Cynergy4ME

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Table of contents

1 Executive summary

This deliverable D3.5 provides an overview of the hardware components developed and specified in WP3.3 to support Supply Chain 4 demonstrators. It covers two complementary contributions:

- the radar-based V2V (radar-to-radar) communication for SC4 Demo 4.1 "Traffic Flow Optimization",
- the satellite-enabled sensing component based on artificial corner reflectors (ACRs) and InSAR processing supporting SC4 Demo 4.2 "Road Condition Monitoring with Satellite Data".

Demo 4.1 evaluates three traffic scenarios—emergency braking, traffic-jam detection/mitigation, and platooning—under three operating conditions (baseline, radar-based V2V communication, and V2I communication) in a simulation-driven assessment environment, with the WP3.3 contribution enabling the radar-based communication condition.

The work is driven by the WP1 requirements and KPIs relevant for radar-based communication, in particular the latency target below 15 ms and the demonstration of combined sensing and communication radar capability.

In parallel, the INSAR contribution defines and validates hardware-supported satellite radar reference targets (ACRs) and associated processing steps that allow infrastructure-scale deformation monitoring and risk-layer generation for Demo 4.2 UC3.

Together, the two contributions expand the sensing and communication hardware basis required for SC4 demonstrators and prepare the ground for subsequent integration and validation work packages.

2 Publishable summary

This deliverable summarizes WP3.3 hardware contributions to Cynergy4MIE Supply Chain 4 demonstrators that target safer and more efficient mobility through improved situational awareness and cooperative functions.

For Supply Chain 4 (SC4) Demo 4.1, the deliverable describes an in-vehicle radar platform and its extension approach that allows investigation of radar-based vehicle-to-vehicle communication as an additional localized, low-latency channel, alongside baseline and infrastructure-based communication. The demonstrator focuses on representative traffic scenarios such as emergency braking, traffic-jam mitigation and platooning, assessed in a simulation-based environment

For SC4 Demo 4.2, the deliverable describes the satellite-enabled sensing hardware concept based on artificial corner reflectors and the associated processing steps that support road-condition and risk-layer generation at scale.

3 Introduction & Scope

3.1 Purpose and target group

The purpose of this deliverable is to document and consolidate the WP3.3 hardware components and specifications that enable SC4 demonstrator development, integration, and validation. The report provides engineering-level descriptions of the hardware baselines, project-specific extensions, and planned validation hooks for:

- SC4 Demo 4.1 radar-based V2V communication hardware using an automotive radar kit platform;
- SC4 Demo 4.2 satellite-enabled road monitoring using artificial corner reflectors as stable reference targets for InSAR-based deformation sensing.

The target group includes system architects and integrators (WP2/WP5), algorithms and tooling developers (WP4), and validation teams (WP6), that require consistent and traceable hardware reference aligned with WP1 requirements and demonstrator KPIs.

In addition, the document supports project management and reviewers by summarizing the technical status and the planned next steps toward demonstrator-level verification.

3.2 Contributions of partners

Chapter	Partner	Contribution
1-3	IFAT	Intro and summary
4.1	IFAT	Chapter about Demo 4.1
4.2	INSAR	Chapter about Demo 4.2
5	IFAT	Conclusion
6-9	INSAR/IFAT	References and List of…

3.3 Relation to other activities in the project

The hardware work documented in this deliverable is anchored in the WP1 requirement baseline and supports the system-level architecture and validation flow of the project.

For Demo 4.1, inputs include the SC4 use-case definitions (emergency braking, traffic-jam mitigation, platooning), the three operating conditions (baseline, radar-based V2V communication, V2I communication), and the simulation-based evaluation approach that considers communication effects such as latency and reliability constraints. Outputs are the defined radar hardware baseline, the Cynergy4MIE-specific extension approach for radar-to-radar communication, and the HW/SW partitioning assumptions that will be used by WP4 to implement and assess communication decoding and evaluation tooling, and by WP5/WP6 to plan integration and verification steps against KPIs.

INSAR is directly involved in SC4 Demo 4.2 UC3 Road Condition Monitoring with Satellite Data (Supply Chain 4) and SC5 Demo 5.1 UC2 post-earthquake scene analysis utilizing satellite synthetic aperture radar and C-SLAM (Supply Chain 5). Artificial corner reflector (ACR) algorithms and methods developed in WP3–Task 3.3 are intended to support both use cases. In the road condition context, ACRs can be deployed along critical road corridors and in active zones with limited natural backscatter to create a dense, quality-controlled reference network for InSAR risk layers used in UC3. Here, radar reflectivity simulation, monitoring, and displacements decomposition improve the reliability and interpretability of deformation signals that feed into the dynamic road-condition / risk overlays shared with SC4 partners. In the post-earthquake UC2 scenario, ACRs can be pre-installed around key infrastructure (bridges, dams, slopes or urban sectors) and, where appropriate, co-located with global navigation satellite system (GNSS) observations to tie satellite-derived deformation maps to a stable geodetic reference frame; this increases the accuracy of disruption maps and supports mission planning and validation for multi-agent SAR and C-SLAM operations. Across both supply chains, the ACR toolbox and methods provide a shared, reusable foundation for high-precision satellite radar interferometry within Cynergy4MIE.

4 Description of the technical work

4.1 Hardware Design for Demo 4.1 Traffic flow optimization – Radar Based V2V Communication (IFAT)

SC4 Demo 4.1 "Traffic flow optimization of ADS for emergent extrinsic efficiency" investigates how cooperative, connected driving can improve traffic efficiency and safety by enabling vehicles to share situational awareness and coordinate actions in real time. The demonstrator evaluates three representative traffic scenarios—UC1 Emergency Braking, UC2 Traffic Jam Detection and Mitigation, and UC3 Platooning—each executed under three operating conditions: (A) baseline without communication, (B) V2V radar-based communication, and (C) V2I communication. The overall assessment is performed in a simulation-based environment, where both the traffic behavior and the communication effects like latency, packet loss or bandwidth constraints, can be systematically varied to quantify impacts on scenario-specific KPIs. Figure 1 gives an overview of the partner contribution and interaction within SC4 Demo 4.1.

Within this demonstrator context, WP3.3 focuses specifically on the hardware development enabling Condition B: radar-based V2V (radar-to-radar) communication, led by IFAT as the contributing partner for radar-based communication. The WP3.3 contribution provides the radar communication hardware basis required to transmit/receive the essential cooperative messages that support time-critical maneuvers such as emergency braking warnings and coordinated platooning actions, and to enable a comparative evaluation against baseline and V2I-enabled setups. In this way, WP3.3 delivers the enabling radar-communication building block that Demo 4.1 uses to study how low-latency, localized V2V exchange can increase robustness and performance of cooperative traffic functions under realistic communication constraints.

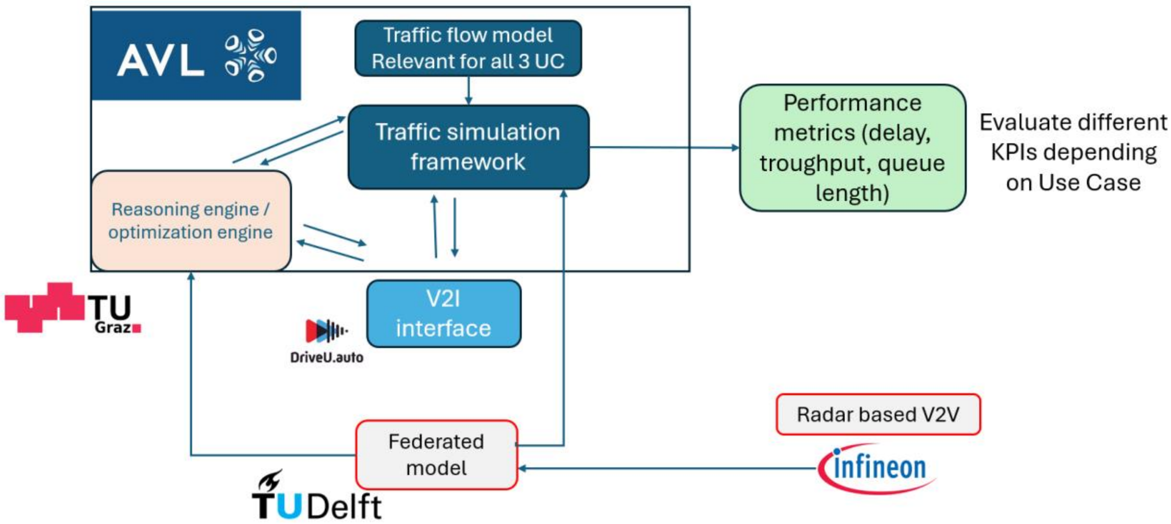

FIGURE 1: DEMO 4.1 OVERALL SETUP

4.1.1 Specification

This chapter translates the WP1 requirements baseline into a concise specification view for SC4 Demo 4.1, providing the traceable link between system-level expectations and the technical implementation focus in WP3. The following Table 1 consolidates the subset of WP1 requirements that are directly relevant for the radar-based V2V communication contribution and defines the measurable targets that will be used to verify compliance and demonstrator readiness.

Together with the key performance from WP1.4 – Demo 4.1 indicators driving the hardware design and validation effort:

· KPI-2: Radar-based communication latency below 15 ms.

· KPI-4: Demonstrate a combined communication and sensing automotive radar system

Figure 2 shows the anticipated in-vehicle setup where the front radar acts as the V2V communication receiver and the rear-looking radars act as transmitters.

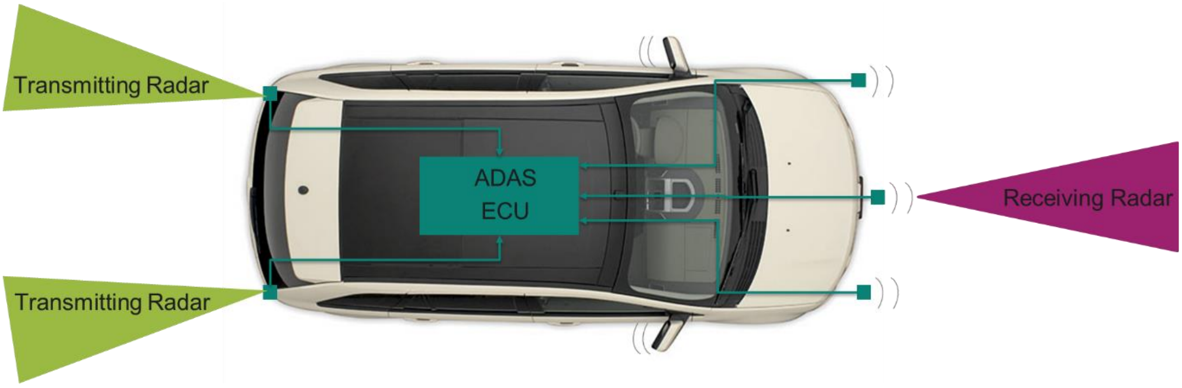

FIGURE 2: ANTICIPATED SETUP IN A CAR SHOWCASING THE USAGE OF THE FRONT RADAR AS RECEIVER AND THE BACK LOOKING RADARS AS TRANSMITTER

TABLE 1: DEMONSTRATOR 4.1 HARDWARE REQUIREMENTS

Req. ID	Main Category	Requirement Type	Functional Area	Priority	Description	Rationale
F4.1.4	Functional Suitability	Radar- Based Communication	Radar- Based Communication	Medium	The system shall use automotive radar to transmit information about vehicle (de)acceleration and turn direction, and shall synchronize multiple radar sensors.	Provides a low-latency, alternative communication channel for local traffic optimization. Synchronization is needed for multiple communication partners.
NF4.1.1	Performance	Latency	Radar- Based Communication	High	Latency of radar-based communication shall be below 15 ms.	Short latency is key for local traffic flow optimization like platooning and emergency braking, offering an advantage over V2X.
NF4.1.2	Performance	Range	Radar- Based Communication	High	The range of radar-based communication shall be at least 150 m.	A 150 m range covers full local traffic flow scenarios in urban environments.

4.1.2 Identification of components

The demonstrator builds on an existing in-Vehicle Advanced Radar Kit platform, as depicted in Figure 3 and Figure 4, used as a stable baseline for sensing, control, and in-vehicle integration. The baseline kit provides an automotive mmWave radar front-end with an embedded control/compute domain and an in-vehicle interface via Automotive Ethernet (1000BASE-T1) to connect to the in-vehicle ADAS/ compute environment.

4.1.2.1 Radar Kit Key Components

At hardware level, the radar front-end is based on a radar MMIC (Monolithic Microwave Integrated Circuit). The MMIC integrates key RF building blocks required for Frequency-Modulated Continuous-Wave (FMCW) radar operation, including waveform generation (ramp generation) and receiver conversion stages that provide digitized radar data to the embedded controller for further handling.

The embedded controller manages radar configuration and data handling and provides the interface towards the in-vehicle compute system used in the demonstrator setup.

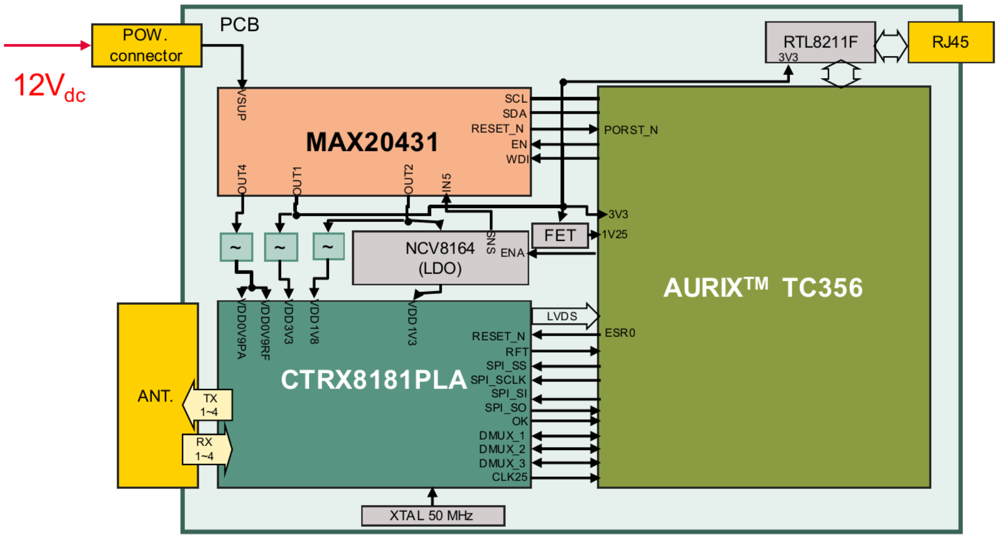

FIGURE 3: RADAR KIT HARDWARE ARCHITECTURE FOR COMBINED RADAR SENSING AND V2V COMMUNICATION DEMONSTRATION

FIGURE 4: RADAR KIT PROTOTYPE HARDWARE FOR COMBINED SENSING AND COMMUNICATION TESTS

Radar MMIC: Infineon CTRX

The Radar Kit RF front-end is based on the Infineon CTRX radar MMIC family. Based on the first Cynergy4MIE technical review, this MMIC includes an advanced radar transmitter ramp generator and a digital PLL/sequencer that is already capable to support the planned communication approach in this project, i.e., encoding data into FMCW ramp characteristics as described in the Design Concept.

A potential outcome of this project is to derive new or refined requirements to further optimize the radar MMIC for communication (e.g., ramp programmability, modulation flexibility, robustness, and verification hooks). This depends on the research outcome and demonstrator validation results generated within Cynergy4MIE and will be consolidated once quantitative results are available.

MCU: Infineon AURIX Microcontroller

The Radar Kit uses an Infineon AURIX microcontroller (MCU) as the embedded controller for radar configuration, deterministic timing control, and data handling. The AURIX MCU acts as the control anchor of the radar module and supports the interface towards the compute environment via Ethernet in the demonstrator setup.

For Demo 4.1, the AURIX MCU is treated as the stable platform layer responsible for reliable sensor control and data provisioning, while communication decoding and demonstrator-level evaluation can be executed on an external compute unit.

4.1.2.2 Cynergy4MIE-Specific Extension For Radar-Based V2V Communication

Cynergy4MIE extends the baseline Radar Kit to enable radar-to-radar V2V communication for Demo 4.1 Condition B, allowing direct comparison against the baseline and V2I conditions.

Baseline is the radar sensing chain and in-vehicle integration over Automotive Ethernet.

Newly developed on this stable baseline is the communication feature enablement using the radar waveform mechanism described in the Design Concept, plus demonstrator-specific auxiliary signals/ interfaces required for controlled development, testability, and synchronization in the prototype setup.

The radar-based communication method developed in Cynergy4MIE is intended to be usable with already existing automotive radar sensor MMICs. The idea is to avoid requiring a separate dedicated V2V radar, and instead reuse the radar sensor that is already widely available in today's vehicles for both sensing and communication.

For the demonstrator, the existing radar module is modified for development and validation purposes. Specifically, limited auxiliary board-level signals/interfaces are added to support prototype integration and the chosen synchronization approach (e.g., deterministic timing alignment during experiments). These additions enable repeatable testing and KPI evaluation.

Target direction for a future radar module: once the concept is matured, the intent is to implement radar-based communication without introducing additional external hardware modules, leveraging the radar sensor already present in the vehicle while preserving the primary sensing function.

4.1.2.3 *Firmware Interface and Processing Split*

The Radar Kit can provide processed radar outputs. For Demo 4.1, the current strategy is to keep the baseline firmware stable and focus on showcasing the radar-based communication feature. Communication decoding and demonstrator-level evaluation are executed on an external compute unit to keep the setup modular and to support rapid iteration against KPI targets.

4.1.3 Draft concept design

The concept design described in this section presents a novel approach for enabling Vehicle-to-Vehicle (V2V) communication using existing automotive radar systems. By encoding data directly into the frequency ramps of Frequency-Modulated Continuous-Wave (FMCW) radar signals, this method allows for communication between vehicles without introducing additional hardware. The proposed demonstrator system showcases how vital driving information, such as braking indicators or turn signals, can be transferred between vehicles on the road. This mechanism has the potential to enhance road safety and efficiency immediately, leveraging radar technology that is already present in modern vehicles.

FIGURE 5: TRAFFIC SCENARIO

The demonstrator system is intended to replicate a realistic automotive environment, where radar sensors function both as environmental detectors and as data transmission devices. The outlined design leverages idle periods within a radar's operational cycle to transmit encoded information without interfering with its primary function. This section provides details on the proposed communication technique and examines how the system operates, including its hardware and signal processing framework.

System Overview

The foundation of the radar-based communication system is built around the already available automotive radar kit from Infineon as described in the previous chapter. The demonstrator intends to show how two vehicles driving in a queue at a fixed distance can communicate. A leading vehicle's rear-facing radar acts as the transmitter and encodes data in its frequency ramps. The following vehicle's front-facing radar acts as the receiver and decodes the transmitted information through signal processing. While automotive radar traditionally serves obstacle detection functions, this dual-functionality setup demonstrates its capability to handle data transmission as a means of achieving V2V communication using the radar sensing hardware that is part of state-of-the-art cars.

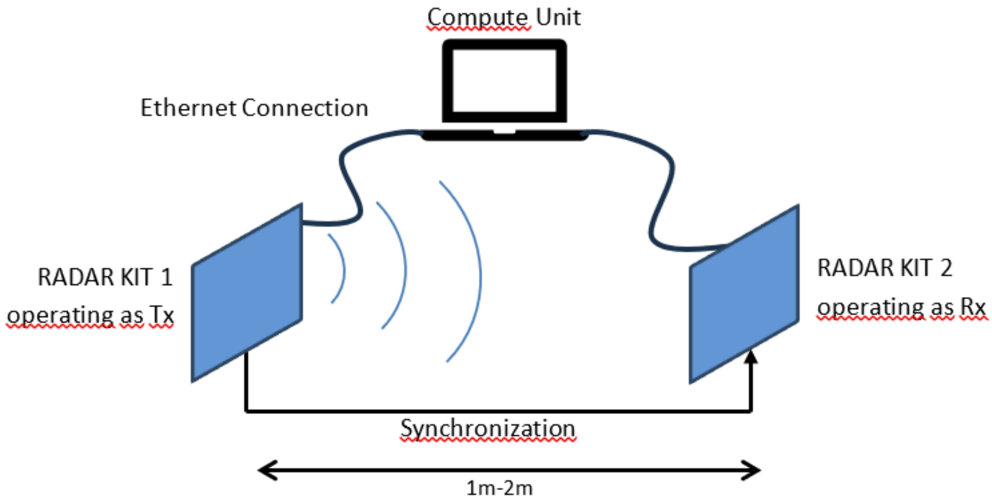

FIGURE 6: PRINCIPAL HARDWARE SETUP

The communication design ensures that the radar's original environment-sensing function is preserved while utilizing unused low-power durations for data modulation and transmission. The signal processing chain on the receiving radar then extracts the transmitted data and reconstructs the original messages. A synchronized setup between the radar systems ensures seamless communication.

Working Principle of the Demonstrator Setup

The demonstrator enables data transmission between two radars using the proposed frequency-modulation framework. The essential steps in the system operation are outlined below:

Transmission Process:

- A data source, such as a notebook or microcontroller, serves as the input terminal where data symbols (e.g., braking indicators, turn signals) are specified.
- These symbols are encoded into frequency ramps by varying the slope steepness, with the radar hardware generating and transmitting the modulated waveforms.
- The radar's rear-facing antenna transmits the modulated waveform to the following vehicle.

Reception and Decoding Process:

- The receiving radar antenna captures the modulated signal from the leading vehicle.
- The signal is down-converted for processing using a Continuous Wave (CW) reference signal.
- Digital signal processing decodes the signal to obtain the data. The decoded symbols are displayed on a notebook or other visualization endpoints, simulating the successful transmission of critical vehicular data.

Synchronization:

- Accurate synchronization is essential for establishing seamless communication. In the demonstrator, a wired synchronization method via Ethernet is implemented to achieve precise timing between the two radar units. In practice, over-the-air synchronization techniques could be deployed to achieve similar results.

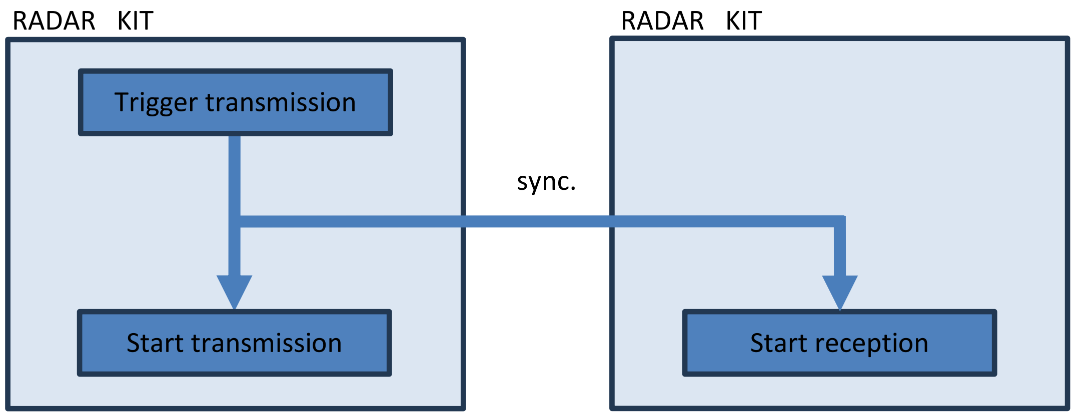

FIGURE 7: PRINCIPLE OF INTERNAL TRIGGERING OF TRANSMISSION AND RECEPTION

Feasibility and Implications:

The proposed radar communication system leverages existing automotive radar hardware, making it an immediately implementable solution for enabling V2V communication. By avoiding the need for additional components, the system mitigates cost and complexity barriers while maximizing the utility of current radar deployments on vehicles.

4.1.4 First results

At the current stage, the work has established the technical feasibility and integration direction for the radar-based V2V communication concept in SC4 Demo 4.1. The demonstrator setup and dataflow have been defined to enable radar-to-radar communication by encoding symbols into FMCW ramp characteristics while preserving the radar's primary sensing function, with a controlled prototype synchronization approach implemented via Ethernet for repeatable experiments. Initial design reviews indicate that the selected radar platform (Infineon automotive radar kit) provides the necessary waveform generation capabilities to support this approach, and the HW/SW partitioning has been set such that communication decoding and demonstrator evaluation can be executed on an external compute unit while keeping the radar kit firmware stable for sensor operation. The next technical step is the end-to-end prototype validation in the target Demo 4.1 scenarios (Condition B) with quantitative measurements focusing on the project KPIs, in particular verifying radar-based communication latency below 15 ms and demonstrating combined sensing-and-communication capability on an automotive radar module.

4.2 Hardware Design for Demo 4.2 Road condition monitoring – Artificial Corner Reflector Sensors (INSAR)

Under Supply Chain 4 – Demonstrator 4.2 "Road Condition Monitoring with Satellite Data", INSAR defines a satellite-enabled sensing component that uses interferometric synthetic aperture radar (InSAR) and artificial corner reflector (ACR) to monitor road infrastructure and its surroundings at scale. ACR units are deployed near critical road sections as stable, calibrated in-situ targets for satellite radar measurements, enabling high-precision displacement time series to be derived from multiple satellite tracks and decomposed into vertical and horizontal displacement components, capturing landslides, subsidence, slope instability and structural deformation in the vicinity of roads. Around these sensors, satellite radar data are further processed to delineate "zones of influence" where terrain or structural changes may affect road infrastructure or its neighbourhood, providing an early-warning layer for landslides, embankment failures and ground settlement that may impact road safety. These zones are translated into dynamic road-condition and risk layers that can be overlaid on advanced driver-assistance systems (ADAS) maps, directly supporting SC4 KPIs related to dynamic risk overlays, improved road-irregularity detection, temporal evolution of road conditions and optimized deployment of vehicle-based sensors. Within WP3 and Task 3.3, ACR sensors are treated as dedicated components of the sensing infrastructure, complementing other sensors by providing a stable reference for precise satellite-based deformation measurements. INSAR develops algorithms and methods to process satellite radar imagery and ACR signals (Czikhardt et. al., 2021), derive displacement time series, and diagnose ground or structural behaviour, supported deployment based on signal-to-clutter ratio (SCR), planning, and quality-control tools that ensure suitable installation sites and reliable measurements. All results are integrated into a web-based visualization platform, equipped with an interface for external sensors and, where necessary, custom web map services. It allows to ingest and visualize satellite products, ACR time series, and additional spatial data that can be inspected and exploited by other partners and demonstrators. The overall objective is to move from a reactive, purely vehicle-centric sensing to a proactive, satellite-guided monitoring concept that helps infrastructure managers and automated driving systems (ADS) developers prioritise field inspections, optimise the deployment of ground-based sensors and maintain up-to-date risk layers within ADAS maps.

4.2.1 Identification of components

Artificial corner reflectors (ACRs) are dedicated hardware targets for synthetic aperture radar onboard satellites that provide a stable, well-defined radar response, and in our concept, they exist in two main forms: passive corner reflectors and compact active transponders (CAT) (Czikhardt et. al., 2022). Passive corner reflectors (Figure 7) are purely mechanical reflectors, typically metal trihedrals, that reflect the incoming radar signal back towards the sensor; they behave like ideal point scatterers with very high radar cross section (RCS) and excellent phase coherence, making them robust, maintenance-free reference points for calibration and deformation monitoring. Active compact transponder units (Figure 8), by contrast, are compact electronic "radar transponders" that receive the incident satellite radar signal, amplify it and transmit it back to the satellite in a controlled way, offering a strong, programmable, and highly coherent response that can be optimised for specific satellites, polarizations and observation geometries. Both types of ACRs share the same role in the system architecture: they act as precisely located, long-term stable reference targets that anchor displacement time series, support accurate geolocation and calibration of satellite radar data, and provide reliable ground truth for monitoring subtle motions of road infrastructure and its surroundings.

FIGURE 8: PASSIVE CORNER REFLECTOR (LEFT) AND COMPACT ACTIVE TRANSPONDERS (MIDDLE, RIGHT)

4.2.2 Draft concept design

4.2.2.1 Signal-to-clutter Ratio Analysis

Signal-to-clutter ratio (SCR) analysis (Czikhardt et. al., 2022) is a key first step when working with artificial corner reflector sensors, as it quantifies how strongly the reflector signal stands out against the surrounding radar backscatter (“clutter”). By combining the known radar cross section (RCS) of a given reflector design with long-term estimates of background clutter from Sentinel-1 data, SCR analysis produces spatial maps of expected reflector performance. These maps are then used to screen candidate locations and identify sites where the required reflectivity threshold for a given displacement accuracy is met, and where reflectors are sufficiently separated from other strong scatterers. In this way, SCR analysis directly supports decisions on where passive corner reflectors and compact active transponders can be installed to provide stable, coherent targets for deformation monitoring around road infrastructure.

Within this project stage, we have implemented this concept in practice. Algorithms for processing satellite radar data and signals from artificial radar reflectors/sensors have been developed, including functions for SCR estimation and reflector performance assessment. Reflectivity analysis of Sentinel-1 data was carried out for selected pilot areas, including the A2 highway site near Graz (Demo 4.2), as a preparatory step for potential deployment of artificial radar reflectors and for deriving general design guidelines for suitable monitoring locations. The resulting SCR layers and guidelines are used to support planning of future sensor deployment in Demonstrator 4.2 and to ensure that installed ACRs operate in environments where their signal is both detectable and reliable over the long term.

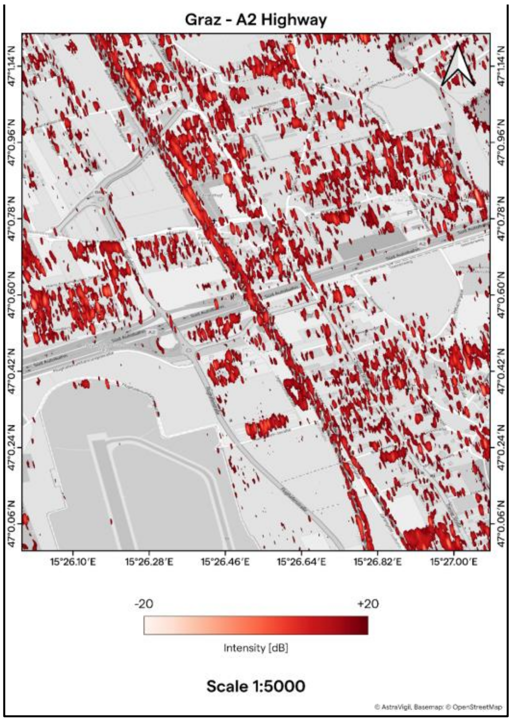

FIGURE 9: EXAMPLE OF ESTIMATED SCR AROUND LINEAR STRUCTURE OF THE A2 HIGHWAY IN GRAZ

Since deployment of sensors in Cynergy4MIE test sites is planned for later phases, several existing corner reflector sensors located in Austria (AUT), Slovakia (SVK) and Czechoslovakia (CZE) were used to test the complete signal-processing chain and its integration into the developed platform. Figure 9 shows the results obtained from the bridge in CZE, where the solution captured reflections from corner reflectors placed on the bridge structure.

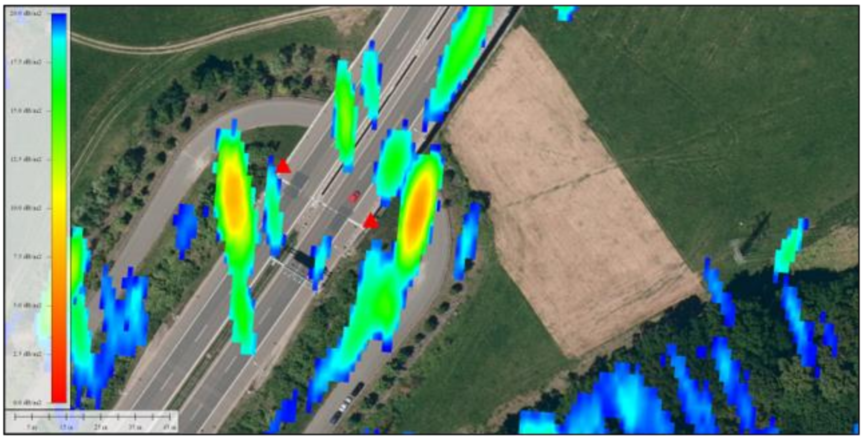

FIGURE 10: EXAMPLE OF ESTIMATED SCR AROUND THE BRIDGE IN CZE

4.2.2.2 Persistent Scatterer Interferometry

Persistent scatterer interferometry (PSI) (Ferretti, 2001) is a multi-temporal satellite radar interferometry technique that focuses on radar targets which remain coherent over long periods of time, such as buildings, or artificial corner reflectors. Starting from a co-registered stack of satellite radar images over the area of interest (Czikhardt et. al., 2021), the PSI chain first builds interferograms and identifies persistent scatterer (PS) candidates based on the stability of their radar amplitude. These points are then connected into a network, and their phase is analysed to separate deformation from other effects by resolving phase ambiguities, estimating and removing the atmospheric phase screen, and modelling residual heights and displacement parameters. The final step converts the corrected phase histories into line-of-sight displacement time series for each PS.

PSI analysis was carried out over the A2 highway segment near Graz using Sentinel-1 data (Bakon et. al., 2014; Teixeira et. al., 2024) from three orbit tracks (ASC146, DSC22, DSC124) for the period January 2020–April 2025. Because asphalt acts as a specular reflector and returns from the road surface itself are limited, displacement information was mainly derived from adjacent stable structures such as poles, noise barriers, buildings and embankments, complemented by partially coherent targets selected using amplitude dispersion and phase-stability criteria. A similar PSI analysis was also performed over the test area in CZE, where existing reflectors and nearby infrastructure elements provide a dense set of monitoring points. In the context of the artificial corner reflector toolbox and WP3 sensor activities, sensors are treated as particularly strong and stable persistent scatterers: once their responses are extracted from the set of satellite radar images and passed through the PSI chain, we obtain precise displacement time series at each reflector location. These artificial reflector-based time series form the basis for subsequent decomposition into vertical and horizontal components and for their integration into road-condition and risk layers for ADS/ADAS applications.

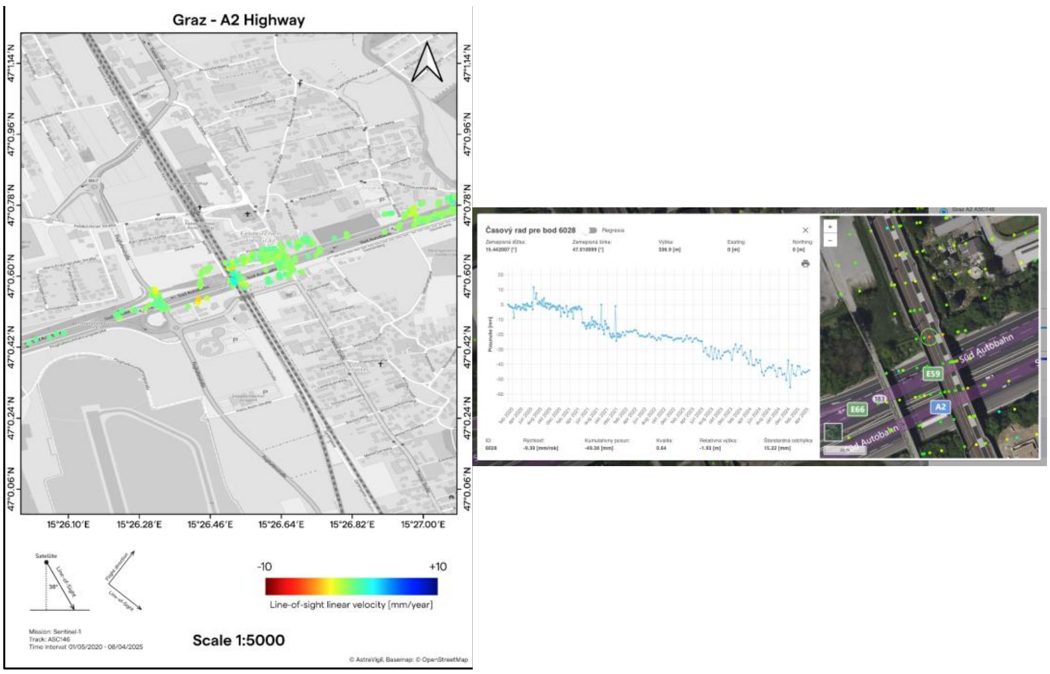

FIGURE 11: EXAMPLE OF ESTIMATED PS VELOCITIES

The figure above is showing movements around linear structure of the A2 highway: A standard visualisation of linear velocity using map composition (left), Example of a time series of a single observation point from web-based GIS platform (right)

4.2.2.3 Decomposition of artificial corner reflector displacement time series

Displacement time series decomposition is the process of converting one-dimensional line-of-sight (LOS) displacement derived from satellite radar images into physically meaningful motion components, typically vertical and horizontal. Each image acquisition geometry (orbit track) sees the ground from a slightly different angle and measures only how much a point has moved towards or away from the satellite over time. For sensors, these LOS displacements are first obtained through PSI processing, which provides precise time series of LOS displacement for each sensor and each satellite orbit. To separate this displacement into vertical and horizontal components, we need LOS displacement time series from at least two independent viewing geometries (e.g. one ascending and one descending Sentinel-1 track) for the same sensor (Papco et. al., 2024). In our case, line-of-sight displacement of the sensor is derived from Sentinel-1 images of two different orbits (Figure 12), describing how much the ground has moved toward or away from the satellite in time and allowing detection of millimetric displacements of the road body and its surroundings. By combining these radar measurements taken from different viewing angles and using the known satellite viewing geometry, the total movement detected by the satellites can be decomposed into two components – vertical and horizontal (east–west). This yields time series of vertical and horizontal displacement at the sensor location, providing a more comprehensive and easier-to-interpret picture of ground and infrastructure behaviour for subsequent analysis and integration into road-condition monitoring layers.

FIGURE 12: LINE-OF-SIGHT DISPLACEMENT OF THE ACR SENSOR DERIVED FROM SENTINEL-1 SATELLITE RADAR IMAGES OF TWO DIFFERENT ORBITS (LEFT) AND DECOMPOSED SIGNAL INTO VERTICAL AND HORIZONTAL (EAST-WEST) COMPONENTS (RIGHT)

4.2.3 Visualisation Platform

Architecture of the platform has been defined, and first steps of the component implementation have already started. The visualisation platform is designed as a web-based solution for the visualization and distribution of InSAR data (Bakon, at. al., 2020). The architecture consists of multiple interchangeable and scalable components (Figure 13) planned to provide the end user with a solid web application for visualizing large amounts of data points in a spatial context via a web browser. The planned functionality includes a set of analysis and visualization tools for InSAR data, base map layers extendable with user-defined WMS services, visualization of data from custom measurements, time series visualization tools, and data export. The system follows a client–server approach. Users interact with the system through a web browser, which communicates securely with server components that perform different tasks. The servers handle application processing, map-related features, and the delivery of downloadable files. Communication is performed using secure web connections and well-defined interfaces, ensuring that the user interface is kept separate from internal data handling and file storage. This separation improves security, reliability, and maintainability of the system.The architecture specifies a PostgreSQL database with a PostGIS extension for spatial data manipulation, with all components running in an isolated Docker environment to ensure stability, scalability, and security. Within this environment, line-of-sight displacement time series from artificial corner reflector sensors will be displayed together with their vertical / horizontal decomposed components, enabling users to inspect detailed motion behaviour at individual sensor locations. The platform also ingests external sensor data via a dedicated interface, so sensor measurements, and other spatial data streams can be combined into integrated map layers that support road-condition monitoring, risk-zone delineation and exchange of information with other SC4 demonstrators.

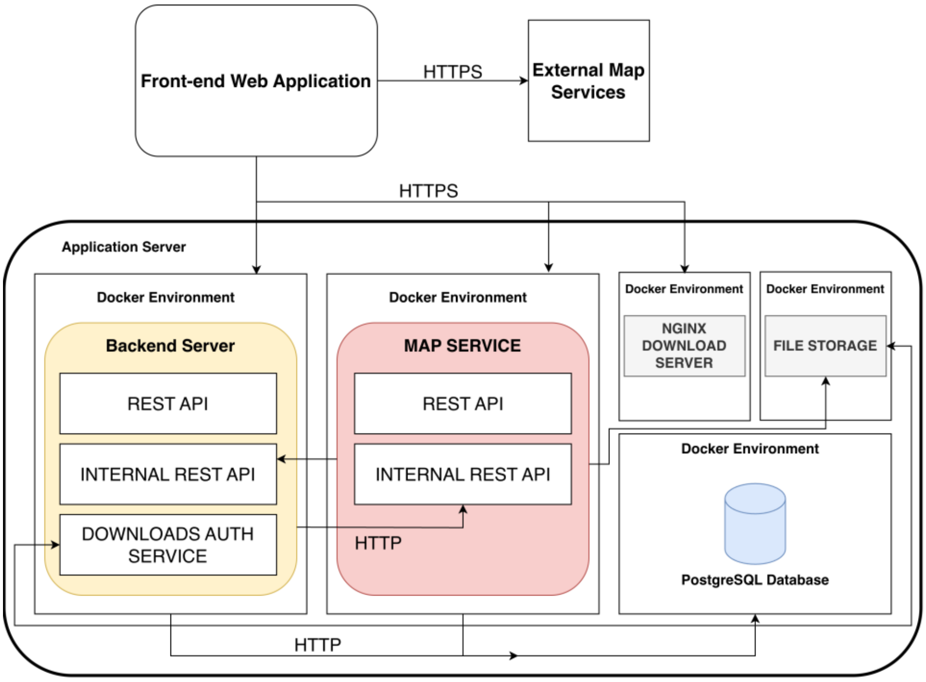

FIGURE 13: ARCHITECTURE OF THE VISUALISATION PLATFORM

5 Conclusion

5.1 Contribution to overall picture

This deliverable contributes WP3 hardware building blocks that support SC4 demonstrator realization. It provides the technical baseline and the implementation-oriented specifications required for follow-up integration and validation activities, ensuring traceability to requirements and KPI targets for the demonstrators covered in this report.

For Demo 4.1, the work delivers the enabling radar hardware basis to investigate radar-based V2V communication as an additional cooperative channel in local traffic interactions. The described hardware baseline, module adaptations for demonstrator operation, and the processing split are intended to support controlled experiments and KPI-driven evaluation, particularly for low-latency cooperative manoeuvres (e.g., emergency braking warnings and platooning coordination).

The work presented in this deliverable contributes a complete concept of satellite radar sensing and the use of artificial corner reflectors, which extend the project's sensor layer beyond vehicle and ground-based technologies. By developing algorithms and tools for sensor exploitation in the context of satellite radar imaging and their integration into a web-based GIS platform, we turn artificial corner reflectors into operational components for scalable infrastructure-monitoring. These methods directly support Demonstrator 4.2 in Supply chain 4 and Demonstrator 5.1 in Supply chain 5 by providing stable reference targets, high-precision deformation products and dynamic risk layers that can be fused with in-situ sensors. In the broader project context, they form a reusable technical foundation that WP4 will implement and embed into HW/SW tools, enabling proactive, satellite-guided sensing for automated driving systems and multi-agent emergency response applications.

5.2 Relation to the state-of-the-art and progress beyond it

The contributions in this deliverable address two different but complementary state-of-the-art baselines: cooperative vehicle interaction for traffic efficiency (Demo 4.1) and infrastructure-scale deformation monitoring for road-condition risk layers (Demo 4.2). The following paragraphs summarize how each topic progresses beyond current practice and how this progress will be assessed within the project.

For Demo 4.1, the work investigates progress beyond the conventional separation of "radar for sensing" and "V2X radios for messaging" by exploring radar-to-radar communication using existing automotive radar sensing hardware. The target progress is assessed against WP1 requirements and KPI objectives relevant for WP3, including radar-based communication latency below 15 ms and demonstration of combined sensing-and-communication radar.

For Demo 4.2, our approach goes beyond the state of the art by tightly integrating wide-area InSAR monitoring with ground-based and vehicle-based sensors, using artificial corner reflectors as stable reference targets that anchor satellite-derived deformation measurements and improve their accuracy. This enables proactive, millimetre-level detection of slope instability and subsidence around roads using historical satellite data, instead of relying only on reactive detections from TPMS, LiDAR or cameras. In addition, risk zones defined based on the satellite radar data are used to guide where and when to deploy vehicle with on-board sensors, making road monitoring more targeted, scalable and efficient.

5.3 Impacts to other WPs, Tasks and SCs

The hardware definitions and specifications reported here are intended to be consumed by follow-up activities in the project, including algorithm/tool implementation, integration, and validation. This section describes how the outputs of WP3 hardware workflow into later WPs and demonstrator execution.

For Demo 4.1, the radar hardware baseline and demonstrator-specific extensions provide the technical reference for subsequent work that implements and evaluates the communication decoding and KPI measurement tooling and for integration/verification planning. The described HW/SW split enables controlled experimentation and repeatable measurements under the Demo 4.1 operating conditions used for evaluation (baseline vs radar-based V2V vs V2I).

The outcome of this activity will be used in the next stage of the project, specifically in Demonstrators SCD4.2 Road Condition Monitoring (SC4) and SCD5.1 Multi-agent and Cooperative Sensing & Control in Emergency Response Applications (SC5). Further work will continue in WP4, which is focused on the technical implementation of algorithms into the project's hardware and software tools; here, INSAR is directly involved in Task 4.4, where the UC "Algorithms for processing InSAR data and fusing it with in-situ sensors" will partly build on the results of Task 3.3. A very similar relationship is expected in Task 4.5 "Algorithms, Embedded HW and SW for Multi-agent Sensing and Control", where methods and tools developed in WP3 will be further implemented, adapted and validated in multi-agent sensing and control scenarios.

5.4 Contribution to demonstration

This deliverable supports the planned SC4 demonstrations by providing the WP3 hardware basis and associated specification references for the demonstrator components described in Chapter 4. The content is organized per demonstrator topic and is intended to directly support the execution of demonstrator experiments and KPI evaluation.

TABLE 2 CONTRIBUTION TO DEMONSTRATION

Partner/Topic	Description
IFAT	Demonstrator SC4 D4.1 Traffic flow optimization of ADS for emergent extrinsic efficiency
INSAR	Demonstrator SC4 D4.2 Road Condition Monitoring – UC3: Road Condition Monitoring with Satellite Data
INSAR	Demonstrator SC5 D5.1 Multi-agent and Cooperative Sensing & Control in Emergency Response Applications – UC2: Post-earthquake scene analysis utilizing satellite SAR and C-SLAM

6 References

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7 List of abbreviations

Abbreviations	Description
ACR	Artificial Corner Reflector
ADAS	Advanced Driver-Assistance Systems
ADS	Automated Driving Systems
API	Application Programming Interface
ASC	Ascending Orbit Track (Sentinel-1 track identifier, e.g., ASC146)
BASE-T1	Single-Twisted Pair Ethernet Physical Layer Standard (part of 1000BASET1)-T1)
CAT	Compact Active Transponder
C-SLAM	Collaborative Simultaneous Localization And Mapping
DSC	Descending Orbit Track (Sentinel-1 track identifier, e.g., DSC22)
ECU	Electronic Control Unit
FMCW	Frequency-Modulated Continuous-Wave
GA	Grant Agreement
GHz	Gigahertz
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
HTTPS	Hypertext Transfer Protocol Secure
IFAT	Infineon Technologies Austria AG
INSAR	INSAR.SK s.r.o.
IoT	Internet Of Things
KPI	Key Performance Indicator
LOS	Line Of Sight
MCU	Microcontroller Unit
mmWave	Millimeter Wave
MMIC	Monolithic Microwave Integrated Circuit
Nginx	Web Server / Reverse Proxy
Node.js	JavaScript Runtime For Server-Side Applications
ODD	Operational Design Domain
PC	Personal Computer
PHY	Physical Layer
PLL	Phase-Locked Loop
PostGIS	Geographic Information System Extension For PostgreSQL
PostgreSQL	Relational Database System
PS	Persistent Scatterer
PSI	Persistent Scatterer Interferometry
RCS	Radar Cross Section
REST	Representational State Transfer
RF	Radio Frequency
SAR	Synthetic Aperture Radar
SC	Supply Chain
SCR	Signal-To-Clutter Ratio
SLAM	Simultaneous Localization And Mapping

SNR	Signal-To-Noise Ratio
SPU	Signal Processing Unit
UC	Use Case
V2I	Vehicle-To-Infrastructure
V2V	Vehicle-To-Vehicle
V2X	Vehicle-To-Everything
WMS	Web Map Service
WP	Work Package

8 List of figures

9 List of tables

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