www.csem.ch • info@csem.ch

ESTEC/Contract No. 4000107142/12/NL/AK

Ultra-wideband as a multi-purpose robust and reliable wireless technology for testing, spacecraft and launcher communications

TN 7.2 Executive Summary

A study performed by:

and

CSEM SA
www.csem.ch

Jaquet-Droz 1
Case Postale
CH-2007 Neuchâtel

T +41 32 720 5111
F +41 32 720 5700
info@csem.ch

Authors

Prepared by	Date	Signature
Ph. Dallemagne	08.12.2014	

Document Change Record

Issue	Date	Comments
0.2	08.12.2014	First draft.

Distribution List

Name	Organisation	Copies
Jean-François Dufour	ESA-ESTEC	1 electronic copy
Patrice Pelissou	ADS	1 electronic copy

Abbreviations

BER	Bit Error Rate
FEC	Forward Error Correction
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
MAC	Medium Access control layer (OSI model)
Mbps	Megabits per seconds (aka. Mbit/s)
OSI	Open Systems Interconnection
PAN	Personal Area Network
PHY	Physical layer (OSI model)
RF	Radio Frequency
RTU	Remote Terminal Unit
SAN	Spacecraft Area Network
SN	Sensor Node
SNR	Signal to Noise Ratio
TBC	To Be Confirmed
TDMA	Time Division Multiple Access
UWB	Ultra-Wideband
UCS	UWB-based Communication System
WDC	Coordinator Node
WSN	Wireless sensor network

Table of Contents

1 Foreword and introduction

1.1 Objective of the document

The objective of this document is to give an overview of the objectives of the project, its challenges, the encountered difficulties, the solved problems, the remaining issues and the roadmap to a general solution.

1.2 Structure of the document

The document is divided into 4 chapters followed by an Appendix.

The first chapter introduces the document. The second chapter describes the project. The third chapter describes the principle of the UWB4SAT system, including the protocol. The fourth chapter gives the potential roadmap to a UWB4SAT system that can be used in the target applications.

2 The UWB4SAT project

2.1 Introduction

The UWB4SAT project has been proposed in response to the European Space Agency (ESA) invitation to tender ITT/AO/1-7206/12/NL/AK - Ultra-wideband as a multi-purpose robust and reliable wireless technology for testing, spacecraft and launcher communications.

The objectives of this 18-month project were to:

- evaluate the potential of UWB-based communication technologies with respect to the wireless communication within satellites and to the interconnection with other cabled communication systems, such as Spacewire and AFDX,
- Based on the supposedly positive assessment of the UWB technology, a communication system will be designed and prototyped in order to verify the results of the first phase, both from a theoretical point of view as well as through empirical measurement of the developed system.

Beyond the statement of work published by ESA, the UWB4SAT project is also built from the requirements expressed by an end user (Airbus Defence and Space), the study of the state-of-the-art UWB physical layers available for data transmission and the state-of-the-art in protocols and wireless propagation simulation.

The ultimate objective of the project is to draw conclusions about the potential of ultra-wide band wireless technology in the context of the satellite (see Figure 1). Therefore it was necessary to develop a UWB system (radio, CPU, interfaces, protocol, scheduling, etc.) and to define the metrics, to translate the application requirements into technical requirements and to develop the test suites that will assess the UWB4SAT system with respect to the selected metrics.

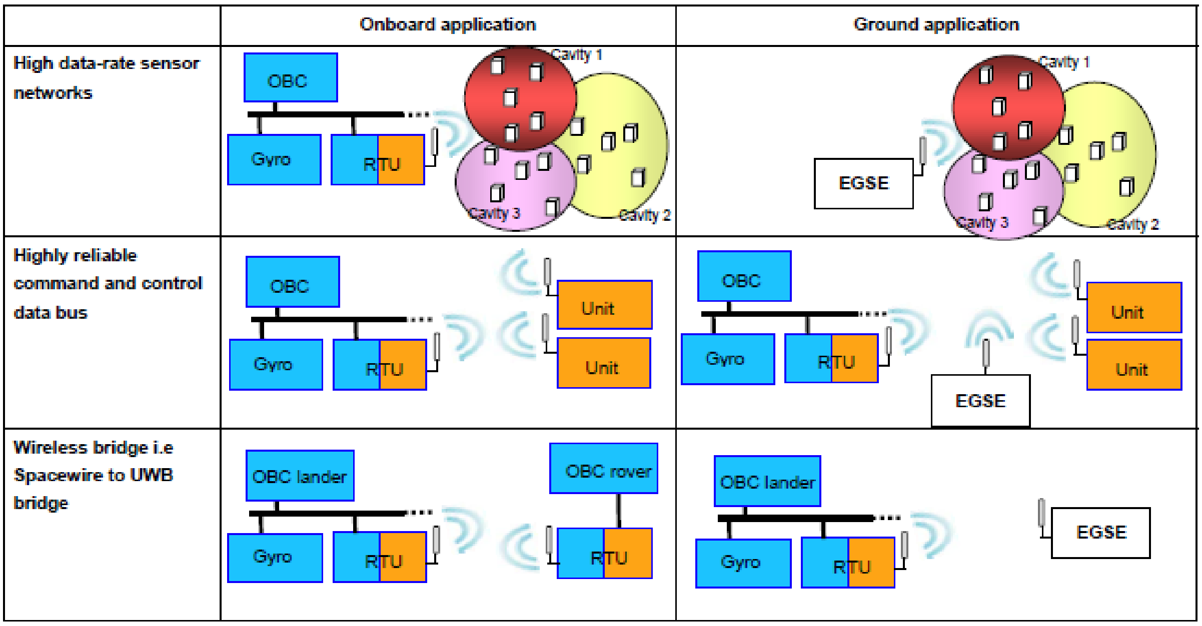


Figure 1 - Configurations for the 3 use cases (reprinted from TN1.1)

The UWB4SAT therefore delivered results in many domains:

- The satellite application requirements;
- The analysis of the existing solutions and standards;
- The design and building of a hardware platform;
- The design and development of a protocol;
- The design and development of the test suites;
- The analysis of the test results, conclusion and recommendation for the next steps towards communication in satellite.

The UWB4SAT system is made of hardware, software and its documentation.

2.2 Deviations from the Statement of Work

The following deviations have been identified and justified:

- A number of points have been described in a document different than the one that was initially planned. A few points have not been done. Such deviations are listed hereafter.
- Reliability analysis is absent from the current Technical Notes, since the precise hardware components that will be used on the actual installations is not known at this stage. Moreover, the reliability characteristics of the Decawave UWB transceiver (one of the central components) are not known, which preclude the evaluation of the global reliability of a node or the complete UCS.
- For the same reasons, the description of the mechanical characteristics of an installed node and its mechanical interfaces (attachments, fixtures, etc.) is not given at this stage.

- Trade-offs are listed and discussed in the Deliverable TN 4.3 [7]
- The bridge application has not been considered for the test, given the limited data rate of the Decawave DW1000 chip. However, in order to prepare for the support of such application by a future release of the chip, an analysis of the performance and bottlenecks of the DW1000 has been done and corrective actions are suggested in the final activity report.

3 The UWB4SAT system

3.1 System architecture

3.1.1 Design choices

The design of the UWB4SAT communication system reuses the IEEE 802.15.4 IR-UWB physical layer [9] and the Decawave board that implements it. The MAC protocol follows one on the options of IEEE 802.15.4e [12], LLDN, with some restrictions and some adjunctions notably in terms of low-power modes. To support the S/C communication needs, two upper layers, one for management and one for data transfer, have been defined.

The possible options to support the mission requirements have been analysed. One of the IEEE 802.15.4e options, namely LLDN, seems a good candidate for the steady operations because of its performances and its flexible handling of transmission errors. However, some of the requirements may only be met using two different IR-UWB networks with LLDN. One of the requirements, the UC1 latency constraint, cannot be met at all with IEEE 802.15.4 IR-UWB because of the long preambles.

3.1.2 Architecture

The general architecture of the UWB4SAT Communication system is illustrated in Figure 9.

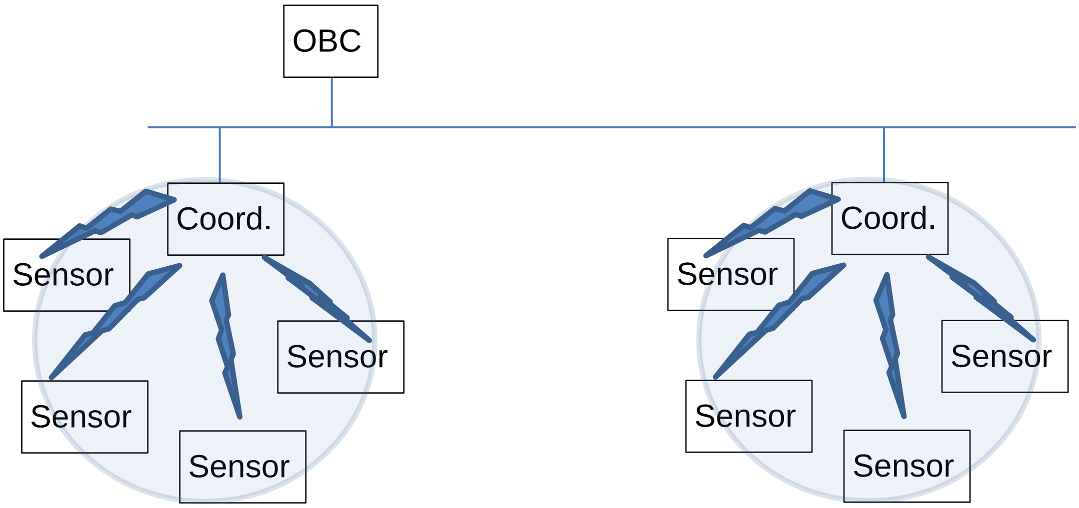


Figure 2: Network architecture for high data rate sensor scenario

The topology of the UCS is a star. Several UCS can coexist in the same environment. They can be connected to a single OBC to address different applications or combine their capacity to fulfil the application requirements.

3.2 Hardware: coordinator and node

The UWB4SAT nodes are based on a development kit that serves as the development and validation platform: a UWB development board (Decawave EVB1000) hosts all the protocols and application software and implements the IR-UWB physical layer. It is used both for all variations of the UWB4SAT nodes: sensor nodes and Coordinator nodes (and Bridge nodes that are physically identical to Coordinators), which are schematically represented in Figure 3 and Figure 4.

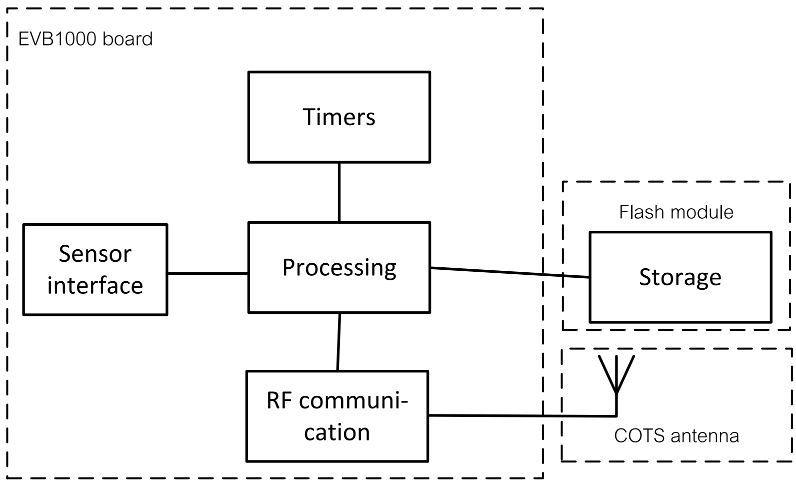


Figure 3: Sensor Node physical architecture

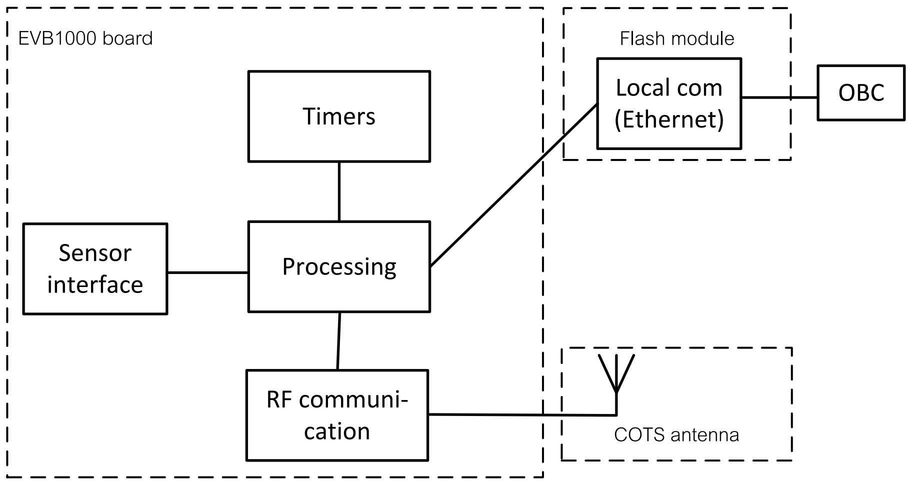


Figure 4: Coordinator Node physical architecture

The Coordinator and the Bridge nodes also include an Ethernet interface (see Figure 5, Figure 6 and Figure 7).

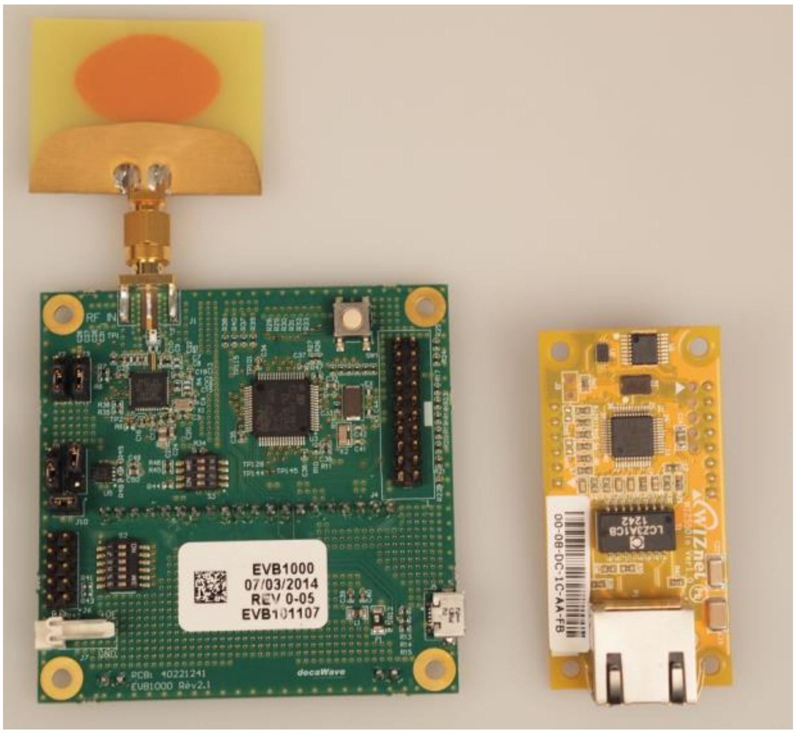


Figure 5 - The two development kits involved in the UWB4SAT Coordinator and Bridge nodes

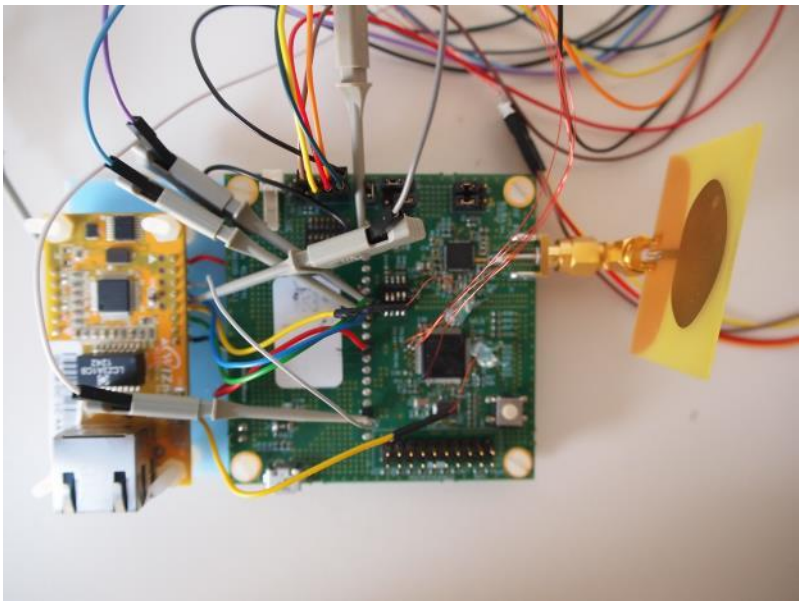


Figure 6 - The two development kits of the UWB4SAT Coordinator, assembled and wired on the lab test bench

Figure 7: the master in its casing

Figure 8: a sensor node in its casing

3.3 The UWB4SAT protocol

The UWB4SAT protocol is based on a TDMA medium access control. The protocol is described in details in TN5.4 [7].

3.3.1 Overview

The protocol used for the synchronisation uses a TDMA approach. The basic parameters of the protocol are discussed hereafter.

The slot duration is currently to 1 ms. The minimum slot duration with the current hardware is 200 us. 250 us should be used as the theoretical minimum slot duration for robustness reason, thus the maximum number of slots per second is 4000.

The protocol supports in principle as many nodes as necessary. However, 5 nodes are delivered for the purpose of the test, up to 10 are supported in the current configuration and more nodes can be supported after applying different parameters to the implemented protocol. As a matter of fact, having 5, ten or more nodes in the test network would lead to the same behaviour and results.

The actual beacon duration is less than 1 ms. The beacon gives the necessary information to the sensor node for them to know when to send their data; the beacon sends a slot assignment vector. A sensor node shall not send packets which may exceed the duration of their assigned slot, i.e. 1 ms.

The structure of the cycle is illustrated below:

Beacon	SN21	SN22	SN23	SN24	SN25	empty or retransmissions	…
1 ms	1 ms	1 ms	1 ms	1 ms	1 ms	4 ms	

Figure 9: UWB4SAT TDMA cycle

The TDMA cycle lasts for 10 ms in the test configuration.

3.3.2 Tests in lab and on satellite mock-up

The tests of the UWB4SAT systems have been done primarily at Airbus Defence and Space and at secondarily at CSEM. All tests performed aimed at the evaluation of the ability of the Decawave DW1000 chip to fulfil the needs and requirements identified in the use cases described in TN1.1 [1].

4 Roadmap and recommendations

4.1.1 Evaluation and recommendations

Decawave DW1000-based UCS

The tests performed on the UWB4SAT system have shown that the current hardware is limiting the performance of the UCS in many respects. A number of points are detailed in [17], in which some recommendations for the use of the UCS platform are also given. The major issue with the Decawave DW1000 is the problem with the error increase while improving the link budget, which makes impractical for deployment. It is not rad-hard. It is limited to 6.8 Mbit/s.

The Decawave DW1000 is useable for data transfer applications. A TDMA protocol can be run on top of it, with correct performance. The signal and timings requirements seem to be met and compliant with the IEEE 802.15.4a standard.

The Decawave DW1000 chip benefits from a good documentation and a responsive e-mail support, in spite of the focus that us deliberately put on ranging instead of data communication. In addition, it offers some possible optimisations (SPI, double-buffering) that can increase its performance.

Processor requirements

The UWB4SAT system is based on the Decawave EVK1000 board; this board is equiped with an ST STM32F105 (Cortex M3) processor. It is a modern microcontroller based on an ARM-based design. The processor is evaluated in [17], in which further recommendations about the usage of the resources typically available on such controllers, as well as valuable improvements are suggested.

4.1.2 Way forward

As a conclusion of the UWB4SAT project, this paragraph describes a realistic development plan and options for a UWB4SAT system that could “fly”.

The first issue to be solved is the mismatch between the link budget and the error rate. The Decawave team shall find a solution (hardware of software).

Then, the next important step is the support for the space environment, namely make the chip resistant to radiations, including RF component, the micro-controller, additional flash memory, etc.

Other improvements could also improve the resolution or the precision of the synchronisation or automatic insertion of some time-stamping information at the instant of transmission as well as soon as the first bytes are decoded when received.

Finally, there is a need for higher data rates, to allow for more nodes to be supported in the target application. However, this must be accompanied by other improvement to increase the reactivity of the transceiver and the parallelism of the transfers (e.g. add a double buffering in transmission as well). A possible approach would be to include the CPU on the same die (System on Chip) to accelerate the exchanges.

5 Appendix

5.1 Annex A: Statement of work requirements

The statement of work list functional and technical requirements, listed with their assessment result in the next tables.

Table 1: Functional requirements

Number	Requirement	Verification Method	
R-001	The UWB-based Communication System shall play the role of data communication interface between the on-board computer and/or RTU and/or EGSE and the satellite sub-systems.	R	PC
R-002	The UWB-based Communication System shall play the role of data communication interface between the on-board computer and/or RTU and/or EGSE and dedicated standalone on-board sensors.	R	C
R-003	The UWB-based Communication System shall allow bi-directional data traffic.	R	C
R-004	The UWB-based Communication System shall access the RF medium in a very deterministic way.	R/T	C
R-005	The UWB-based Communication System shall present	R/T	C

	a near-fixed latency (better than 100ms TBC) with a low jitter (better than 50us TBC).		
R-006	The UWB-based Communication System shall permit a precise measurement of latency and jitter values.	R/T	C
R-007	The UWB-based Communication System shall support the star topology.	R/T	C
R-008	The UWB-based Communication System shall support wireless data routing to increase the network's reliability in case of failure.	R/T	PC
R-009	It shall be possible to use two different networks in parallel (e.g. one network for command and control and a network for sensor data acquisition).	R/T	C
R-010	It shall be possible to use two identical networks in a cold redundancy configuration.	R/T	N/A
R-011	It shall be possible to use cross-strapping techniques.	R/T	N/A
R-012	The UWB-based Communication System's interface to the OBC, RTU, EGSE or Sub-systems shall be one or several of the following: Ethernet [RD22], Spacewire [RD18], SPI, milbus 1553b [RD17], or RS422 [RD20].	R	C
R-013	There shall be an interface to connect the UWB-based Communication System to a host microcontroller from or instead of the main interfaces mentioned in requirement R-012 when the system is used by a "standalone" sensing unit (e.g. sensor).	R	PC
R-014	The bandwidth/timeslot allocation/reservation shall be statically configurable (e.g. preliminarily loaded in non-volatile memory) as well as dynamically configurable (e.g. following requests for reservations).	R/T	C
R-015	The minimum payload data throughput supported by the UWB-based Communication System shall be 1Mbps.	R	C
R-016	The over-the-air data rate shall be 27Mbps.	R	NC
R-017	The UWB-based Communication System shall consist of a single board.	I	C
R-018	The UWB-based Communication System shall use energy-saving techniques to reduce overall power consumption (e.g. sleep modes).	R/T	N/A
R-019	The UWB-based Communication System shall not consume more than 1 watt peak of power during nominal operations (TBC).	R/T	C
R-020	The UWB-based Communication System shall provide means to verify the correct status/behaviour of all the	R/T	C

	implemented functionalities.		
R-021	The UWB-based Communication System shall ensure the link budget between all the nodes of the network.	R/T	PC

Table 2: Electrical interface requirements

Number	Requirement	Verification Method	
R-022	The UWB-based Communication System shall have a single power source feed.	R	C
R-023	The UWB-based Communication System may support a battery-powered source feed in the case of sensors.	R	C
R-024	The master power interface shall be compatible with typical on-board equipment power supplies [3V - 12V].	R/T	C

Table 3: EMC requirements

Number	Requirement	Verification Method	
R-025	The UWB-based Communication System shall not interfere with other standard spacecraft equipment and systems in accordance with the guidelines found in [AD3].	T/A	C
R-026	The UWB-based Communication System shall sustain external interferences from other standard spacecraft equipment and systems in accordance with the guidelines found in [AD3].	T/A	C

Verification methods: R= Review of Design, I= inspection, T= Test, A= analysis

No specific requirement has been expressed for Mechanical interface, Structural, Thermal, Radiation or Product Assurance aspects.

5.2 Annex B: System requirements

Table 4: Critical Review of System Requirements

Requirement	Review of requirement	
The Contractor shall identify the requirements (e.g. functional, configuration, interface, environmental and operational) and constraints and define the use-cases	TN 1.1	C
The defined requirements and constraints shall be detailed to permit a complete technology suitability evaluation (PHY, MAC, NWK layers, environments, levels of determinism, etc.) of the communication	TN 1.1 and TN 1.2	C

systems		
The Contractor shall identify the building blocks of the communication systems for these applications	TN 3.1	C
The Contractor shall perform a preliminary space-grade component availability check	None that fits the purpose	-
The Contractor shall review each of the existing ultra-wideband standards	TN 2.1, TN 2.2, TN 4.2	C
The Contractor shall perform a qualitative evaluation and comparison of these standards and available implementations	TN 2.2, DP 3.1, TN 4.2	C
The Contractor shall also identify and define the internal building blocks (architecture) specific to existing or typical UWB-based Communication Systems and establish their availability	TN 4.4, TN 4.5, TN 5.1	C
The Contractor shall perform an EMC assessment and relevant simulations for both IEEE 802.15.4a (pulse) and WiMedia (OFDM) physical UWB technologies	TN 4.2, DP3.1, TN 5.6	C
The Contractor shall propose methods to perform UWB signal measurements	TN 6.1	C
The Contactor shall perform an evaluation of the suitability of the physical (PHY) and medium access control (MAC) layers of the IEEE 802.15.4a ultrawideband standard	TN 5.2	C
The Contractor shall, through modelling, simulations and empirical measurements whenever possible, compare the performance and robustness of the pulse-position-based UWB physical layer (IEEE802.15.4a) against the common wireless standards physical layers	TN 6.3-TN 6.4	C
The Contractor shall design a versatile, robust and deterministic communication system and the protocol stack on top of the IEEE802.15.4a physical layer	TN 4.1, TN 5.1,	C
The Contractor shall consolidate the preliminary system technical specification together with the preliminary programmatic aspects	TN 5.1	C
The Contractor shall present a preliminary process in developing or procuring these building blocks	TN 5.1	C
The Contractor shall also consolidate the technological aspects by characterizing the capabilities of the different critical technologies and determining their status	TN 5.2	C
The Contractor shall validate the system baseline	TN 3.1	C

according to the consolidated system technical specification		
The Contractor shall also perform a preliminary evaluation of the system level impacts and establish comparisons with equivalent, more traditional communication systems	TN 2.2, TN 3.1	C
The possibility to use redundant RF links in hot or cold redundancy shall be assessed and implemented if judged beneficial for the given applications (proof of concept)	Not implemented - dropped	-
The task 4 shall be concluded by a PDR	PDR	C
The contractor shall perform the detailed design of the Application demonstrator's hardware and software	TN 4.5, TN 4.6	C
The Critical Design data package shall cover the UWB communication system components and modules and the application demonstrators	TN 4.5	C
The Critical Design data package shall include (in final issue) the design report	TN 4.4	C
The Critical Design data package shall include the preliminary mechanical design, the electrical and mechanical ICD	TN 5.5	C
The Critical Design data package shall include the preliminary mechanical analysis	N/A	-
The Critical Design data package shall include the preliminary simplified reliability analysis, the preliminary RF interference analysis	TN 5.1	C
The Critical Design data package shall include (in their final issue) the specifications of the FPGAS/SOC(s), the software documentation, the design development	TN 5.1	C
The Critical Design data package shall include (in their final issue) the test plan containing the verification Plan, test procedures, preliminary list of critical electronics components to be further tested and validated	TN 5.1	C
A detailed Reliability analysis shall be provided	Dropped - COTS	-
A preliminary Radiation Assessment (e.g. for GEO) shall be provided in order to assess the robustness wrt typical GEO radiation requirements	TN 5.6 – dropped in absence of rad-hard Decawave or ST components	-
All information required for the manufacturing of the breadboard shall be provided in a Manufacturing File	TN 6.5	C

A network of at least ten nodes shall be created	Test setups	C
Functional and performance testing shall be done in a stepwise fashion	TN 6.1-TN 6.2	C
Functional and performance validation shall be done in a stepwise fashion	TN 6.3-TN 6.4	C
The system shall be mounted into demonstration set-up (satellite mock-up e.g. Venus Express, made available from ESA) for performing “in situ” testing	TN 6.3-TN 6.4	C
The test results shall be analysed and assessed in regard of the objectives of the activity	TN 6.3-TN 6.4	C
The Contractor shall make a presentation showing the contract achievements (at a Final Presentation Event synchronized with other Data Systems final presentations)	FP	C
The Contractor shall post on his website a page(s) showing the developed UWB Communication System	WEB1.0	C
The activity shall be concluded by a final presentation including a demonstration of the delivered system	FP, FAR	C

5.3 Annex C: Application requirements

The next paragraphs list the different requirements by categories and assess the compliance of the UWB4SAT communication system.

5.3.1 Generic requirements

Number	Requirement	SOC	Comments
R-GEN-001	The UWB based Communication System (UCS) shall support the star network topology.	C	By design
R-GEN-002	The UCS shall use the master / slave communication model.	C	By design
R-GEN-003	The UCS shall allow bi-directional data traffic.	C	By design
R-GEN-004	The UCS topology shall ensure the link budget in all the cavities of the satellite and in the whole spacecraft in case where the cavities are communicating.	C	See ADS test report
R-GEN-005	The protocol shall ensure the correct data transmission considering the multipath/fading effect due to communication inside metallic	C	See ADS test report

Number	Requirement	SOC	Comments
	cavities.		
R-GEN-006	Slave nodes of the UCS shall not autonomously initiate a transfer.	C	Sensor answers after receiving beacon from master which allocates a time slot
R-GEN-007	The UCS shall work with networks with up to 400 slave nodes.	C	Each slave may get one or several dedicated time slots. Addresses are 16 bit long (64K nodes supported)
R-GEN-008	The UCS shall provide a minimum payload data throughput of 10 Mbit/s.	**NC**	The DecaWave chip is limited to 6.8Mbit/s and max. throughput around 4 Mbps
R-GEN-009	The UCS communication scheme shall be message based. *Note :Short messages are exchanged between the master node and the slave nodes to transmit commands or acquisitions.*	C	By design
R-GEN-010	One message of the UCS shall be made of two parts: the interrogation of the master node and the answer of the slave node. *Note :When the message is a command, the interrogation from the master holds the command data, the answer from the slave provide slave status / command acceptance information. When the message is an acquisition, the interrogation from the master specifies the desired acquisitions; the answer from the slave contains the actual acquisition data.*	C	By design. The protocol uses a TDMA scheme in which the master sends a beacon, which explicitly mention which node can trasnsmit in which subsequent time slot.
R-GEN-011	The UCS message shall allow the transmission of up to 256 bytes of user data. *Note :These bytes can be used to transfer command data from the master to the slave, or acquisition data from the slave to the master.*	C	The protocol allows for up to 125 bytes (standard) or up 1021 bytes (Decawave extension option) long payload. Segmentation and reassembly of longer messages is possible but not yet

Number	Requirement	SOC	Comments
			implemented.
R-GEN-012	In a UCS message, the time between the master's interrogation and the slave's answer shall be configurable per message from 10µs up to 50ms with a time step of 100 µs. *Note: Some commands or acquisitions may require getting the slave answer right away, while for some others it may be preferable to give the slave some time to answer.*	**NC**	See explanation in **Error! Reference source not found.** and **Error! Reference source not found.**.
R-GEN-013	A slave node of the UCS shall initiate the transmission of its answer to a master interrogation with a timing accuracy better than 5µs with respect to the delay specified in the master's interrogation. *Note : the accuracy is mainly driven by the sinus test where the frequency between two master-slave messages is 40KHz.*	**NC**	Time dispersion of the slave answer around 15µs
R-GEN-014	The UCS shall support interleaving of master's interrogation and slaves' answers. *Note :This is needed in order to improve the overall efficiency of the system.*	C	Thje master has full control over the beacon frequency and it can choose which node muct transmit. Node interrogation interleaving is therefore possible.
R-GEN-015	The UCS shall support the transmission of broadcast messages from the master to all the slaves. *Note :For these kinds of messages, no slaves answers are expected.*	C	

<u>Cyclic on-time message requirements</u>

Number	Requirement	SOC	Comments

Number	Requirement	SOC	Comments
R-GEN-016	The UCS shall provide means to reserve time slots for transmission of cyclic on-time messages. *Note :These kind of messages are used to transmit commands or get sensor acquisition data in a cyclic manner at a precise time.*	C	
R-GEN-017	The UCS master node shall initiate the transmission of the cyclic on-time messages with a timing accuracy better than 1 µs. *Note :The user sends a request to the UCS master node to reserve a time slot for the transmission of a cyclic on-time message, if the requested is granted, then UCS master node shall transmit the message on time*.	C	500ns timing accuracy is measured
R-GEN-018	The UCS shall support cyclic on-time message with frequency up to 2 KHz. *Note :This requirement is derived from use case 1 in order to acquire real-time monitoring accelerometers.*	C	Time slot is configurable: the minimum size of the time slot is 500µs -
R-GEN-019	The UCS shall support at least 20 cyclic on-time messages at a 2KHz maximum frequency *Note : This requirementis derived from use case 1 in order to acquire 20 accelerometers in real-time*	**PC**	Time slot is configurable: the minimum size of the time slot is 500µs or less if overlap is used in the implementation. So the cyclic on-time messages at a 2KHz frequency are achievable for only one sensor. 20 cyclic on-time messages can be sent at 2 kHz if several samples can be grouped into a single packet by the node. See **Error! Reference source not found.**.
R-GEN-020	The UCS shall support at least 500 cyclic on-time messages at a 1Hz frequency *Note : This requirementis derived from use case 2. This allows to specify two cyclic message values at min and max frequencies.*	C	1/(500µs*500)=4Hz

Number	Requirement	SOC	Comments
R-GEN-021	The UCS shall support cyclic on-time messages at different frequencies from 1Hz to 2KHz. *Note : the cyclic on-time message frequency could vary from one message to an another.*	C	2KHz for only one sensor
R-GEN-022	The user shall be able to update the contents of a cyclic on-time message up to 10µs before the scheduled transmission time of the message. *Note :So the use can update commands data just before command transmission.*	C	The DW1000 chip allows for the update of the buffer during the transmission of the preamble, immediately preceding the packet itself would be sent. Warning: this feature requires a very accurate calibration of the system depending of the selected preamble length.

Synchronization requirements

Number	Requirement	SOC	Comments
R-GEN-023	The UCS shall provide means to distribute synchronization pulses to slave nodes. *Note :This is needed to synchronise acquisitions of sensors.*	C	
R-GEN-024	The UCS shall be able to distribute synchronization pulses of frequencies ranging from 1Hz to 20KHz. *Note :The 20 KHz frequency is needed for acoustic tests in use case 1, for use case 2 frequencies up to 128Hz could be acceptable.*	PC	See section **Error! Reference source not found.**. Not implemented.
R-GEN-025	The UCS shall be able to distribute pulses of different frequencies to different slaves. *Note : Some slave might require a 1 Hz synchronization pulse, while others require 16 Hz.*	PC	See section **Error! Reference source not found.**. Not implemented.
R-GEN-026	The UCS shall be able to synchronize the pulses with an external time reference. *Note :A PPS signal from ultra stable clock could be used as external time reference*.	PC	This is possible to run an IEEE 1588 on the master, although not implemented.

Number	Requirement	SOC	Comments
R-GEN-027	The timing accuracy of the synchronization pulses shall be better than 1µs with respect to the external time reference.	C	500ns timing accuracy is measured
R-GEN-028	The synchronization pulses jitter shall be lower than 1µs.	C	500ns jitter is measured

Modularity requirements

Number	Requirement	SOC	Comments
R-GEN-029	The UCS network shall allow, physically, the addition or the suppression of 1 to N slaves without blocking the operation of the system. *Note: the network shall allow the implementation of new slaves late in the project.*	C	

Observability requirements

Number	Requirement	SOC	Comments
R-GEN-030	The UCS shall provide housekeeping data with as a minimum the slave battery voltage (if applicable), the received signal strength indicator (*RSSI*) from the slave, the RSSI from the master, faulty packet count from slave to master and from master to slave	NA	Out of scope for this study OK for fault packet count
R-GEN-031	The UCS shall permit a precise measurement of latency and jitter values.	C	
R-GEN-032	The UCS shall allow to verify the reception and execution of a command from the OBC to the master and from the master to the slaves.	C	

5.3.2 Specific requirements for the Self-powered wireless sensor application

Network topology requirements

Number	Requirement	SOC	Comments
R-UC1-001	For on-ground application, the UCS shall be composed of one master (or several if needed) and one host microcontroller (PC) simulating the OBC of the spacecraft.	C	
R-UC1-002	The H/W & S/W interface between the master(s) and the OBC shall be representative of the flight one (SpaceWire, MIL-STD-1553…) for flight application or an Ethernet link with EGSE for ground application.	C	
R-UC1-003	The acquisition of the vibration data at each sensor level shall be performed at a maximum sampling rate of 20KHz.	NA	Out of scope for this study
R-UC1-004	The UCS shall allow to configure the sensor in two different modes : a “recording mode” where all the data are saved in a sensor memory area and a “real time mode” where the data are sent to the master.	NA	Out of scope for this study
R-UC1-005	In the “recording mode” : once the master sent the measurement order, the vibration data are acquired and stored in a memory area in the sensor and dated with an accuracy of 10µs.	NA	Out of scope for this study
R-UC1-006	The data shall be post-treated after the test in the sensor (i.e FFT, PSD, rms) and transmitted to the master on request. Time and frequency data shall be transmitted.	NA	Out of scope for this study
R-UC1-007	All the 400 accelerometer data shall be recovered and saved by the master in less than 30mn.	NA	Out of scope for this study
R-UC1-008	All the sensor data shall be stored in the master in a memory area.	NA	Out of scope for this study
R-UC1-009	In the “real time” mode : the UCS shall be able to acquired a maximum of 20 sensors during a sinus tests at a sampling rate of 2KHz per sensor, to treat them in order to abort the test if the measured level is above a certain criteria.	**PC**	See R-GEN-019

R-UC1-010	The abort time between the measurement at sensor level and the abort decision done by the master shall not exceed 100µs (TBC).	NA	Out of scope for this study
R-UC1-011	In order to be attractive, the sensor shall be composed of the electronic parts, the RF transceiver, the accelerometer itself and the power source. *Note : the sensor unit shall integrate the sensor itself.*	NA	Out of scope for this study
R-UC1-012	The wireless sensor dimensions shall be at least <1cm side.	NA	Out of scope for this study
Number	**Requirement**		
R-UC1-013	The Sensor mass shall be as light as possible (at least < 20g). *Note: This includes the power source.*	NA	Out of scope for this study
R-UC1-014	The Sensor life time for ground application shall be compatible of a storage time = 2 years (sleep mode) and a communication time of 1hour30mn@20KHz or 3hours@2KHz.	NA	Out of scope for this study
R-UC1-015	The Sensor life time for flight application shall be compatible of a storage time = 2 years (sleep mode) and 2hours@20KHz.	NA	Out of scope for this study
R-UC1-016	The accelerometer performances for ground application shall be : - Max measured level: 100g - Accuracy: 0.1g - Bandwidth: 7KHz - First mode of resonance : 20KHz *Note: current accelerometer performances*	NA	Out of scope for this study
R-UC1-017	The accelerometer performances for flight application shall be : - Max measured level: 1g - Accuracy: 100µg - Bandwidth: 1KHz - First mode of resonance : 2KHz *Note: current accelerometer performances*	NA	Out of scope for this study

Protocol requirements

Number	Requirement	SOC	Comments
R-UC1-018	The UCS communication protocol shall be independent from the main spacecraft system bus (e.g. MIL-STD-1553 or SpaceWire).	C	
R-UC1-019	The UCS master shall act as a remote terminal unit on the main system bus. *Note: the master shall transmit data on the main system bus only after a request coming from the on board computer*	NA	Out of scope for this study
R-UC1-020	The polling (interrogation cycle) of the UCS master shall be independent from the satellite DHS system controlled by the OBC. The sensor data shall be stored/refreshed in the master and shall be made available to the wired satellite data bus. *Note :the RF network protocol cycle shall be independent of the satellite data bus cycle.*	C	
R-UC1-021	The UCS master, being a MIL-STD-1553 RT or other, shall store an history of 3 readings of the sensors data on a rolling buffer, which shall be retrieved after a MIL-STD-1553 bus controller request. *Note : enables access to an history of the data read by the sensors*	NA	Out of scope for this study

Quality of transmission requirements

Number	Requirement	SOC	Comments
R-UC1-022	The packet error rate shall be less than smaller then 10^{-6} over mission life time.	**PC**	PER was measured better than 1e-5.

Observability requirements

Number	Requirement	SOC	Comments
R-UC1-023	From ground operation, the vibration data shall be visualized in real time in a user friendly environment (plot of the level according to the time…). The real time tolerance shall not exceed 100µs between emission of the data and display. *Note : During sinus test, tens of sensors are monitored in real-time in order to abort the test if needed.*	NA	Out of scope for this study

Reliability requirements

Number	Requirement	SOC	Comments
R-UC1-024	Any failed sensor shall not disturb or block the network	C	
R-UC1-025	In the case of several sensor networks i.e one per cavity, the UCS shall allow to reconfigure one network in order to support the wireless data routing in case of failure of one another network.	NA	Out of scope for this study
R-UC1-026	The master shall be used two UWB transceivers in cold redundancy	NA	Out of scope for this study

5.3.3 Specific requirements for highly reliable command and control data bus application

Asynchronous on-demand message requirements

Number	Requirement	SOC	Comments
R-UC2-001	The UCS shall provide means to transmit asynchronous on-demand messages.	C	Currently, the protocol supports on-demand exchanges from the master that are assigned using the TDMA scheme. Another possible approach would include a contention period into the cycle, after the TDMA slots (not implemented)
R-UC2-002	The latency between the request to transmit an asynchronous message and the actual transmission time shall be bounded.	C	It is bounded by the fact that the opportunity for the sensor node to reply is planned in advance.

Reliability requirements

Number	Requirement	SOC	Comments
R-UC2-003	The message error rate shall be lower than 10^{-6} (TBC)over mission life time	**C**	PER was measured better than 1e-5
R-UC2-004	The UCS shall be single failure tolerant. *Note :This typically requires duplication of the transceivers and transmission channels.*	NA	Out of scope for this study
R-UC2-005	In particular, the UCS shall be robust to a “babbling idiot” type of failure.	NA	Out of scope for this study

5.3.4 Specific requirements for wireless bridge application

Number	Requirement	SOC	Comments
R-UC3-001	The UCS shall support a bridge setup in which two nodes are communicating in point-to-point mode. *Each node is one side of the wireless bridge.*	C	
R-UC3-002	In bridge configuration the UCS shall support bi-directional communications in full duplex mode.	PC	The bridge would support only half-duplex communication if only one transceiver is used. However, half-duplex communication offers a very close quality of service.
R-UC3-003	The transmission latency of a message from one side of the bridge to the other shall be bounded. *The latency should be as low as possible.*	PC	The communication channel will act as a black channel without the knowledge of the transferred data. The time constraints will be checked at both ends of the communication link.
R-UC3-004	The UCS shall provide a minimum payload data throughput of 10 Mbit/s in full-duplex.	**NC**	Limitation to 6.8Mbps data rate (DecaWave chip) ; max throughput around 3Mbps
R-UC3-005	If a SpW-to-UWB bridge is developed then the SpW interface shall be compliant with the ECSS-E-ST-50-12C.	NA	Out of scope for this study
R-UC3-006	If a CAN-to-UWB bridge is developed then the CAN interface shall be compliant to the ISO 11898.	NA	Out of scope for this study
R-UC3-007	The probability of loss of command or command packet shall be smaller then 10^{-6}(TBC) over mission life time.		PER was measured better than 1e-5

Observability requirements

Number	**Requirement**	**SOC**	**Comments**
R-UC3-008	The UCS shall provide housekeeping data with as a minimum the RSSI from both sides, wireless protocol packet error count, SpaceWire/CAN packet count, SpaceWire/CAN faulty packet count	NA	Out of scope for this study OK for fault packet count
R-UC3-009	The UCS shall permit a precise measurement of latency and jitter values.	C	

Reliability requirements

Number	Requirement	SOC	Comments
R-UC3-010	The UCS shall be single failure tolerant. *Note :This typically requires duplication of the transceivers and transmission channels.*	NA	Out of scope for this study
R-UC3-011	In particular, the UCS shall be robust to a “babbling idiot” type of failure.	NA	Out of scope for this study

5.3.5 Environment requirements

Electrical interface requirements

Number	Requirement	SOC	Comments
R-ENV-001	The UCS shall have a single external power source feed (for master and slaves) except in the case of sensors where they shall own an internal battery in order to be completely wireless.	C	
R-ENV-002	The master power interfaces shall be compatible with typical onboard equipment power supplies [28V -50V]	**NC**	3.3V power source
R-ENV-003	The power interface for autonomous slaves shall be compatible with typical battery voltage [3-4.2V]	C	
R-ENV-004	The UCS master/slave shall consist of a single board	**NC**	DecaWave board + microcontroller development board
R-ENV-005	The UCS master/slave shall not consume more than 1W peak during nominal operation (except for the sensor)	C	
R-ENV-006	The UCS shall use energy-saving techniques to reduce overall power consumption (e.g sleep mode).	NA	Out of scope for this study

Thermal requirements

Not applicable for this study.

Only ambient temperature is considered.

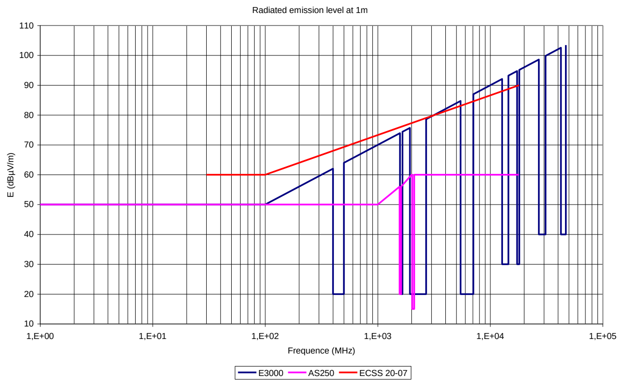
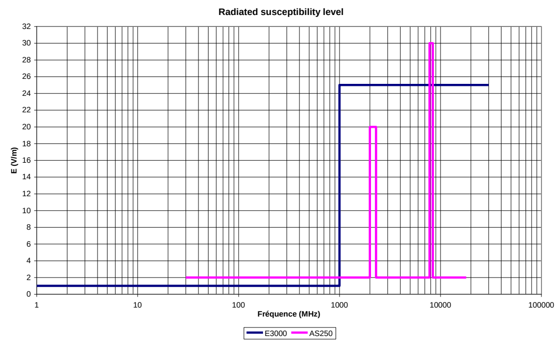
Vibration requirements

Not applicable for this study.

Radiation requirements

Not applicable for this study.

EMC requirements

Number	**Requirement**	**SOC**	**Comments**
R-ENV-007	The UCS shall not use the frequency channels 5,6, 7 and 9.	C	Tests were performed on channel 1
R-ENV-008	The UCS shall not radiate narrowband noise with required levels here below.  Figure 0-1 : Radiated emission specification at 1m *Note : the specified measurement bandwidth for f>1GHz is 1MHz.*	**PC**	Considering P=-41dBm/MHz and G = 0dBi then E-field at 1m is equal to 64dBµV/m
R-ENV-009	The UCS shall not be disturbed when submitted to the narrowband CW signal as specified in the figure here below.  Figure 0-2 : Radiated susceptibility specification	**PC**	Tests demonstrated that UCS is disturbed when a NB emits in the same frequency range an E-field value higher than 4V/m (6.8Mbps)

6 Annex D: list of deliverables

The data package 2 contains all documentation and electrical schematics of the delivered systems, requirements, specification, design, development and evaluation of the UWB4SAT system. It includes the following documents:

Table 5: Deliverables for Phase 1

Document identifier	Title
TN 1.1	Requirement justification file
TN 1.2	Preliminary functional specification (first issue)
TN 2.1	Commercial UWB technology assessment
TN 2.2	Assessment and comparisons of UWB technologies
DP2.1	Simulation models, programs and results datapack
TN 3.1	Evaluation of UWB technologies for on-board applications
DP3.1	Models, simulation programs and measurement data
TN 4.1	Consolidated technology plan and matrix
TN 4.2	Communication system analysis document (see AD03 Annex C)
TN 4.3	Preliminary functional specification (second issue)
TN 4.4	Preliminary design file
TN 4.5	Architectural Design Report and Design Justification (list of key electrical parts included)
TN 4.6	Unit & Board Interface Specification / Compatibility Trade-off Report
DP4.1	Simulation models, programs and results datapack
P1SR	Phase 1 Summary Report
Doc Pack1	Documentation Package 1 containing the final versions of the phase’s technical notes and reports.

Table 6: Deliverables for Phase 2

Document identifier	Title
TN 5.1	Consolidated technology plan and matrix (final issue)
TN 5.2	Communication system analysis document (see AD03 Annex C) – (final issue)
TN 5.3	Functional specification (final issue)
TN 5.4	Detailed design file
TN 5.5	ICD
TN 5.6	Preliminary Radiation Assessment
TN 5.7	FMECA Reliability analysis
DP5.1	Manufacturing files
TN 6.1 TN 6.2	Test Procedures System Level Verification and Validation Test Procedures
TN 6.3 TN 6.4	Functional and performance test report Test analysis report
TN 6.5	Electrical Schematics

Table 7: Final documents

AFR 1.0	Final activity report
WEB1.0	Web page on CSEM web site
DP7.1	Document package 2

All deliverables have been delivered.

7 Applicable and reference documents

[1] P.Pelissou, M. Patte, "Requirement justification file", Ultra-wideband as a multi-purpose robust and reliable wireless technology for testing, spacecraft and launcher communications, Deliverable TN1.1, ESTEC/Contract No. 4000107142/12/NL/AK

[2] P.Pelissou et al., ASTRIUM, "Evaluation of pulsed-based UWB technology for on-board applications, Part 2: UWB performance", Deliverable TN3.1, ESTEC/Contract No. 4000107142/12/NL/AK

[3] J.-D. Decotignie, CSEM, "Preliminary Design", Ultra-wideband as a multi-purpose robust and reliable wireless technology for testing, spacecraft and launcher communications, deliverable TN4.4, ESTEC/Contract No. 4000107142/12/NL/AK

[4] Ph. Dallemagne, CSEM, "Architectural Design Report and Design Justification", Ultra-wideband as a multi-purpose robust and reliable wireless technology for testing, spacecraft and launcher communications, deliverable TN4.5, ESTEC/Contract No. 4000107142/12/NL/AK

[5] J.-D. Decotignie, et al., CSEM, Communication system analysis document, UWB4SAT Technical Note 5.2 "Communication system analysis document", CSEM, 2014.

[6] J.-D. Decotignie, et al., CSEM, Functional specification, UWB4SAT Technical Note 5.3 “Functional Specification”, CSEM, 2014.

[7] D. Piguet, et al., CSEM, Detailed design file, UWB4SAT Technical Note 5.4, “Detailed Design File” CSEM, 2014.

[8] Y. Brunet, et al., CSEM, TN 6.x,”Test specification”, CSEM, 2014.

[9] IEEE Std 802.15.4a™-2007. IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements, Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs). Amendment 1: Add Alternate PHYs.

[10] IEEE Std 802.15.4-2011. IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) (Revision of IEEE Std 802.15.4-2006).

[11] IEEE Std 8802-2-1994, ISO/IEC Standard for Information Technology- Telecommunications and Information Exchange Between Systems- Local and Metropolitan Area Networks- Specific Requirements- Part 2: Logical Link Control

[12] IEEE Std 802.15.4e-2012, IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer (Amendment to IEEE Std 802.15.4-2011), 2012, pp. 1 – 225

[13] AD.3 ECSS-E-40B ECSS E-40 Software Engineering Standards, European Space Agency.

[14] Felix Bachmann et al., Documenting Software Architecture: Documenting Interfaces, Technical Note CMU/SEI-2002-TN-015, Architecture Tradeoff Analysis Initiative, Carnegie Mellon University, Software Engineering Institute, Pittsburg, June 2002.

[15] Consolidated technology plan & matrix, UWB4SAT Technical Note 5.1 “Consolidated Technology Plan and Matrix”, CSEM, 2014.

[16] DW1000 User Manual v2.02, Decawave, 2014, http://www.decawave.com/sites/default/files/resources/dw1000_user_manual_2_02.pdf

[17] Ph. Dallemagne, Y. Brunet, AFR 1.0, UWB4SAT Activity Final Report, CSEM, 2014

