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ENABLING ON-BOARD RELATIVE RANGING WITH COMMERCIAL OFF-THE-SHELF SOFTWARE-DEFINED RADIOS: THE VULCAIN MISSION INTER-SATELLITE IOD

Francesco De Cecio [a*], **Enrico Belloni** [a], **Giovanni Zanotti** [a], **Michèle Lavagna** [a], **Camille Pirat** [b], **Giuseppe Leccese** [c]

[a] *Department of Aerospace Science and Technology, Politecnico di Milano, Italy*

[b] *European Space Agency (ESA-ESTEC), The Netherlands*

[c] *Italian Space Agency (ASI), Italy*

[*] Corresponding Author: francesco.dececio@polimi.it

A growing interest in spacecraft formation-flying is observed in the current trend of space missions. An increased scientific return is indeed possible by employing multiple agents who can act by combining their acquisitions toward a common scientific goal. In particular, the Vulcain CubeSat mission, funded by the Italian Space Agency under the Alcor program and coordinated by ESA under GSTP, currently in phase B, aims at obtaining stereoscopic images of volcanic sites by simultaneous acquisition of the same target from two platforms flying in a tandem configuration. Thus, a robust relative GNC architecture is essential to ensure formation keeping while guaranteeing platform safety, and, in particular, the navigation system shall be as reliable and accurate as possible. One of the technological objectives of the Vulcain mission is hence to demonstrate high-precision RF-based ranging through a dedicated S-band inter-satellite link. This paper presents the implementation of an innovative one-way ranging scheme for the Vulcain formation, in which each platform transmits a GNSS-like signal. The design process takes into account compatibility with International Telecommunication Union (ITU) regulations and with spacecraft configuration to achieve a satisfactory link budget. Moreover, the signal is designed to carry both a navigation message, containing the state of the transmitting spacecraft, and a pseudo-random noise sequence to be used in a delay-locked loop for time-of-flight estimation. Both the classical GNSS observables, pseudorange and carrier-phase, are retrieved on the receiver side. Considering an S-band carrier frequency, the achievable performance has been preliminarily assessed and is expected to reach centimeter-level precision in range estimation. The whole development is aimed at making the signal processing sustainable on a commercial off-the-shelf software-defined radio, in the novel approach of embedding navigation capabilities in a communication subsystem. Therefore, the navigation performance parameters of the signal are highlighted and their impact on both the ranging accuracy and the hardware proposed for the Vulcain mission will be assessed through a dedicated verification and testing campaign.

Keywords: Vulcain, formation flying, Inter-satellite ranging

Nomenclature

$\sigma_{\varepsilon_\rho}$	: standard deviation of the pseudorange error
c	: speed of light
t_c	: chip period of the pseudorandom number code
B_{DLL}	: bandwidth of the delay-lock loop
t_{eml}	: spacing between early and late PRN code replica
t_{acc}	: integration time of the DLL accumulator
C/N_0	: carrier-to-noise density ratio

Abbreviations

DEM	: digital elevation map
ECI	: earth-centered inertial
EKF	: extended kalman filter
GNC	: guidance, navigation and control
GNSS	: global navigation satellite system
IR	: infrared
ISL	: inter-satellite link
LEOP	: Launch and Early Orbit Phase
LTAN	: local time of the ascending node
LVLH	: local-vertical local-horizontal
PRN	: pseudo random number
VIS	: visible
VLEO	: very low-earth orbit

1. Introduction

The Vulcain mission, currently in Phase B, is a space initiative funded by the Italian Space Agency (ASI) under the Alcor program and coordinated by the European Space Agency (ESA) through the General Support Technology Programme (GSTP). The mission's primary objective is to obtain stereoscopic images of volcanic sites by simultaneously capturing the same target from two identical 12U CubeSat platforms, flying in a tandem configuration with inter-satellite distance of 300 km. The mission operates in Very Low-Earth Orbit (VLEO), with a nominal altitude of 400 km and the two satellites are inclined in attitude of about 20° off-nadir during scientific acquisition for instrument co-pointing. A geometric in-flight representation of the formation is shown in Figure 1.

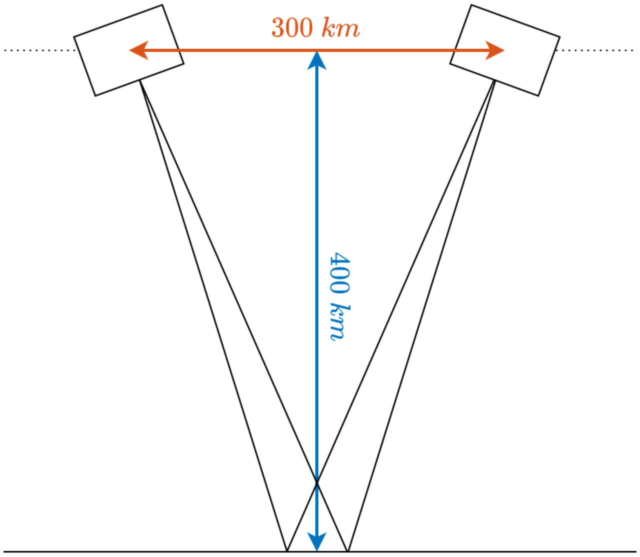

Fig. 1: Simplified geometric representation of the Vulcain formation.

To achieve its scientific objectives, the mission employs a payload consisting of a customized multispectral thermal camera and a Commercial Off-The-Shelf (COTS) visible camera. Starting from the data collected by these payloads, it will be possible to generate more than ten different scientific products, such as surface temperature and digital elevation map (DEM), providing insights into volcanic activity and supporting hazard assessment.

Accurate knowledge of the formation geometry between the two CubeSats is crucial for ensuring the quality of the stereoscopic imagery and the safety of the platforms, particularly during the Launch and Early Orbit Phase (LEOP), when the probability of collision is higher due to the closer proximity of the spacecraft. To address this challenge, the mission's relative navigation subsystem will utilize various techniques to retrieve the Relative Orbital Elements (ROE) of the CubeSat formation. This will be accomplished using an Inter-Satellite Link (ISL) established between the platforms via a dedicated radio, allowing precise relative positioning.

2. Inter-satellite link based navigation experiment

To ensure a real-time knowledge of the formation geometry, the mission employs a dedicated Relative Navigation subsystem designed to determine the ROE of the CubeSat formation. The ROE provide a set of parameters that describe the relative motion and configuration of the two spacecraft in orbit, enabling the precise monitoring and control of the tandem formation. Multiple techniques will be used to determine these elements, allowing for robust and accurate relative positioning throughout the mission.

2.1 Technique comparison

All the navigation techniques implemented in this subsystem exploit a radio-frequency (RF) ISL established between the two CubeSats, which allows the satellites to exchange signals and derive relative range and velocity information. The use of the ISL provides a direct and efficient method for the satellites to autonomously determine their relative positions, making it an essential tool to achieve precise formation knowledge and ensuring the mission's scientific and safety objectives. The approaches used for relative navigation encompass both direct and indirect ranging techniques, as summarized in Table 1.

2.2 Innovative aspects

The Vulcain mission IOD incorporates several innovative features in its approach to using an RF-ISL for relative navigation. These innovations are centered on three key aspects:

1. *Utilization of COTS RF Hardware.* The navigation system is designed to rely exclusively on COTS components for its RF hardware, specifically employing Software-Defined Radios (SDR) and antennas. By using widely available and cost-effective hardware, the mission aims to demonstrate that high-performance relative navigation can be achieved with standard Telemetry, Tracking, and Command (TTMTC) equipment on CubeSat platforms. Additionally, the processing required to extract the ranging measurements will be executed directly on the System-on-a-chip (SoC)

Table 1: ISL-based relative navigation techniques

Navigation technique	Description	Features	Rationale
Indirect ranging (ISL-NAV)	Relative state computed by differencing processed GNSS solutions exchanged via ISL.	- Full relative state estimation - Use of delayed measurements may introduce estimation errors	- Baseline for relative navigation - Robust and easy to implement
CDGNSS*	Relative state computed by differencing and processing raw GNSS observables.	- Precise relative state estimation - Still an indirect relative measurement	- Selected as a reference solution to be compared a posteriori with the on-board filter solution
One-way ranging (ISL-IOD)	GNSS-like ranging signal transmitted over ISL. Distance retrieved via delay estimation (time of flight) and refined with phase measurements.	- Independent from GNSS - Direct measurement of inter-satellite distance - Requires dedicated hardware for ranging signal processing	- In-Orbit Demonstration (IOD) - Can reach sub-millimetric precision with proper ambiguity resolution - Suitable for future advanced applications

*Performed on ground ex-post.

within the SDR. This on-board signal processing capability would provide a novel navigation functionality for CubeSats, potentially making sophisticated navigation systems more accessible and affordable for a wider range of missions.

2. *Evaluation of Navigation Performance Over Long Baselines.* The Vulcain mission seeks to assess the navigation accuracy and robustness of the COTS-based system across long inter-satellite baselines, with separations reaching up to 300 km. This evaluation is particularly important for missions involving CubeSat formations or swarms, where maintaining precise relative positioning over extended distances is challenging.

3. *Cross-Validation of Navigation Techniques.* To further enhance the accuracy and reliability of the relative navigation system, the mission will perform a cross-validation of different ranging techniques. This includes indirect ranging methods, Carrier-Phase Differential GNSS (CDGNSS), and GNSS-like one-way ranging. By comparing the results from these various techniques, the Vulcain mission aims to refine the measurement models and improve the overall navigation solution. The ability to integrate and validate multiple navigation methods not only increases the robustness of the system but also contributes to making these advanced technologies more accessible to small satellite missions in the future.

3. Inter-satellite link design

Establishing a radio-frequency link between two spacecraft requires compliance with strict regulations set by the International Telecommunications Union (ITU). These constraints are crucial for ensuring that the inter-satellite communications do not interfere with other space-based and terrestrial communication systems [1]. The ITU regulations impose requirements that affect the following aspects:

1. *Admissible Frequency Bands for Space-to-Space Transmissions.* The ITU specifies the permissible frequency bands that can be used for communication between spacecraft. These frequency bands are selected to minimize interference with other services, such as terrestrial communication, Earth observation systems, and GNSS. Selecting the appropriate frequency band is critical, as it determines not only the availability of compatible hardware but also the transmission bandwidth and signal propagation characteristics. Table 2 summarizes the frequency bands authorized for ISL, along with the pros and cons of each band in relation to Vulcain case.

2. *Maximum Allowable Power Flux Density (PFD) at the Earth's Surface.* Another critical limitation imposed by the ITU concerns the maximum Power Flux Density (PFD) that the transmitted signal can produce at the Earth's surface. This regulation is designed to prevent the satellite transmissions from causing harmful

Table 2: Admissible frequency bands for space-to-space transmissions

Band	Frequency [MHz]	Pros	Cons
L-band	1164-1300 1559-1610	- Loose constraints on PFD - COTS SDR and antenna available	- Lower bandwidth - Interference with GNSS signals
S-band	2025-2110 2200-2290	- High bandwidth and accuracy - COTS SDR and antenna available - GOMX-4 heritage	- Tight constraints on PFD
C-band	5010-5030	- Loose constraints on PFD - Higher bandwidth and accuracy	- Very limited COTS availability
K-band	22550-23150	- Loose constraints on PFD - Very high bandwidth and accuracy - COTS SDR and antenna available	- Huge transceiver dimensions - High power demand

interference to ground-based communication services operating in the same or adjacent frequency bands. The PFD limit is especially relevant for low-altitude satellites, where transmitted signals could otherwise reach the ground with significant intensity. It is needed to prove the compliance with maximum levels in any possible operative conditions, thus even in not foreseen attitude configuration, with the ISL antenna pointing towards the Earth with the boresight.

To identify a feasible baseline, K-band has been discarded because of the very high impact on the whole platform, being extremely big and power-hungry. The C-band option has been discarded as well due to a too limited COTS availability. While L-band represents a valuable option to overcome PFD limitations, it is expected to exhibit a strong interference with traditional GNSS signals. Therefore, this trade-off allowed selecting an S-band link at 2200 MHz that balances the technical requirements of the mission with regulatory compliance.

Furthermore, to close the link with an adequate SNR while satisfying the stringent constraints on maximum PFD, an additional trade-off has been performed. In particular, to keep as low as possible the EIRP of the platforms (and hence minimize PFD), the configuration of the platforms considering the nominal operational attitude shall maximize ISL antennas mutual visibility and hence their gain in the line-of-sight direction. To address this point, three drivers have been followed: to guarantee ISL navigation capabilities during nominal operations whenever possible, to minimize the number of attitude manoeuvres needed to switch between different modes, and to have two identical platforms. Hence the pointing requests from different subsystems have been assessed and are reported in Table 3 together with an indicative occurrence frequency of each.

Table 3: Pointing requests from each subsystem.

Pointing mode	Request	Occurrence frequency
THRUSTING	EP axis towards the direction opposite to the velocity	30 min every 8 h
OBSERVATION	Payloads towards 20 deg off-nadir	Few min every 140 min (mean value)
ISL-NAV	ISL antenna visibility at max 70 deg	Whenever possible
ISL-IOD	ISL antenna visibility at max 20 deg	In IOD phase

Three attitude profiles, each coupled with a platform configuration, are presented in the following paragraphs. Three components are sketched in the configuration images: the electric propulsion unit (indicated as EP), the ISL antenna, and the payload optics (indicated as PL).

Case 1. The first case features the installation of the ISL antenna on the Earth-facing surface of the platforms (the same of the payloads) and is represented in Figure 2. However, the PFD constraints are violated when closing the link in the OBSERVATION mode. Therefore, a dedicated pointing mode shall be added to perform ISL (both NAV and IOD), requiring a 70 deg slew for each OBSERVATION/ISL transition.

Case 2. The second case features the installation of the ISL antenna on the top face of the platforms and is represented in Figure 3. In this case a better visibility condition between ISL antennas can be guaranteed in the OBSERVA-

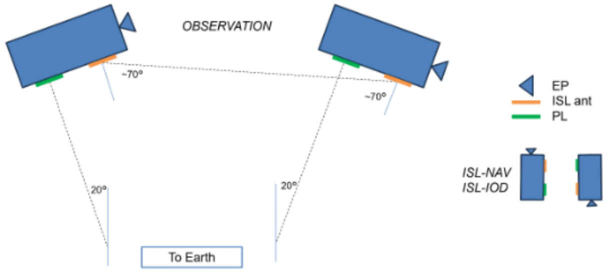

Fig. 2: ISL configuration - Case 1.

TION mode, allowing simultaneously scientific data acquisition, ISL-NAV and ISL-IOD. However, a 180 deg slew is required at every transition between OBSERVATION and THRUSTING. Moreover, only the leading platform is manoeuvring, introducing an asymmetric wear of the reaction wheels and potentially the need for formation reconfiguration within the mission duration (leader/follower swap).

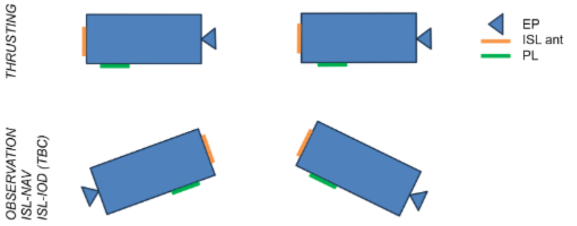

Fig. 3: ISL configuration - Case 2.

Case 3. The third case considers different configurations for the leading and trailing spacecraft, thus relaxing the initial driver of identical platforms. The ISL antennas are mounted on the bottom and top faces of the leading and trailing satellite respectively, as reported in Figure 4. As in Case 2, scientific data acquisition, ISL-NAV, and ISL-IOD can be executed without varying the platforms attitude. Moreover, in this case, only a 20 deg slew is required to acquire the THRUSTING attitude. No platform swap is therefore foreseen.

A comparison of the three cases, summarizing the pros and cons for each architecture, is provided in Table 4. The baseline selection is aimed at minimizing complexity of design, assembly, and operation of the spacecraft formation while guaranteeing satisfactory ISL performance.

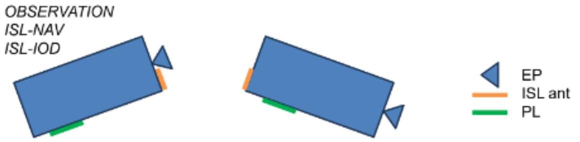

Fig. 4: ISL configuration - Case 3.

The importance of the relative navigation baseline (ISL-NAV) as a fallback method to compute the inter-satellite distance autonomously onboard, in case of contingencies, is a strong driver to push for maximizing the ISL windows and thus to perform it also during nominal operations. Moreover, given the impact of having two different platforms on the whole mission schedule, it is preferred not to investigate further case 3. Therefore, case 2 is selected as baseline. The impact of performing 180 deg slews on the ADCS of the leading platform will be assessed in the following phases.

Concluding, the proposed ISL baseline exploits an S-band communication system arranged in the configuration represented in case 2. In Section 4.2, a link budget demonstrating the compliance of this design with PFD limitations is provided.

4. Signal design

4.1 Signal structure

To enable both the exchange of absolute GNSS solutions for indirect ranging and the ability to directly compute ranges between spacecraft, the Vulcain mission adopts a signal structure modeled after the GPS L1 C/A signal. This approach leverages a proven and reliable framework, while incorporating key modifications to meet the mission's specific needs. The main differences in the signal structure are the carrier frequency, set at 2200 MHz, and the navigation message data rate, set at 250 bps. In this scheme, the same navigation message bit is modulated over four complete PRN sequences, which is expected to be sufficient for successful correlation and detection, provided the signal is correctly tracked after the initial fix. In standard GPS L1 signal, a navigation bit is spread across 20 PRN sequences to allow discrimination among 32 PRNs, even in low signal-to-noise ratio (SNR) conditions. However, such low SNR conditions are not foreseen for the Vulcain mission, so this level of discrimination is not required.

The signal is modulated using a direct-sequence spread spectrum (DSSS) technique. In this method, the navigation message is spread by modulating it onto a pseudorandom noise (PRN) code, which provides robustness with respect to low SNR. The spread signal is then modulated onto the S-

Table 4: Comparison between ISL strategies.

Case	Pro	Cons
1	- Identical platforms	- Impossible to perform science and ISL simultaneously - 70 deg slew required
2	- Identical platforms - Simultaneous science and ISL	- 180 deg slew required - Asymmetric wear of RWA - Need for formation reconfiguration
3	- No major slews foreseen - Simultaneous science and ISL	- Different platforms - Possible interaction with thruster plume

band carrier at 2200 MHz using Binary Phase Shift Keying (BPSK), a modulation scheme that allows efficient transmission of the signal with minimal power requirements. A scheme of the modulation process is provided in Figure 5.

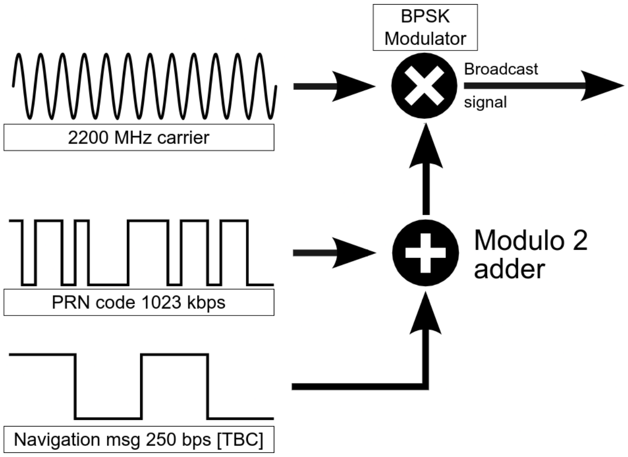

Fig. 5: Ranging signal structure.

The content of the navigation message is critical to ensure the spacecraft's relative navigation capabilities. Each message contains the absolute state of the transmitting spacecraft, including its position and velocity in the Earth-Centered Inertial (ECI) reference frame, as computed by its onboard GNSS receiver. The message is structured with a synchronization preamble to aid in signal acquisition, followed by the spacecraft's state data, a timestamp to mark the precise epoch of the transmission, and a footer that contains a Cyclic Redundancy Check (CRC) for error detection.

This navigation message will be transmitted once per second, while the actual state information will only be updated every 10 seconds, feeding to the radio a new navigation message prepared by the GNC onboard computer using the data collected from the GNSS receiver. This ensure 10 times redundant transmission of every message to further improve the chances of a correct reception. This transmission structure allows for robust use of the communication link while avoiding unnecessary computational efforts on both the ISL radios and onboard computers devoted to GNC, since preliminary model in the loop tests has proven that the relative navigation solution is performing well even with less frequent updates.

4.2 Link budget

The ISL link budget presented in Table 5 is the result of an optimization process to ensure a reliable tracking of the ranging signal under the constraint of maximum allowable PFD. The budget has been computed considering the performance parameters of the Vulcain mission hardware, together with those of the formation geometry. In particular, the selected ISL radio is the GOMspace NanoCom SDR MK3 with a TR-600 transceiver tuned for S-band operations, coupled with its 8 dBi active patch antenna ANT2150-ISL, specifically designed for ISL purposes. The selected modulation is BPSK. The channel capacity presented in Table 5 is driven by keeping a positive margin link budget, while complying with ITU PFD regulations. This poses a challenge given that the involved inter-satellite distance is quite large and that both communication terminals have relatively low gain. The proposed strategy to solve this trade-off is to start from setting power and bandwidth values that comply with PFD limits and then checking the performance obtained in the link budget.

Considering roughly 1400 kbps of net datarate, resulting in a 1680 kHz bandwidth, with an RF output power of 30 dBm, compliance with PFD is obtained. In fact, this link results in a PFD at Earth (in any 4 kHz band) of -144.3 dBW/m^2/4 kHz, which is below the maximum allowed for this kind of service (Space-to-Space) in the S-band region of the spectrum, i.e. -144.0 dBW/m^2/4 kHz. The resulting link budget performance provides a slightly positive link margin for the spread signal, that should be however enough to guarantee ranging signal tracking, whereas an high SNR is obtained for the de-spread signal, ensuring a proper reception of the navigation message.

Table 5: Link Budget Parameters

Parameter	**Value**
Link Distance [km]	300
Frequency [MHz]	2200.0
Bandwidth [kHz]	1680.0
Net datarate [kbps]	1338.4
Gross datarate [kbps]	1400.0
Symbolrate [ksps]	1400.0
RF out power [W]	1.0
Gain TX [dBi]	8.0
Loss TX line [dB]	-3.0
Loss misalign. point + polarisation [dB]	-2.4
EIRP [dB]	3.90
Loss Free Space [dB]	-148.83
Loss Atm. + Iono. [dB]	-0.01
Loss RX line [dB]	-3.0
Gain RX [dBi]	8.0
RX Noise Figure [dB]	2.80
T noise RX [K]	308.0
G/T [dB/K]	-21.0
Bit Error Rate target (spread signal)	0.1
Eb/N0 required [dB]	1.00
SNR real [dB]	0.209
SNR target [dB]	0.209
Spread signal Link Margin [dB]	0.001
Navigation message data rate [bps]	250
Navigation message bandwidth [kHz]	0.30
SNR real (after despreading) [dB]	37.7
SNR target (navigation message) [dB]	-29.8
Link Margin (after despreading) [dB]	67.5

4.3 Preliminary Performance Evaluation

The target accuracy of the relative navigation system is dictated by the Vulcain mission requirements, which specify that the inter-satellite distance shall be estimated with a precision of at least 10 meters (3σ). To evaluate whether the proposed system meets this requirement, a preliminary performance assessment of the ranging accuracy was conducted.

Using the procedure outlined by Psiaki and Mohiuddin [2], a rough estimate of the system's ranging accuracy was calculated. By applying the relevant parameters, as outlined in Table 6, to Eqn 1, a lower boundary for the 3σ ranging accuracy was determined to be approximately 15 cm. This result suggests that the proposed system not only meets but significantly exceeds the minimum precision requirement of the mission, demonstrating the potential of the design for precise inter-satellite distance measurement.

$$\sigma_{\varepsilon_\rho} = c t_c \sqrt{\frac{B_{\mathrm{DLL}} t_{\mathrm{eml}}}{2 t_c C/N_0} \left(1 + \frac{1}{t_{\mathrm{acc}} C/N_0}\right)} \qquad (1)$$

Where:

- $\sigma_{\varepsilon_\rho}$ is the standard deviation of the ranging error.
- c is the speed of light.
- t_c is the chip period of the pseudorandom number code.
- B_{DLL} is the bandwidth of the delay-lock loop (DLL).
- t_{eml} is the spacing between early and late code replicas used in the DLL's discriminator.
- t_{acc} is the integration time of the accumulator used in the DLL's discriminator.
- C/N_0 is the received carrier-to-noise density ratio.

Table 6: Vulcain ranging signal parameters and accuracy estimate

Parameter	**Value**
t_c	1/1023 ms
t_{eml}	1 chip (= 1/1023 ms)
t_{acc}	4 ms
C/N_0	1.78 MHz (62.5 dB-Hz)
B_{DLL}	0.1 Hz
$\sigma_{\varepsilon_\rho}$	0.1475 m

5. Breadboard Verification and Testing Campaign

The feasibility of the proposed navigation and communication system is currently being validated through a dedicated breadboard verification and testing campaign. This campaign is structured into four progressive stages, transitioning from a purely software-based Model-in-the-Loop (MIL) Simulink environment to a Hardware-in-the-Loop (HIL) configuration. This incremental approach allows for comprehensive verification, starting with the simulated system's performance and gradually testing its compatibility with the hardware selected for the Vulcain mission.

Each stage introduces additional hardware elements, progressing towards a full hardware-in-the-loop configuration that closely resembles the final system. This staged testing approach ensures that any issues related to system performance or hardware integration are identified and resolved early in the development process, reducing the risks associated with real-time hardware deployment in space.

5.1 Stage 0 - Model in the Loop

In the first stage, the GNC models of the two spacecraft are entirely simulated using Simulink. These models, which have been coded in accordance with guidelines for automatic code generation for AOCS/GNC Flight SW, interact with the dynamic and kinematic environment (DKE) and simulated ground station to test the basic functionality of the navigation algorithms. The simulated outputs from the NovAtel GNSS model provide the estimated position and velocity for each spacecraft. The performance of the system is evaluated entirely within the software environment to validate the correctness of the algorithms architecture. This stage, illustrated in Figure 6, ensures that the navigation, guidance and control logic performs as expected in a validated Functional Engineering Simulator (FES).

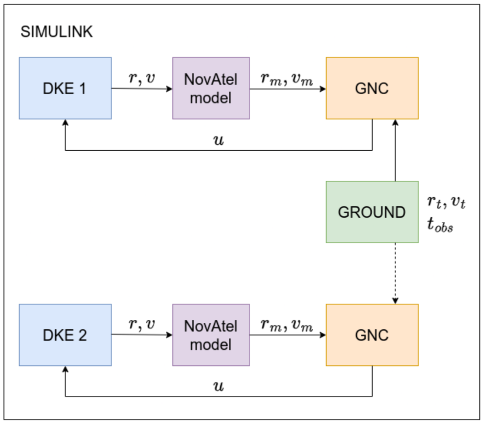

Fig. 6: Stage 0 - GNC models of the two spacecraft connected through Simulink line.

5.2 Stage 1 - Model in the Loop with SDR

The second stage introduces HIL verification, where real hardware components starts to be incorporated into the simulation. In this stage, the GNC models remain simulated, but the ISL between the spacecraft is emulated using the ADALM-PLUTO SDR. The GNSS data is transmitted between simulated spacecraft via the SDR, allowing for a more realistic test of the communication link and signal processing pipeline. Figure 7 depicts the setup.

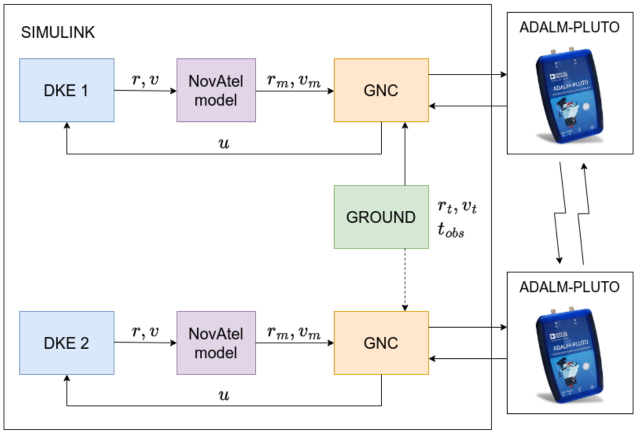

Fig. 7: Stage 1 - GNC models of the two spacecraft connected through ADALM-PLUTO SDR.

5.3 Stage 2 - Embedded Computers with SDR

Stage 2 builds upon the previous stage by further integrating hardware elements. The GNC models, which were previously simulated, are now executed in real-time on two embedded computers (Avnet ZedBoard) whose SoC is the same of the proposed GNC OBC. The ADALM-PLUTO SDR remains responsible for simulating the communication link. This setup allows for testing the system's performance under more realistic conditions, where actual hardware limitations such as processing power and real-time operation can affect performance. Figure 8 shows the embedded computers and SDR setup, which closely mimics the operational environment of the CubeSat platforms.

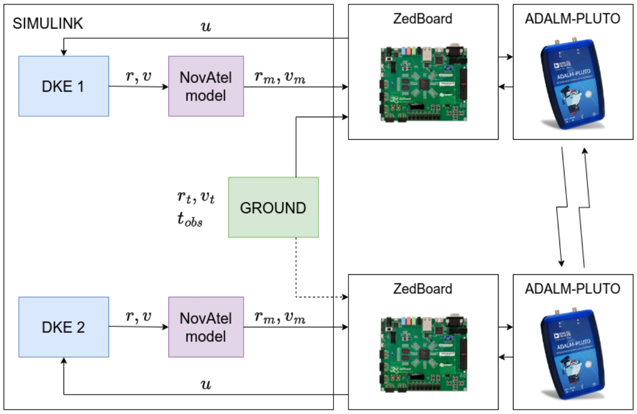

Fig. 8: Stage 2 - GNC model of the two spacecraft deployed (after autocoding) onto two embedded computers connected through ADALM-PLUTO SDR.

5.4 Stage 3 - Full Hardware Integration

The final stage of the breadboarding campaign, Stage 3, involves the full integration of the selected hardware components for the Vulcain mission. The GNC models are now running on the engineering model (EM) of actual Vulcain onboard computer, while the communication link is managed through an engineering model of the Vulcain ISL SDR. This stage, shown in Figure 9, provides a complete hardware-in-the-loop test that replicates the actual mission configuration as closely as possible. By this stage, the system should demonstrate full compatibility with the chosen hardware, ensuring that it meets the mission's performance and reliability requirements.

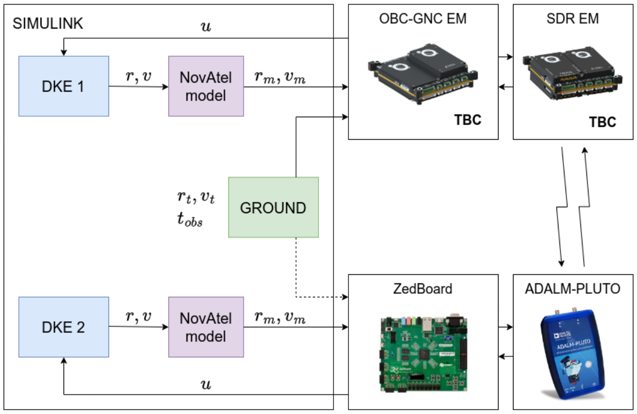

Fig. 9: Stage 3 - GNC model of the two spacecraft deployed (after autocoding) onto an engineering model of Vulcain OBC and connected through an engineering model of the ISL SDR.

6. Conclusions

The Vulcain mission aims at demonstrating significant advancements in the field of inter-satellite relative navigation using commercial off-the-shelf (COTS) software-defined radios (SDRs). This paper presented a novel approach to achieving this goal by leveraging a one-way ranging technique that transmits GNSS-like signals over an inter-satellite link (ISL). The use of COTS hardware not only reduces costs but also validates that high-performance navigation can be achieved with standard equipment.

The results suggest that this novel approach can achieve centimeter-level accuracy in range estimation between the CubeSats. The proposed signal design demonstrates a path forward for embedding sophisticated navigation capabilities into communication systems, making them more accessible to a wider range of missions.

Moreover, the testing and validation approach through a four-stage breadboard campaign, progressing from software-based models to hardware-in-the-loop (HIL) testing, will ensures that the system is thoroughly verified under realistic conditions. This methodology reduces the risk of failure in actual mission deployment by identifying and resolving integration challenges early in development.

These findings will contribute to making advanced navigation systems more feasible for small satellite missions, which increasingly play a critical role in scientific and commercial space exploration.

7. Acknowledgements

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