared data for location processing is optional.

The following conventions shall apply to all TOA/FOA data shared between MEOLUTs:

- The exchanged files shall be limited to a maximum number of [2000] TOA/FOA data records (number to be implemented as a configurable value to allow possible future adjustments).
- Beyond the maximum number of records, the older records (based on TOA) shall be removed from the TOA/FOA data file to be exchanged.
- TOA/FOA data files shall be pushed every [60] seconds (periodicity to be implemented as a configurable value to allow possible future adjustment) by the MEOLUT to all linked MEOLUTs. No accurate time synchronization shall be required.
- Any possible duplicated TOA/FOA data records shall be removed, and not inserted into the exchange file.

- END OF ANNEX C -

ANNEX D

MEOLUT COVERAGE AREA

The coverage area of a stand-alone MEOLUT shall, at a minimum, be derived from the executed MEOLUT satellite pass tracking. Each possible beacon location within the MEOLUT coverage area shall meet the following geometrical beacon-satellite-MEOLUT conditions, with the following assumptions:

- a minimum MEOLUT-to-satellite elevation angle of 5 degrees,
- beacon-to-satellite elevation angle between 5 and 60 degrees (portion of antenna radiation pattern that is specified in document C/S T.001) unless the national administration demonstrates performance above 60 degrees measured from operational beacons,
- a minimum of three satellites in beacon-MEOLUT mutual visibility (i.e., within the above elevation conditions).

- END OF ANNEX D -

ANNEX E

OPTIONAL PROCESSING OF INTERFERENCE USING THE 406 MHZ REPEATER BAND

[TBC]

E.1 Introduction

This annex describes how the 406 MHz repeater system aboard some of the Cospas-Sarsat satellites can be used by MEOLUTs to perform interference monitoring of the 406 MHz band. The repeater can be used, only in the local-mode coverage area, to detect and locate 406 MHz interference in the 406 MHz band.

E.2 Functional Description

To detect and locate interfering signals in the 406 MHz band (i.e. non-beacon signals), the approach needed is different than for beacon signals because interferers do not transmit in the same format as a beacon signal. Interferers generally transmit continuous signals for several seconds, minutes, or even hours, compared to the one-half second burst of a beacon signal. Processing such interfering signals produces a long Doppler curve which can be used to compute the location. No identification code can be extracted from an interfering signal, since its modulation, if any, would not be in the correct format.

E.3 Operational Recommendations

406 MHz interference monitoring is encouraged for all MEOLUTs on a best effort basis. As much data as possible should be collected and recorded.

When a new 406 MHz interferer is detected on at least a few satellite passes, the MEOLUT/MCC operator is encouraged to inform the appropriate Search and Rescue authorities in the area of the interferer (i.e. locations and times) and to periodically report such interference to the ITU using national procedures and also to include such information in their annual status reports to Cospas-Sarsat. Detailed instructions for interference reporting are included in Cospas-Sarsat document C/S A.003.

E.4 Performance Specification

E.4.1 Processing Time

Additional processing of the 406 MHz repeater band shall not significantly affect the overall processing time of the PDS channels.

E.4.2 Location Accuracy

Under the following signal characteristics: a. linear frequency drift is less than forty (40) Hz per minute, and b. a minimum of four (4) minutes of data which includes the TCA, is received by the LEOLUT, the location accuracy should be better than twenty (20) km for at least seventy percent (70%) of the locations.

- END OF ANNEX E -

ANNEX F

JDOP DEFINITION

F.1 JDOP Implementation Algorithm

JDOP definition

JDOP is defined as the Horizontal Dilution of Precision using DOA observations assuming uncorrelated observations with identical standards deviations per observation type:

σ_{TOA} = 25 µs for all TOA observations, and

σ_{TOA} = 0.25 Hz for all FOA observations.

The following algorithm shall be used:

Let there be N MEOSAR satellites visible simultaneously at the beacon location and the participating MEOLUT(s) above an elevation angle of 5 degrees. Let these (ECEF) locations be denoted as:

$\{x_b, y_b, z_b\}$ and $\{\dot{x}_b, \dot{y}_b, \dot{z}_b\}$ the approx. position and velocity of the alert beacon

$\{x_i, y_i, z_i\}$ and $\{\dot{x}_i, \dot{y}_i, \dot{z}_i\}$ the approx. position and velocity of satellite *i* (*i* =1,..,N).

The linearized observation equations can then be written as

$$\begin{bmatrix} \Delta R_i \\ \Delta \dot{R}_i \end{bmatrix} = \begin{bmatrix} H_{TDOA} \\ H_{FDOA} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = \begin{bmatrix} \alpha_i - \alpha_{ref} & \beta_i - \beta_{ref} & \gamma_i - \gamma_{ref} \\ \dot{\alpha}_i - \dot{\alpha}_{ref} & \dot{\beta}_i - \dot{\beta}_{ref} & \dot{\gamma}_i - \dot{\gamma}_{ref} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \qquad (1)$$

where

$$\begin{aligned} \alpha_i &= \frac{\partial R_i}{\partial x_b} = -x_{bi} & \dot{\alpha}_i &= \frac{\partial \dot{R}_i}{\partial x_b} = x_{bi}\left[x_{bi}\,\dot{x}_{bi} + y_{bi}\,\dot{y}_{bi} + z_{bi}\,\dot{z}_{bi}\right] - \dot{x}_{bi} \\ \beta_i &= \frac{\partial R_i}{\partial y_b} = -y_{bi} & \dot{\beta}_i &= \frac{\partial \dot{R}_i}{\partial y_b} = y_{bi}\left[x_{bi}\,\dot{x}_{bi} + y_{bi}\,\dot{y}_{bi} + z_{bi}\,\dot{z}_{bi}\right] - \dot{y}_{bi} \\ \gamma_i &= \frac{\partial R_i}{\partial z_b} = -z_{bi} & \dot{\gamma}_i &= \frac{\partial \dot{R}_i}{\partial z_b} = z_{bi}\left[x_{bi}\,\dot{x}_{bi} + y_{bi}\,\dot{y}_{bi} + z_{bi}\,\dot{z}_{bi}\right] - \dot{z}_{bi} \end{aligned} \qquad (2)$$

with the coordinate and velocity differences

$$\begin{aligned} x_{bi} &= (x_i - x_b)/R_i \\ y_{bi} &= (y_i - y_b)/R_i \\ z_{bi} &= (z_i - z_b)/R_i \end{aligned} \quad \text{and} \quad \begin{aligned} \dot{x}_{bi} &= (\dot{x}_i - \dot{x}_b)/R_i \\ \dot{y}_{bi} &= (\dot{y}_i - \dot{y}_b)/R_i \\ \dot{z}_{bi} &= (\dot{z}_i - \dot{z}_b)/R_i \end{aligned} \tag{3}$$

with $R_i = \sqrt{(x_i - x_b)^2 + (y_i - y_b)^2 + (z_i - z_b)^2}$ (4)

The subscript "ref" in equation (1) refers to the reference satellite, relative to which all DOA observations are build.

If there are N pairs of DOA observations available, the left hand side is a [2N×1] matrix, where ΔR_i is the [N×1] sub-matrix with the linearized TDOA observations converted from seconds to meter, and $\Delta \dot{R}_i$ is the [N×1] sub-matrix with the linearized FDOA observations converted from Hz to m/s.

$$\begin{aligned} \Delta R_i &= (TOA_i - TOA_{ref})\, c \\ \Delta \dot{R}_i &= (FOA_i - FOA_{ref}) \frac{c}{f_b} \end{aligned} \tag{5}$$

with f_b, the beacon transmission frequency, and c the speed of light.

The matrix at the right contains the 3 beacon position unknowns, where the first two elements represent the horizontal position and the third one the vertical position (e.g. Δx, Δy and Δz could point to the East, North and zenith respectively).

For the DOP concept, all observations are assumed to be uncorrelated and have identical standards deviations per observation type, i.e., σ_{TDOA} for all TDOA observations, and σ_{FDOA} for all FDOA observations. The variance-covariance matrix of the linearized observations, C_{DOA}, is then given by

$$C_{DOA} = \begin{bmatrix} C_{TDOA} & 0 \\ 0 & C_{FDOA} \end{bmatrix} = \begin{bmatrix} \sigma_{TDOA}^2 \cdot I & 0 \\ 0 & \sigma_{FDOA}^2 \cdot I \end{bmatrix} = \begin{bmatrix} 2\sigma_{TOA}^2 \cdot I & 0 \\ 0 & 2\sigma_{FOA}^2 \cdot I \end{bmatrix} \tag{6}$$

And the variance-covariance matrix of the unknowns, G, is given by

$$G = \left(\frac{1}{2} \sigma_{TOA}^{-2} \; H_{TDOA}^T H_{TDOA} + \frac{1}{2} \sigma_{FOA}^{-2} \; H_{FDOA}^T H_{FDOA} \right)^{-1} \tag{7}$$

In analogy to the HDOP concept in GNSS, the standard deviation of the estimated horizontal location can be given as the trace of the matrix G:

$$\sigma_{HorzPos} = \sqrt{G_{11} + G_{22}} \tag{8}$$

In contrast to the DOP concept in GNSS, here the contribution of the beacon-satellite geometry cannot be separated from the measurement accuracy as two different observation types have been used. Therefore the auxiliary matrix G' is defined by

$$G' = \frac{1}{2}\sigma_{TOA}^{-2}\, G = \left(H_{TDOA}^{T} H_{TDOA} + \frac{\sigma_{TOA}^{2}}{\sigma_{FOA}^{2}} H_{FDOA}^{T} H_{FDOA} \right)^{-1} \qquad (9)$$

and JDOP is then given as

$$JDOP = \sqrt{G'_{11} + G'_{22}} \qquad (10)$$

The expected standard deviation for the estimated horizontal location is given by

$$\sigma_{HorzPos} = \sqrt{2}\, \sigma_{TOA} \times JDOP \qquad (11)$$

Some closing remarks:

1. The definition of G' in equation (9) contains a multiplication factor based on the variances of the TOA and FOA measurements. These variances must be given in meter and meter/second respectively. With the proposed values of 25 µsec and 0.25 Hz, the multiplication factor is thus equal to

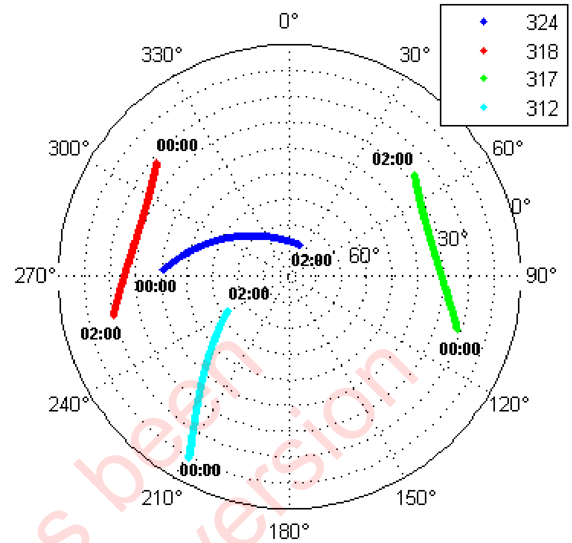
$$\frac{\sigma_{TOA}^{2}}{\sigma_{FOA}^{2}} = \left(\frac{25\,\mu\text{sec}}{0.25\,\text{Hz}} \cdot \frac{c}{c/f_b} \right)^{2} = \left(10^{-4}\,\text{s}^{2} \cdot f_b\right)^{2} = \left(40600\,\text{s}\right)^{2}$$

   taking f_b = 406.05 MHz, the middle of the C/S frequency band.

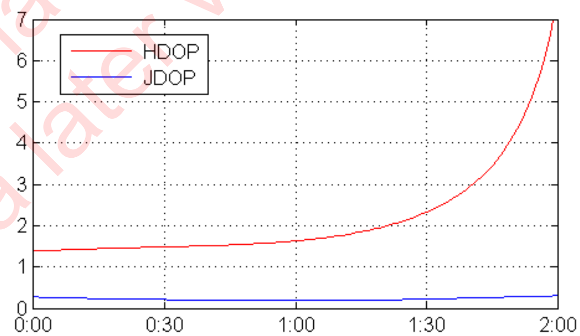
2. The achievable JDOP is dependent not only on the beacon and satellite positions, but also on the MEOLUT(s) position. Only satellites that are both visible at the beacon and MEOLUT(s) should be taken into consideration for the JDOP computation.
3. JDOP is also dependent on the number of available antennas at the MEOLUT(s). Only satellites that can actually be tracked should be taken into consideration. E.g., for a stand-alone MEOLUT with four antennas, the maximum number of satellites can be four at most. If more satellites could be tracked, i.e., if more satellites are visible both at the MEOLUT and beacon, the JDOP algorithm should determine the minimum JDOP out of all potential combination of satellites. If the JDOP is used to characterize an actual test situation, then of course only the satellites that are involved in the test should be taken into consideration when computing JDOP.
4. Also, regarding the choice of the reference satellite with respect to which the DOA observations are built, all satellites out of the N satellites should be evaluated as reference and the one giving minimum JDOP should be chosen.
5. The minimum elevation angle of 5 degrees is in line with document C/S R.012, Annex N.

F.2 JDOP Compared to HDOP

Here JDOP and the classical HDOP are compared in an example with 4 DASS satellites simultaneous observed by an alert beacon and MEOLUT, both in Toulouse, see the sky plot to the right.



The figure beneath shows the resulting values for the classical HDOP and MEOSAR JDOP.



Towards 02:00, HDOP increases rapidly due to the near alignment of all four satellites and the beacon in a single plane. If only HDOP is considered, one could interpret this an unfavourable time for a MEOSAR localization. The JDOP however shows only a slight increase towards the end of the evaluated epoch, indicating that a localization is still feasible with a good accuracy.

The table below shows some values for the JDOP, which is between 0.19 and 0.30 during this time-span. The expected standard deviation of the horizontal location can be estimated as

$$\begin{aligned} \sigma_{HorzPos} &= JDOP \cdot \sqrt{2}\ \sigma_{TOA} \\ &= JDOP \cdot \sqrt{2} \cdot \ [25\,\mu s] \cdot c \\ &= JDOP \cdot 10.6 \quad [km] \end{aligned}$$

The location accuracy with a 95% confidence level is equal to 2.4477 $\sigma_{HorzPos}$.

time	JDOP	$\sigma_{HorzPos}$	95%
00:00	0.275	2.9 km	7.1 km
01:00	0.187	2.0 km	4.9 km
02:00	0.303	3.2 km	7.9 km

F.3 Numerical Example for JDOP Computation

This attachment provides a numerical example for all steps in the JDOP computation. For this example, the beacon-satellite constellation from section N.2 will be evaluated at epoch 01:00.

The approximate beacon position in ellipsoidal WGS-84 coordinates is given as:

φ_b [deg]	λ_b [deg]	h_b [m]
43.55896	1.48373	144.0

Approximate beacon position in ECEF coordinates [m]:

x_b	y_b	z_b	$\dot{x}_b$	$\dot{y}_b$	$\dot{z}_b$
4627932.896	119871.625	4372810.338	0.0	0.0	0.0

Satellite position in ECEF coordinates [m]:

i	x_i	y_i	z_i	$\dot{x}_i$	$\dot{y}_i$	$\dot{z}_i$
1	14473971.955	-7832995.284	20830145.566	131.653767	2646.645504	907.553640
2	9491732.521	-19294589.707	15760160.626	1821.654768	-757.320984	-2113.407054
3	10794083.534	19129385.521	15316333.557	-1703.556362	-849.593981	2271.346027
4	23929166.460	-10809572.853	3090142.279	-240.428338	388.774588	3207.984673

Satellite position relative to beacon position in ECEF coordinates [m]:

i	$x_i - x_b$	$y_i - y_b$	$z_i - z_b$	$\dot{x}_i - \dot{x}_b$	$\dot{y}_i - \dot{y}_b$	$\dot{z}_i - \dot{z}_b$
1	9846039.059	-7952866.909	16457335.228	131.653767	2646.645504	907.553640
2	4863799.625	-19414461.332	11387350.288	1821.654768	-757.320984	-2113.407054
3	6166150.638	19009513.896	10943523.219	-1703.556362	-849.593981	2271.346027
4	19301233.564	-10929444.478	-1282668.059	-240.428338	388.774588	3207.984673

Satellite position relative to beacon position in ECEF coordinates (normalized):

i	x_{bi}	y_{bi}	z_{bi}	$\dot{x}_{bi}$	$\dot{y}_{bi}$	$\dot{z}_{bi}$
1	0.4742469545	-0.3830599176	0.7926884165	0.000006341271	0.000127479036	0.000043713472
2	0.2112202242	-0.8431118038	0.4945184559	0.000079109001	-0.000032888178	-0.000091778927
3	0.2706265010	0.8343095287	0.4803008509	-0.000074767472	-0.000037287874	0.000099687222
4	0.8687240104	-0.4919204157	-0.0577312604	-0.000010821374	0.000017498250	0.000144387316

Derivative of range R and range-rate Ṙ with respect to the beacon position in ECEF directions:

i	$\partial R_i/\partial x_b$	$\partial R_i/\partial y_b$	$\partial R_i/\partial z_b$	$\partial \dot{R}_i/\partial x_b$	$\partial \dot{R}_i/\partial y_b$	$\partial \dot{R}_i/\partial z_b$
1	-0.4742469545	0.3830599176	-0.7926884165	-0.000011640325	-0.000123198871	-0.000052570669
2	-0.2112202242	0.8431118038	-0.4945184559	-0.000079309352	0.000033687904	0.000091309856
3	-0.2706265010	-0.8343095287	-0.4803008508	0.000073830068	0.000034397967	-0.000101350903
4	-0.8687240104	0.4919204157	0.0577312604	-0.000012064461	-0.000004539003	-0.000142866432

Derivative of range R and range-rate Ṙ with respect to the beacon position in local topocentric directions {East, North, Zenith}:

i	$\alpha_i=\partial R_i/\partial x_b$	$\beta_i=\partial R_i/\partial y_b$	$\gamma_i=\partial R_i/\partial z_b$	$\dot{\alpha}_i=\partial \dot{R}_i/\partial x_b$	$\dot{\beta}_i=\partial \dot{R}_i/\partial y_b$	$\dot{\gamma}_i=\partial \dot{R}_i/\partial z_b$
1	0.3952111986	-0.2545746564	-0.8826096831	-0.000122856161	-0.000027879262	-0.000046970680
2	0.8482982656	-0.2279009305	-0.4779657085	0.000035730173	0.000120201826	0.000006100303
3	-0.8270224462	-0.1467446168	-0.5426784416	0.000032474746	-0.000124918568	-0.000015711361
4	0.5142494235	0.6314961269	-0.5803104101	-0.000004225095	-0.000095138564	-0.000107274291

where the rotation matrix from ECEF to the local topocentric coordinate frame at the beacon position is given by

$$R = \begin{pmatrix} -\sin\lambda_b & \cos\lambda_b & 0 \\ -\sin\varphi_b\cos\lambda_b & -\sin\varphi_b\sin\lambda_b & \cos\varphi_b \\ \cos\varphi_b\cos\lambda_b & \cos\varphi_b\sin\lambda_b & \sin\varphi_b \end{pmatrix}$$

$$= \begin{pmatrix} -0.025893079495 & 0.999664718010 & 0 \\ -0.688869611749 & -0.017842938034 & 0.724665638465 \\ 0.724422671127 & 0.018763824984 & 0.689100654787 \end{pmatrix}$$

Now the JDOP is computed for all choices of reference satellite. For *ref* = 1, the values are

$$H_{TDOA} = \begin{bmatrix} \alpha_2 - \alpha_{ref=1} & \beta_2 - \beta_{ref=1} & \gamma_2 - \gamma_{ref=1} \\ \alpha_3 - \alpha_{ref=1} & \beta_3 - \beta_{ref=1} & \gamma_3 - \gamma_{ref=1} \\ \alpha_4 - \alpha_{ref=1} & \beta_4 - \beta_{ref=1} & \gamma_4 - \gamma_{ref=1} \end{bmatrix} = \begin{bmatrix} 0.453087067 & 0.026673726 & 0.404643975 \\ -1.222233645 & 0.107830040 & 0.339931242 \\ 0.119038225 & 0.886070783 & 0.302299273 \end{bmatrix}$$

$$H_{FDOA} = \begin{bmatrix} \dot\alpha_2 - \dot\alpha_{ref=1} & \dot\beta_2 - \dot\beta_{ref=1} & \dot\gamma_2 - \dot\gamma_{ref=1} \\ \dot\alpha_3 - \dot\alpha_{ref=1} & \dot\beta_3 - \dot\beta_{ref=1} & \dot\gamma_3 - \dot\gamma_{ref=1} \\ \dot\alpha_4 - \dot\alpha_{ref=1} & \dot\beta_4 - \dot\beta_{ref=1} & \dot\gamma_4 - \dot\gamma_{ref=1} \end{bmatrix} = \begin{bmatrix} 0.000158586 & 0.000148081 & 0.000053071 \\ 0.000155331 & -0.000097039 & 0.000031259 \\ 0.000118631 & -0.000067259 & -0.000060304 \end{bmatrix}$$

$$G' = \left(H_{TDOA}^T H_{TDOA} + \frac{\sigma_{TOA}^2}{\sigma_{FOA}^2} H_{FDOA}^T H_{FDOA} \right)^{-1} = \begin{bmatrix} 0.010467671 & 0.002734429 & -0.011444031 \\ 0.002734429 & 0.024406890 & -0.031069667 \\ -0.011444031 & -0.031069667 & 0.125022699 \end{bmatrix}$$

with $\frac{\sigma_{TOA}^2}{\sigma_{FOA}^2} = \left(\frac{25\,\mu\text{sec}}{0.25\,\text{Hz}} \cdot \frac{c}{c/f_b} \right)^2 = \left(10^{-4}\ \text{s}^2 \cdot f_b\right)^2 = 40605^2$,

$$\begin{aligned} JDOP_{ref=1} &= \sqrt{G'_{11} + G'_{22}} \\ &= \sqrt{0.010467671 + 0.024406890} \\ &= 0.186747317 \end{aligned}$$

The computation of H_{TDOA}, H_{TDOA}, *G'* and *JDOP* is repeated for *ref*=2, 3 and 4; this results in four JDOP values, one for each choice of reference satellite:

ref = 1: $JDOP_{ref=1}$ = 0.186747317
ref = 2: $JDOP_{ref=2}$ = 0.220439416
ref = 3: $JDOP_{ref=3}$ = 0.201995322
ref = 4: $JDOP_{ref=4}$ = 0.237619737

The final JDOP value is then the minimum of these four values:

JDOP = min($JDOP_{ref=i}$) = 0.186747317

- END OF ANNEX F -

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