EXECUTIVE SUMMARY REPORT

ANGELOS (AUGMENTING GNSS TO PREVENT LOSS OF SERVICE)

Prepared by:	Alex Owens (GMV NSL) Terri Richardson (GMV NSL)
Approved by:	Terri Richardson (GMV NSL)
Authorized by:	Mark Dumville (GMV NSL)

ESA Contract No.:	4000131316/20/NL/GLC/hh
Code:	ESA-OSIP-ANGELOS-ESR
Version:	1.0
Date:	12/11/2021

DOCUMENT STATUS SHEET

Version	Date	Pages	Changes
1.0	12/11/2021	8	First version of the deliverable submitted to ESA.

EXECUTIVE SUMMARY

Currently, GNSS is the backbone of most Position, Navigation and Timing (PNT) solutions, in providing 24/7 continuous, all-weather, global coverage to an unlimited number of receiver-equipped users. There is an increasing dependency on the availability and reliability of GNSS. However, GNSS is widely known to be vulnerable to an evolving range of threats (natural and man-made, unintentional and deliberate). This drives the demand for an alternative, complementary and backup system to protect those critical applications that depend on GNSS from a safety, security and/or liability perspective. Harbour to harbour autonomous shipping will especially require robust and reliable PNT solutions with high integrity performance levels, as the availability of a human navigator is removed/decreased.

Recent analysis within the UK has aimed at quantifying the dependency on GNSS. Results estimate that a loss of GNSS for 5 days would generate a loss of £5B in economic activity to the UK [1]. This is the latest information and the authors suggest that this is a conservative estimate. Interesting to note however that this only accounts for a complete denial of GNSS. The report does not account for the impact of disturbances, disruption and confusion caused by degraded conditions to the myriad of applications.

To date, several studies have been undertaken in the maritime sector into the Ranging -mode concept. R-mode is a positioning system concept that involves the transmission of timely synchronised ranging signals using communications channels of existing maritime radio infrastructure [2].

Two core options have been analysed for R-mode: 1) use of MF beacons (DGNSS), 2) use of AIS/VDES. The second option is understood to be widely preferred due to reasons including MF susceptibility to sky-wave interference, narrow bandwidth and uncertainty over the long-term future of MF beacons [3]. VDES is the planned successor to AIS (Automatic Identification System), intended to address the current issue of over-crowding of AIS. It supports ship-to-ship and ship-to-coast communications as well as a satellite component. R-mode has the potential to be applied to both the terrestrial and satellite components of VDES, which may be referred to as VDE-TER and VDE-SAT respectively.

To this end, under the ESA Open Space Innovation Program (OSIP), a concept named Augmenting GNSS to Prevent Loss of Service (ANGELOS) has been developed, a system capable of providing Positioning, Navigation and Timing services for Maritime applications through a combination of space-based and terrestrial infrastructures. ANGELOS harnesses the satellite component of VDES to deliver a PNT service that will not be restricted to only terrestrial service areas alone. The concept also exploits existing recommendations for the signal of VDE-SAT, driving a standard acceptable to deliver ranging based services. ANGELOS aims to ensure that a VDES R-mode system benefits from the GNSS receiver industry in order to make the solution acceptable to the market and to become a reliable choice for augmentation to GNSS, for those applications that require uninterrupted access to PNT.

The study begins by considering the maritime domain, where various trends in the maritime sector that hold significance to the study are introduced and discussed. GNSS reliance and vulnerability are also analysed at a high level. Each of these trends and raised issues are summarised, where they are important in framing a consolidated list of user requirements. Concepts relevant include maritime traffic, increasing marine regulated travel areas, new communication frameworks and autonomous vessels. Relevant maritime stakeholders and regulators are also introduced to assist in defining the user-level requirements and ultimately, the definition of the system and its capability.

Alternative PNT technologies are judged as part of a response to the raised vulnerabilities of GNSS and the consolidated list of user requirements. Such considered technologies include dead reckoning, eLoran, radar, STL and terrestrial-based ranging from AIS and VDES maritime communication infrastructure. The alternative PNT however held significant shortcomings and limitations that were summarised as part of a list of advantages and disadvantages. It is in response to these shortcomings that ANGELOS is hoped to supplement.

The key system concepts are introduced for a VDE-SAT R-Mode capability, which is followed by a derivation of mission-level targets. Areas raised of particular concern is the time transfer system, receiver technology, RF environment as well as regulatory requirements. The system concept is considered in three core segments: space, control, and sensor. To assist in positioning ANGELOS as a future global system capability, alternative markets are also reviewed at a high level. Applications that are of potential interest for an additional system include Location-Based Services (LBS), Aviation and Automotive markets.

The User Equivalent Range Error (UERE) is evaluated by considering ionospheric contributions, pseudorange estimation error caused by tracking of the channel waveform and also the implementation of the Orbit Determination and Timing System (ODTS). Three different approaches are considered: Ground-based, Autonomous and GNSS- based ODTS. The ground-based approach involves a suite of Earth ground stations performing radiometric tracking with onboard high-accuracy clocks for time synchronisation; the autonomous approach involves using optical-based sensors to provide orbit determination; the GNSS-based approach includes a GNSS receiver on-board the VDES satellites in LEO with the potential addition of correction data for ionospheric errors. Each approach has a direct effect on the deliverable accuracy of the system, but also on the system resilience and feasibility. A system that is independent of GNSS is favoured for the means of PNT system classification but can come with worse performance or complexity to the system architecture. The most significant contribution to the user range error is likely to be the ionosphere, where the delay is more significant for VHF band signals, as considered by ANGELOS, than to GNSS L-band. However, modelling is only performed at a high level and the author notes that further investigation into the effects of ionospheric delay on VDE-SAT R-Mode should be carried out.

In order to quantify the error contributing term for the channel waveform in the UERE, existing VDE-SAT downlink waveforms are analysed in terms of their suitability for ranging. Statistical lower bounds on the ranging error have been derived for four consolidated transmission configurations, representing all eight VDE-SAT downlink MCS/Link IDs from the IALA Technical Specification of VDES [4]. The results support the feasibility of using existing VDE-SAT downlink waveforms (modulated with arbitrary user data) for ranging, noting that this approach would require a more complex receiver architecture compared to using dedicated R-Mode waveforms and would likely result in poorer coverage and performance. Four custom VDE-SAT R-Mode waveforms have also been designed and characterised in terms of the achievable ranging performance and impact on the VDE-SAT channel loading. The performance bounds accurately characterise the effect of different data (ranging) sequences and the threshold effect in Time-of-Arrival (TOA) estimation (i.e. a sudden increase in measurement error below a certain waveform-specific C/N0 threshold). The results suggest that in order to achieve satisfactory performance, while keeping the channel loading within reasonable limits, a VDE-SAT R-Mode System that utilises pseudoranging with four or more satellites will likely need to use Code Division Multiple Access (CDMA), allowing multiple R-Mode satellites to share the same frequency and time resources. In general, the results show that the ranging performance improves in direct proportion to the waveform bandwidth (or symbol rate) and the square root of its energy (or the transmission duration). Therefore, it is recommended that the VDE-SAT ranging signal uses the widest bandwidth available and the longest transmission duration possible, bearing in mind the impact this will have on the VDE-SAT channel loading.

The next step is to use derived UERE for each methodology of ODTS as an input to a service volume and performance analysis. Two types of satellite constellations are considered as an initial analysis, to emulate varying levels of a VDE-SAT R-Mode service. Firstly, a small satellite fleet or 'mini-constellation' to represent an initial 'early service' provision and secondly, a full global constellation acting as a final service with global coverage. Given that VDE-SAT should strive to achieve a global coverage that considers Arctic shipping routes, a polar orbit is required which covers high latitudes. A recommended VDE-SAT altitude of 600 km has been stated in [5], which is the best solution for downlink transmission power, complying with space debris regulations and achieving sufficient coverage given antenna performance. Four current and planned constellations (that are not delivering a VDES service) are utilised for a preliminary analysis of the VDE-SAT R-Mode performance. This is solely to test varying numbers of satellites within a constellation and not representative of a final VDE-SAT solution. These are exactEarth AIS (10-satellite fleet), Kineis IoT (20 satellites, near-Polar inclination), Iridium NEXT (72 satellites) and finally OneWeb mega-constellation (648 satellites). Two scenarios are assessed using GMV NSL's PNT system design and analysis simulation tool, NEMO, the first is a global analysis of performance and coverage and the second is a focused analysis of the UK coast which also includes the simulation of VDE-TER R-Mode transmitting stations to supplement the VDE-SAT solution. It is assumed that the existing AIS base stations situated on the UK coast including those which are operated by the Maritime Coastguard Agency (MCA), will be upgraded to include VDES functionality. A caveat is highlighted that the original purpose of these base stations is intended to support maritime communication systems and so the geometry may not be ideal to support a positioning system. Inputs to the analysis include the UERE budget derived (includes ODTS errors, SIS waveform and ionospheric effects), Keplerian orbit parameters for the designated constellations and integrity parameters derived from IALA and IMO standards and recommendations.

For a small number of satellites in a constellation that is not designed to offer a ranging service (i.e. four satellites in the field of view to a user), ground-based ODTS with a single-satellite positioning technique is the only methodology that produces any form of quantifiable result. Operating as a standalone backup marine navigation system, the results including those with autonomous and GNSS-based ODTS, would not meet the requirements. VDE-SAT operating with a small number of satellites may be able to provide a position fix as the subsequent ranging measurements are taken, but this would imply that the VDE-SAT system would have to work in conjunction with other sensors on-board a vessel to provide redundancy when GNSS experiences outages or failures. A larger number of satellites as is displayed in the Iridium NEXT constellation in combination with VDE-TER ranging stations may begin to approach the requirements stated for a backup system but through the analysis, this is only the case for ground-based ODTS for VDE-SAT. The implementation of autonomous and GNSS-based ODTS for the ranging error gives rise to very similar results in terms of the horizontal position performance but still do not meet the required accuracy. However, the current TRL of the autonomous approach is still very low, with further development of chip-scale atomic clocks (CSAC's) expected which may help to improve timing accuracy and improvement of optical-based orbit determination approaches. Finally, assessing VDE-SAT configured in a mega-constellation, the achieved horizontal position and HDOP in combination with VDE-TER does not offer much improvement than the case with only VDE-SAT. It is clear that VDE-TER enhances the solution for smaller-sized constellations but there appears to be a threshold where an increase in the number of satellites no longer offers tangible benefits to the system in terms of position accuracy. However, the addition of VDE-TER brings notable benefits in terms of the integrity of the system, providing a redundant VDES ranging method if a VDE-SAT is unavailable for a particular reason.

The most practical approach moving forward is a scenario with a small number of VDE-SAT R-Mode satellites that complement ranging with VDE-TER stations in ports and coastal regions. Not only are the coastal regions more at risk of harmful GNSS interference than that of the oceans, but this is the only approach that can deliver an adequate result with a low number of satellites and would allow the start of development and technology demonstration. The main objective in the early stage of deployment should be at least to provide a position fix for when a vessel experiences disruption to GNSS services. Vessels should make use of existing inertial navigation systems once a fix is obtained, as continuity will not be sufficient in the early stages for VDES R-Mode to function as an independent navigation system. It is hence concluded by the analysis that a minimum of two VDE-TER stations should be available for ranging at all times in high-risk areas such as ports, to ensure availability. Finally, regarding the method of ODTS to be recommended, a ground-based approach with satellite control stations and timing dissemination should be utilised in the early stages of development. This is more than feasible for a low number of satellites and so reduces any overall potential complexity in the ground segment.

The next factor to consider is the VDE-SAT R-Mode Ground Segment. A large part of the ground segment architecture will depend on the level of service provided, whether it is a small number of satellites or a full global constellation. Given that the objective of this study is to determine how independent a VDE-SAT R-Mode service can be from GNSS, an important consideration is the orbit determination and timing method. For a navigation system such as Galileo, the scale of the ground segment is particularly large and complex due to the accuracies needed (a larger error in orbit determination of a satellite contributes to a larger user range error). A key dependency on this is time synchronisation. It is important that VDE-SAT R-Mode signals are synchronised to a common reference time such as UTC, in order to maintain interoperability with other PNT ranging systems. Given the recommendation that a ground-based ODTS should be implemented, this indicates that high-accuracy and stable oscillators onboard the satellites are needed in order to reduce the number of ground stations required to correct for clock and ephemeris drift. This presents a difficult challenge to the VDE-SAT R-Mode payload design as typical GNSS clocks use power levels that would be considered too high for use on small satellites, such as CubeSats. In addition to this, they are often large in volume, have a significant mass and are an expensive technology considering that small satellites in LEO will have a shorter life than those in MEO. Chip-Scale Atomic Clocks (CSAC's) and Crystal Oscillators such as OCXO, TCXO, EMXO and VCXO hold good levels of accuracy and may help to provide an alternative to large atomic clocks but ultimately suffer from long-term stability, requiring more regular clock corrections from ground stations.

Taking the approach that VDE-SAT R-Mode requires frequent correction of the satellite oscillator, the ground segment architecture to enable this must be considered. The likes of GNSS systems employ a global suite of sensors in known locations to determine the clock offsets of the space vehicles which are then compensated for via broadcasts with offsets in the navigation data message. Relating to a VDE-SAT R-Mode service, it would be recommended that a similar methodology is implemented where VDES R-Mode sensors (or reference receivers) are deployed in fixed known locations on the shore, where information on clock status and time is passed to the VDE-SAT control segment and/or timing facility to provide relevant corrections for the satellites. This method also implies that an atomic clock reference may not be needed at each ground terminal, but only at a central facility to generate R-Mode System Time (RMST). A time transfer method that would mitigate the need for global distribution of ground station terminals is dissemination via inter-satellite link (ISL). For the implementation of ISL within a

VDE-SAT R-Mode architecture, there are advantages to be gained but also limiting factors that need to be carefully considered. The clear advantage that ISL brings for a small satellite fleet or constellation is less reliance on ground stations for the uplink of mission data. This is particularly useful for instances where a VDE-SAT is passing over oceans where there is limited or no visibility to ground stations. A 'master' satellite with a highly-stable atomic clock may also act as a timing reference for the other satellites in the constellation. Given that ISL time synchronisation is still only at a very low technology readiness level (TRL), it may not be suitable to implement in a VDE-SAT R-Mode system at first deployment, but perhaps as part of future generations of the satellites. GNSS-based time synchronisation is ruled out at this stage to ensure that the VDE-SAT R-Mode system remains non-reliant and hence non-vulnerable to GNSS service outages.

It is intended that the VDE-SAT and VDE-TER communication functions will be fully integrated into the shipborne VDES equipment. Hence the shipborne VDES equipment will preferably utilize one combined transmitting/receiving VDES antenna system. Further, VDE-SAT has been designed to enable signal reception through the standard maritime VHF antenna, i.e. a vertically polarised dipole. Therefore in its present state further development into the user antenna is not a requirement however the additional investigation into the multipath mitigation may be required.

The Multi-System Receiver (MSR) will be the primary "user" of the VDE-SAT R-Mode System. In theory, the unit will house a VDE-SAT R-Mode Sensor module (along with modules for other variants of R-Mode, GNSS and possibly other PNT systems) and provide electrical power and synchronisation signals to the VDE-SAT R-Mode Sensor. The unit also sends configuration & control commands to the VDE-SAT R-Mode Sensor and accepts/processes the response. Commercial receivers for VDES R-Mode have not currently been developed, therefore to achieve the user requirements in ANGELOS, the VDE-SAT R-mode shipborne receiver must be developed and tested.

Finally, a development roadmap is required in order to achieve a fully operational VDES R-Mode System. This will require further concept development of the VDE-SAT Signal and message data design, ODTS feasibility and receiver concepts. This may lead to the technology development of VDE-SAT R-Mode receivers and the satellite payload, demonstration of VDES R-Mode signals and user operation, ultimately leading the way to the full realisation of the service.

REFERENCES

1. Satellite-derived time and position: a study of critical dependencies. Government Office for Science. 2018.
2. R-Mode Baltic – A user need driven testbed development for the Baltic Sea, 27th September 2018, ION GNSS+ 2018, Dziewicki, M., Gewies, S., Hoppe, M.
3. MarRINav D4 PNT R&I Technologies and Integration v1.0, 18th September 2019, Williams, P. et al.
4. The Technical Specification of VDES, IALA Guideline 1139, Edition 3.0, IALA, June 2019.
5. Technical characteristics for a VHF data exchange system in the VHF maritime mobile band, ITU-R M.2092-0, ITU. 2015.

END OF DOCUMENT