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Statens vegvesen

GEOSFAIR - Geohazard Survey from Air

Innovation project for the public sector (2021-2024) - Final report

STATENS VEGVESENS RAPPORTER Nr. 1073

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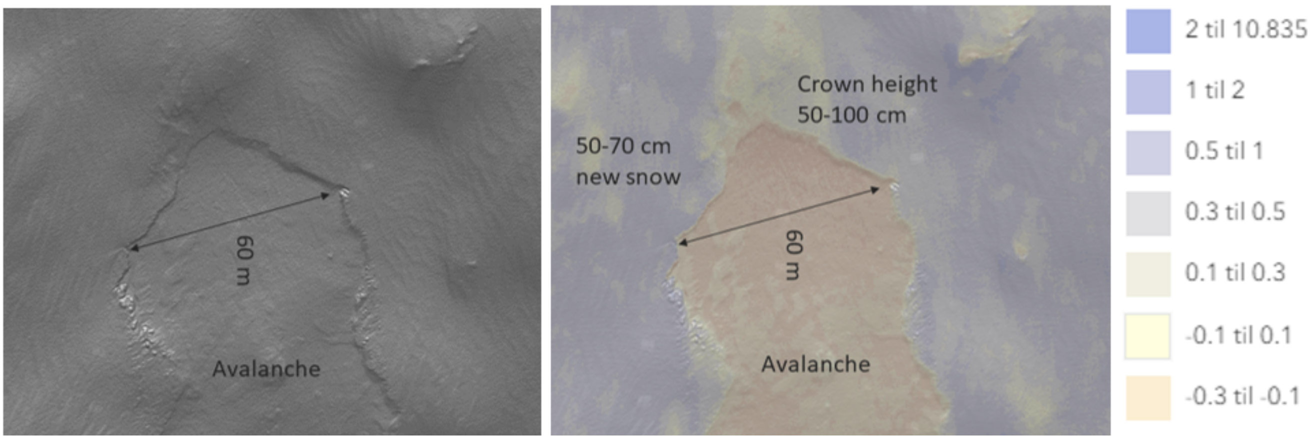

Statens vegvesens rapporter

Tittel
GEOSFAIR - Geohazard Survey from Air

Undertittel
Innovation project for the public sector (2021-2024) - Final report
Forfatter
Tore Humstad (redaktør) med flere (se fullstendig liste på side 3)

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Prosjektleder
Tore Humstad

Godkjent av
Viggo Aronsen

Emneord
snøskred, geosfair, droner, skred, naturfarer

Sammendrag
Prosjektet GEOSFAIR har utviklet metoder for å innlemme droner med sensorer i Statens vegvesen sitt system for beslutning om snøskredfare. Teknologien er testet under realistiske feltforhold, programvare og arbeidsmetodikk er utviklet. Det er gitt anbefalinger om bruk av kamera (for fotogrammetri), lidar og georadar (GPR).

Droner gir nyttig og tidsriktig data for skredvurdering, og de kan erstatte enkelte helikopteroppdrag. Teknologien bidrar til bedre beslutninger, økt sikkerhet og styrket beredskap.

Det anbefales videre utvikling av fjernassisterte og fjernstyrte droneoperasjoner, autonomi og bruk ved flere typer naturfarer.

Antall sider 85

NPRA reports
Norwegian Public Roads Administration

Title
GEOSFAIR - Geohazard Survey from Air

Subtitle
Innovation project for the public sector (2021-2024) - Final report
Author
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Project manager
Tore Humstad

Approved by
Viggo Aronsen

Key words
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Summary
The GEOSFAIR project developed methods for integrating drones equipped with sensors into the NPRA decision making system for avalanche risk assessment. Field and vendor tests, and software and methodology development have been a part of the project. Recommendations are given for use of cameras (for SfM), lidar, and ground-penetrating radar.

Drones provide useful and timely data for avalanche assessment. The technology contributes to better decision making, increased safety, and enhanced preparedness.

Further development is recommended in remotely assisted and remote drone operations, autonomy, and use in various types of natural hazard.

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GEOSFAIR – Geohazard Survey from Air

Innovation project for the public sector (2021–2024)

Final report

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August 26, 2025

Executive Summary

The research effort, GEOSFAIR, developed effective methodologies for integrating uncrewed aircraft systems (UASs – which include aircraft, sensors, and flight operations software) and UAS-collected data into the present Norwegian Public Roads Administrations (NPRA) decision support system for geohazard risk assessment. This effort considered both decision-making requirements and UAS aircraft, sensors, and software specifications.

The goals addressed as part of GEOSFAIR included the following:

- Identify and evaluate UASs that are suitable for NPRA's geohazard applications.
- Specify requirements for adoption of UAS by decision makers within the NPRA and by other road owners and transportation organizations.
- Test UASs and UAS collected data under realistic field conditions and first evaluation of results.
- Develop software and tools that provide usable information and allow rapid integration and support of UAS operations and data into the NPRA decision-making processes.

The specific tasks completed as part of GEOSFAIR were as follows:

- Identified UAS requirements.
- Made recommendations for sensor technologies.
- Automated mission execution.
- Automated data processing workflow.
- Created 3D rendering and an application programming interface (API) plug-in for the resulting data.
- Consolidated requirements for UAS use.
- Tested UASs under field conditions.
- Interpretated and validated the data.
- Developed decision support philosophies.
- Developed data management and utilization.
- Developed organizational requirements.
- Identified other geohazard applications.
- Documented and disseminated results.

The following were the guiding research questions of GEOSFAIR:

- How UASs provide data in support of roadside avalanche monitoring.
- Whether UASs provide data replacement or just enhance existing tools that the NPRA currently employ.

- Whether UAS operations provide useful and timely coverage in locations of avalanche hazard.
- How UASs can be used operationally in steep terrain and in a range of lighting and weather conditions.
- How UASs can be operated remotely and fly autonomously to gather data.
- How new technology can be successfully and economically integrated with the NPRA's current decision-making processes.

The following are the conclusions drawn from GEOSFAIR:

- UASs can be successfully operated by the NPRA.
- Both real-time kinematics (RTK) and non-RTK positioning systems for flying UASs are needed.
- The NPRA does not need to design its own software or other tools.
- Sensors are useful, with the most useful being cameras and photogrammetry, but lidar and ground penetrating radar are also useful.
- The findings suggest that all the NPRA's geohazard experts should be UAS pilots.
- Drone garages will be useful to the NPRA.
- Operation and Maintenance contractors hired by the NPRA should have UAS pilots and equipment.

Acknowledgement

The GEOSFAIR (Geohazard Survey from Air) project has greatly benefited from the support of the Research Council of Norway. Without this support, the project could not have been carried out with the scope and research-based approach it now has. Thank you!

We would like to express our sincere gratitude to everyone who contributed to the project, especially the dedicated, creative, and highly competent colleagues at NGI, SINTEF and the Geomechanics unit at the Operation and Maintenance Division in the Norwegian Public Roads Administration (NPRA), whose expertise, collaboration, and support have been invaluable throughout the project.

Our gratitude also extends to the Borealis project and the Intelligent Transport Systems (ITS) technology unit at the NPRA, represented by Karl Magne Nilsen and Torgeir Vaa, whose financial and moral support was instrumental in initiating the project.

We would also like to thank our international experts, Edward McCormack and Jordy Hendrikx, who have provided significant support in various ways – contributing to reporting, fieldwork, and the ability to place the project results within an international academic context.

Tore Humstad, project manager GEOSFAIR

Norwegian Public Roads Administration

26.8.2025

Content

1 INTRODUCTION

1.1 Background

The project covered in this document is called "Geohazard Survey from Air – Remote Decision Support with Focus on Avalanche Applications," shortened to "GEOSFAIR." The project was organized according to the Research Council of Norway's guidelines for *Innovation Projects for the Public Sector (IPO)*[1]. GEOSFAIR was led by the Norwegian Public Roads Administration (NPRA) in collaboration with the Norwegian research institutes SINTEF and the Norwegian Geotechnical Institute (NGI). The project started in April 2021 and was completed in December 2024.

The primary objective of GEOSFAIR was to develop effective methodologies for integrating uncrewed aircraft systems (UASs, which include the aircraft, flight control systems, and associated software) and UAS-collected data into the present NPRA decision support system for geohazard risk assessment while considering both decision-making requirements and UAS aircraft, sensors, and software specifications. GEOSFAIR focused on hazards from snow avalanches.

As a backdrop for the project, the NPRA was, and still is (as of August 2025), the largest UAS operator in Norway, with more than 130 drones and 215 pilots. Today, 21 of the NPRA pilots operate within the geohazard field.

For the GEOSFAIR project, the NPRA identified the following research and innovation areas, which, if improved, would constitute significant creation of value for natural hazards monitoring:

1. Utilization of new, automated technology to survey terrain while reducing costly crewed helicopter flights and manual tasks.
2. Improve the accuracy and reliability of data that are collected.
3. Implement structured digitalization strategies to remotely monitor sites and to improve preparedness and decision-making ability.

Combining rapid developments in UAS technology, automated digitalization methods, new approaches for advanced data capture, and critical decision support tools provided a unique opportunity for notable cost savings and safety improvements for the NPRA. These improvements would also be available to support other road owners with similar natural hazards challenges (e.g. the Norwegian county roads administrations).

The GEOSFAIR project ideas and team had their foundation in previous proposals and projects. They included the "DroSatNor" project suggested by SINTEF concerning

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[1] Geohazard Survey from Air – Project description at forskningsradet.no

remote sensing from UASs and small satellites, and the "GEORISK" project suggested by NGI concerning dynamic geohazards risk management. In addition, NPRA based its GEOSFAIR application on previous UAS vendor tests and initiatives conducted in Bjorli in 2016 (McCormack et al., 2016), Andøya in 2018 (McCormack et al., 2018), and Lavangsdalen in 2019 (McCormack et al., 2020).

In the NPRA report 655, the findings suggested a new phase within UAS innovation: "*to evaluate practical and realistic use of drones in NPRA operations, in order to assist their staff in making more informed decisions when closing and re-opening roadways or to perform other risk reduction measures.*"

Addressing this finding, an application to the Research Council of Norway (RCN) was submitted in September 2020 under a competitive call for Innovation Projects for the Public Sector. The application was successful, and the final version was accepted by the RCN in March 2021. The application can be found in Appendix C.

1.2 Manned Helicopters by the NPRA

The NPRA often utilizes manned helicopters to support geohazards applications. One important motivation for GEOSFAIR was to evaluate the possibility of replacing costly manned helicopter flights with UAS operations to collect data. This need was noted in innovation area 1 above.

Therefore, the NPRA's total cost of using helicopters was relevant for GEOSFAIR. The project team went through invoices from helicopter companies over the last 15 years (Figure 1). The median yearly costs for manned helicopter flights were found to be 1,200 kNOK.

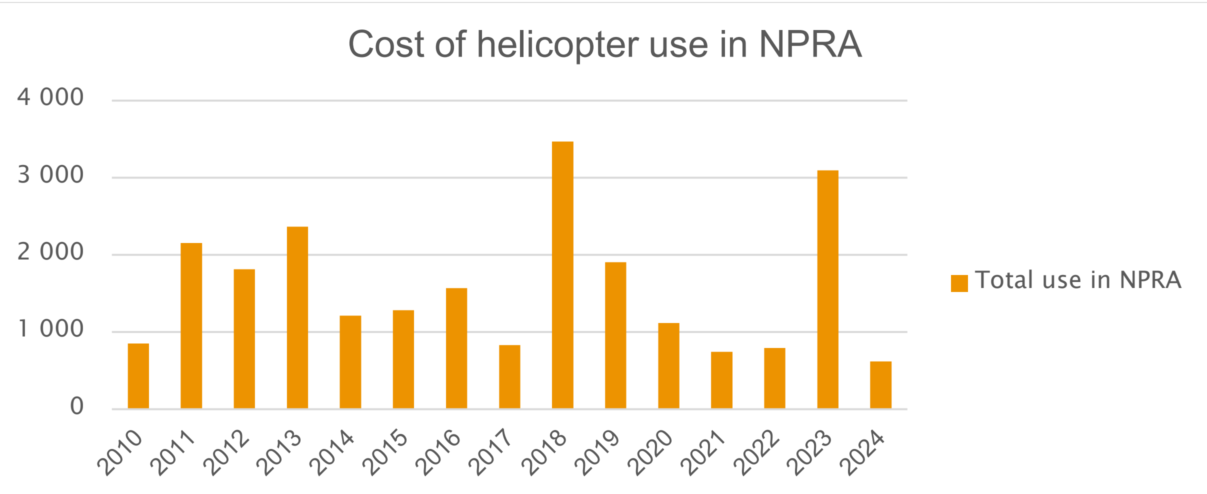

Figure 1: Cost of helicopter use per year in the NPRA (2010 – 2024). Median value: 1,200 kNOK/year. Use for geohazard applications is believed to be ca. 90 % of the total helicopter services (source: NPRA). There has been a general decrease since 2018, except for 2023 when the extreme weather event "Hans" occurred, during which one operation cost 1,500 kNOK alone.

Relevant geohazard applications are mentioned in Table 1, below.

Table 1: Example of helicopter use for geohazard applications

	Geohazard applications	Examples
1	**Site-specific survey**	Survey or mapping of one avalanche path or area, for example, for protection design purposes.
2	**Site-specific inspections**	Inspection of one avalanche path after an avalanche (or landslide) to evaluate the risk of new events.
3	**Local inspections**	Inspection of more than one avalanche path in the same area to evaluate the risk after an avalanche cycle.
4	**Regional inspection (several sites, large distances)**	Inspection of multiple avalanche paths on a regional sale, for instance after a widespread avalanche cycle.
5	**Transport of personnel**	Transport of geohazard experts for inspection on the ground.
6	**Transport of equipment**	Transport of cameras or snow depth sensors.
7	**Scaling of rock and flushing of debris**	Use of an underhanging steel ball to clean loose rocks or a water bucket to flush avalanche or landslide debris.
8	**Avalanche control operation**	Use of underhanging equipment (such as a gas detonator) to controllably release avalanches.
9	**Construction and installation work**	Installation of support structures or avalanche towers.
10	**Combination**	Local inspection prior to a flight and transport of equipment on that flight.
11	**Other**	Tasks that do not fit the above applications.

1.3 NPRA's Decision Support System for Geohazard Risk Assessment

As a part of the research and innovation area 3 aiming to improve preparedness and decision-making ability (see section 1.1), GEOSFAIR aimed to support more informed decisions about road operations and traffic management when the roads are exposed to avalanches and other geohazards. When the project started, the geohazard decision-making system within the NPRA was not clearly defined. Therefore, to evaluate any improvements during this project, efforts were made to illustrate the decision-making ecosystem within the NPRA. A simplified description involves the following actors within the Operation and Maintenance Division:

- Road Operation Manager
- Road Operation Contractor
- Geohazard Engineer (could be a geologist, geotechnical engineer or a hydrologist)
- Decision Authorities for Road and Traffic Management (could be the Road Operation Manager and an operator at one of the Traffic Control Centers).

The connections among these actors and relevant services and tasks are displayed in Figure 2.

The roles are further explained in appendix D.

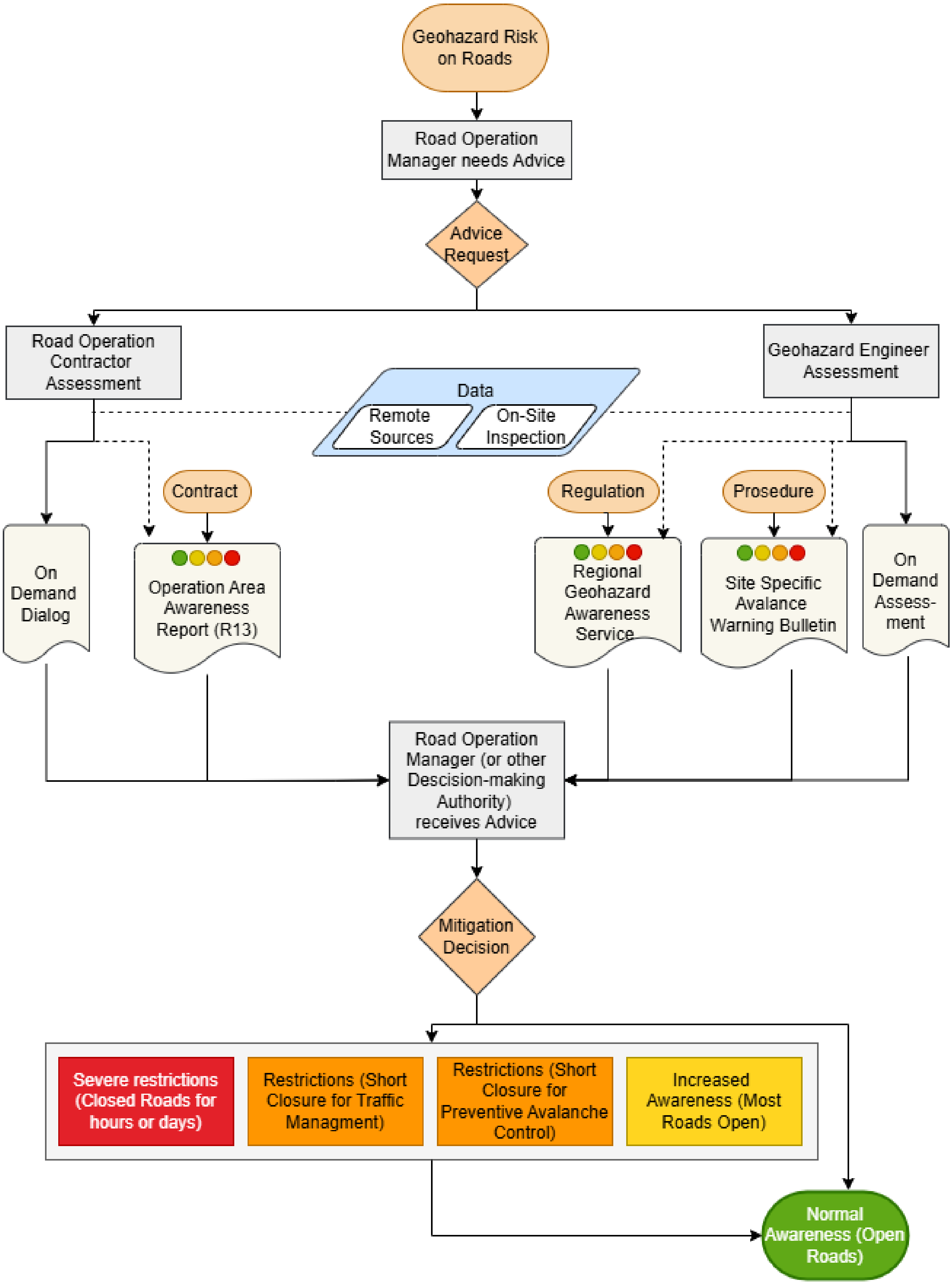

Figure 2: Overview of the geohazard decision system in the NPRA, relevant for the GEOSFAIR project (2021–2024). The data needs, relevant to geohazard assessments, are shown in the blue box. New terminology suggested by GEOSFAIR is shown in **Figure 10**. Mitigation measures are colored in green, yellow, orange, and red according to the corresponding awareness levels within the NPRA.

1.4 Objective and Goals of GEOSFAIR

As noted in the RCN application, the primary objective of GEOSFAIR was as follows:

> *develop effective methodologies for integrating uncrewed aircraft systems (UAS) and UAS-collected data into the present NPRA decision support system for geohazard risk assessment, considering both decision-making requirements and UAS aircraft, sensors, and software specifications.*

Within the scope of this project, the primary focus was on snow avalanche risk assessment, although potential application to other geohazards was considered.

Four verifiable secondary objectives, each of which address a specific challenge, were introduced to achieve the primary objective:

1. Identify and evaluate UAS (aircraft, sensors, and software) that are suitable for NPRA's geohazard applications.
2. Specify requirements for adoption of UAS by decision makers within the NPRA and by other road owners.
3. Test UASs and UAS-collected data under realistic field conditions and evaluate the results.
4. Develop software and tools that provide usable information and allow rapid integration and support into the NPRA decision-making process.

2 PROJECT PLAN

This section provides an overview of the GEOSFAIR project plan. The application to the RCN, which includes a detailed project plan, can be found in Appendix C.

2.1 Knowledge Needs

A range of UAS-carried sensors have been utilized for geohazards research purposes, including light detection and ranging (lidar) sensors, ground penetrating radar (GPR) sensors, and various digital cameras. However, the feasibility of using these sensors for operational-based decision-making processes has yet to be verified. With the emergence of advanced digitalization methods that facilitate machine-to-machine communication and increasingly efficient data management, there exists a large, albeit underexploited, potential for improvement of current workflows. GEOSFAIR aimed to explore how UAS technology could be integrated into critical avalanche monitoring needs of the NPRA and subsequent decision-making processes. GEOSFAIR would be guided by the need to develop knowledge about which UAS technologies (aircraft, sensors, and software) can realistically and routinely address the NPRA's needs. GEOSFAIR addressed urgent knowledge gaps with the associated questions:

1. How will UASs provide data in support of roadside avalanche monitoring?
2. Will UASs provide data either to replace or to enhance existing tools that the NPRA currently employs?
3. Will UASs provide useful and timely coverage in locations of avalanche hazard?
4. Can UASs be used operationally in steep terrain and in a range of lighting and weather conditions?
5. Can UASs be operated remotely and fly autonomously to gather data?
6. How can new UAS and sensor technology be successfully and economically integrated within the NPRA current decision-making processes?

2.2 Research Questions

The research strategy and activities of the GEOSFAIR effort focused on two main research questions (RQ):

> **RQ1**: Can UAS-based tools be used to deliver meaningful information for operational avalanche risk evaluation and mitigation?
> **RQ2**: Can the adoption of UASs and UAS-based measurements demonstrably enhance or accelerate the NPRA's risk-based decision-making processes?

2.3 Scope, Milestones and Deliverables

The GEOSFAIR project was organized into the work packages and tasks shown in Table 2. The project's schedule is shown in Table 3.

Table 2: Work packages and tasks in the GEOSFAIR project (2021 - 2024)

Work packages		Tasks	
1	Hardware – aircrafts as sensor platforms	1.1	Identification of UAS requirements
		1.2	Recommendations for sensor technologies
2	Software – mission planning, automation, and processing workflow	2.1	Automation of mission execution
		2.2	Automation of data processing workflow
		2.3	3D rendering and API plug-in
3	Application – field demonstrations and interpretation of results	3.1	Consolidation of requirements
		3.2	Testing of UASs under field condition
		3.3	Interpretation and validation
4	Integration – enhanced decision support.	4.1	Decision support philosophies
		4.2	Data management and utilization
		4.3	Organizational requirements
		4.4	Identification of other geohazard applications

Table 3: GEOSFAIR project schedule (revised from the original schedule presented in the application, see appendix C)

Task	Year	2021			2022				2023				2024				2025
	Quarter	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1
1.1	Identification of UAS requirements														D1.1		
1.2	Recommendations for sensor technologies																
2.1	Automation of mission execution													D2.1		D2.2	
2.2	Automation of data processing workflow																D2.3
2.3	3D rendering and API plug-in									D2.4							
3.1	Consolidation of requirements							D3.1									
3.2	Test UAS under field condition			D3.2a		D3.2b				D3.2c							D3.2d
3.3	Interpretation and validation																
4.1	Decision support philosophies									D4.2					D4.1		
4.2	Data management and utilization							D4.4									
4.3	Organizational requirements															D4.4	
4.4	Identify other geohazard applications																
Joint dissemination		F1		F2		F3			F4	F5			F6				F7, F8
															W1		D1

(green)	Deliverable as report and/or paper
(light green)	Deliverable included in another deliverable
(orange)	Field work or vendor test
(pink)	Workshop
(grey)	Cancelled

The deliverables (D) mentioned in the table are presented in chapter 4 and in appendix A. The original version is given in Appendix C. The field activities (F) are further described in Table 6 in chapter 3.5 and in chapter 4.3. The workshop (W1) is summarized in chapter 4.7 and Appendix B.

2.4 Resources

The GEOSFAIR project was organized as shown in Figure 3.

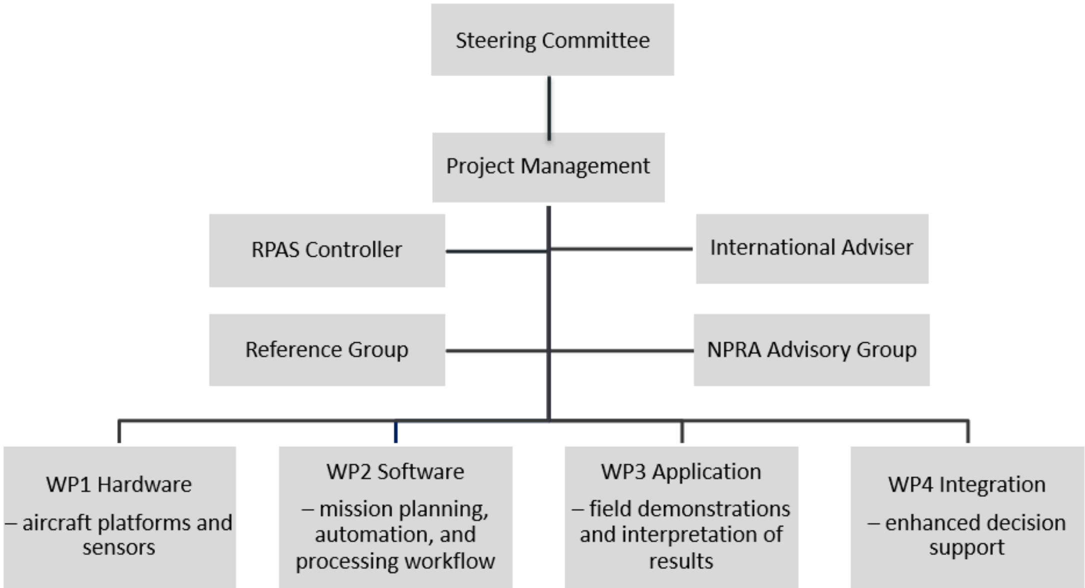

Figure 3: Organization chart for the GEOSFAIR project (2021-2024).

The following personnel were involved in managing, completing, and advising GEOSFAIR:

- Project manager: Tore Humstad, Norwegian Public Roads Administration (NPRA)
- International Adviser: Edward McCormack, Norwegian University of Science and Technology (NTNU) and University of Washington
- Remotely piloted aircraft systems (RPAS) controller: Dag Theodor Andreassen, NPRA
- NPRA Advisory Group: Six NPRA staff, led by Halgeir Dahle, NPRA
- Work package 1: Led by Are Hellandsvik, SINTEF
- Work package 2: Led by Bastien Dupuy, SINTEF
- Work package 3: Led by Regula Frauenfelder, NGI; Deputy Sean Salazar, Norwegian Geotechnical Institute (NGI)
- Work package 4: Led by Emil Solbakken, NPRA

- Scientific reference group: A group of eight international experts from seven countries working in fields relevant to GEOSFAIR (see details in Appendix E)
- Steering Committee: Four directors from NPRA (2), NGI (1) and SINTEF (1) (see Appendix F).

In addition, Dr. Jordy Hendrikx from Montana State University (and later UiT Arctic University of Norway) had a central role in student supervision and project reviews.

Torgeir Vaa, Karl Magne Nilssen, Christian Skjetne, and Jens Tveit from the NPRA all contributed to the project.

From the GEOSFAIR partner SINTEF, Andrew Tobiesen, Arnt Grøver, Aslak Einbu, Irene Jenssen, Richard J. D. Moore, Trine Kirkhus, Asbjørn Berge, Pauline Lorand, Madeline Lee, Karsten Husby, Anders Hansen, Mariann Merz, and Anouar Romdhane all contributed.

From the GEOSFAIR partner Norwegian Geotechnical Institute, Elisabeth Reutz, Sunniva Skuset, Helge Smebye, Dieter Issler, James Strout, Holt Hancock, Anders Kleiven, Peter Gauer, Henrik Langeland, Christian Jaedicke, Kirsten Haaland, and Kjetil Sverdrup-Thygeson contributed.

2.5 Budget

The GEOSFAIR overall budget was 11,900 kNOK[2]. This included 5,950 kNOK from Research Council of Norway (RCN), 5,950 kNOK from the NPRA, 300 kNOK from NGI, and 150 kNOK from SINTEF.

Details about the GEOSFAIR budget are shown in Figure 4.

[2] 1 kNOK = 1,000 Norwegian krones (NOK)

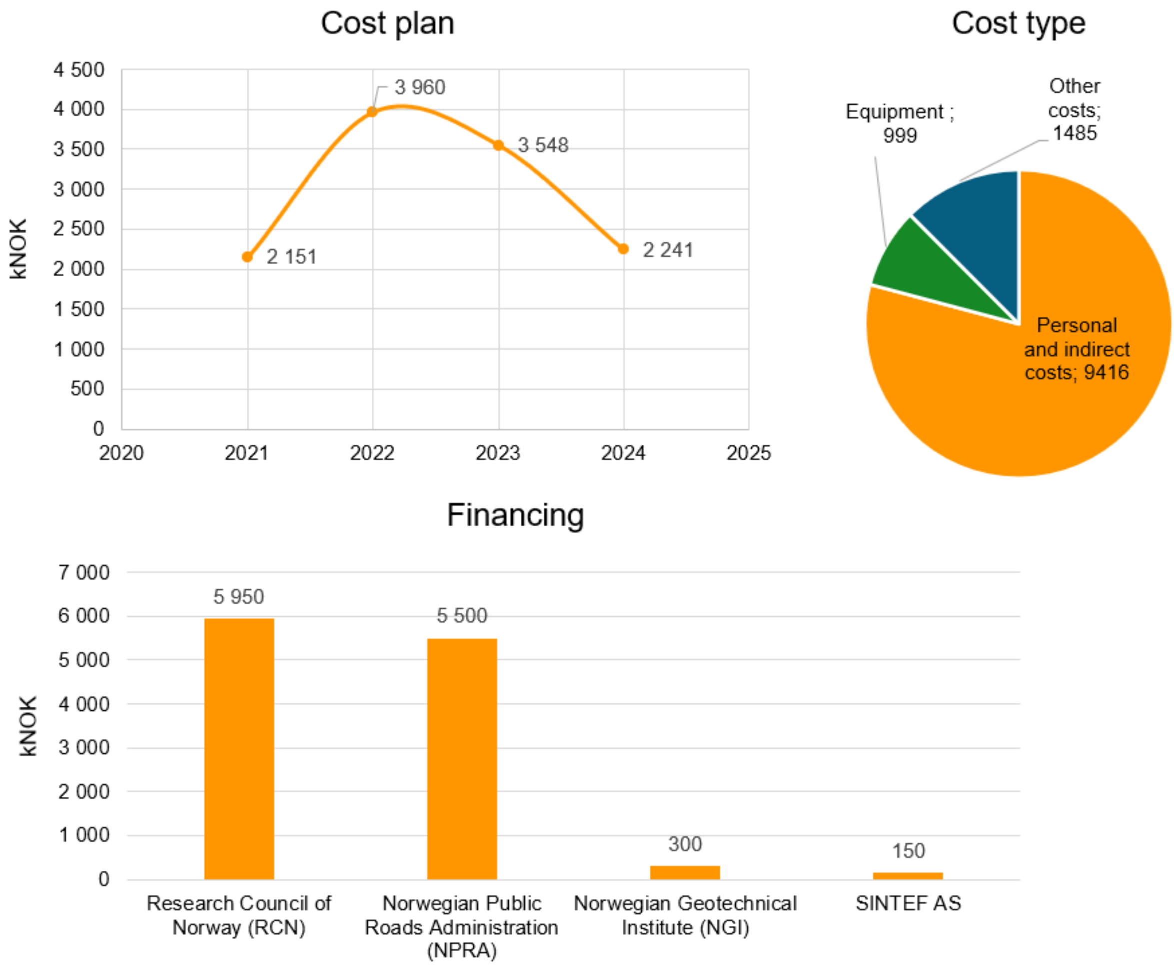

Figure 4: GEOSFAIR budget details

2.6 Risk Management

Risk management was carried out in accordance with statutory requirements for systematic health, safety, and environmental work.

Risk assessments were conducted as part of vendor tests and fieldwork. Avalanche risk assessments were carried out under all work in avalanche-prone terrain (mostly at the avalanche research station 'Fonnbu'), and safety job analyses were performed before recovery of crashed drones. All drone flights were conducted in accordance with national regulations and the companies' own operation manuals. One project employee had a special responsibility for overseeing the latter.

3 METHODS AND PROJECT EXECUTION

This section presents the methodology used to conduct GEOSFAIR research and the data collection approaches.

3.1 Activities

The GEOSFAIR project teams organized the research and innovation through the following activities and reporting to collect data and gain experience:

- State-of-the-art review of UAS and sensor technology
- Questionnaire on the use of UAS by personnel from road administrations
- Vendor test of relevant UAS technologies
- Field tests of the technologies and data collection processes
- Data capture for a local (site-specific) avalanche warning service within the NPRA
- Master theses derived from the project
- Proof of concept tests to apply results to natural hazards monitoring
- Development of guidelines and recommendations
- Final workshop to discuss and disseminate project results.

3.2 Hardware Used

The research team used both less costly, standard UASs without RTK (Real-Time Kinematic technology) positioning and more expensive RTK UASs during the project. Both types of UASs used Global Navigation Satellite System (GNSS) for positioning, and both could be used for aerial photography, surveying, and mapping.

While RTK-equipped UASs offer centimeter-level accuracy, standard UASs have meter-level accuracy. RTK UASs use real-time corrections from a base station, whereas simpler standard, non-RTK UASs do not.

The GEOSFAIR project mostly used off-the-shelf aircraft, but in some cases custom-made aircraft and UAS set-ups were used, especially by scientists and vendors involved in the project.

Table 4 presents the UAS equipment used to collect data for GEOSFAIR.

Table 4: Most common equipment set-up used in GEOSFAIR

Method	Purpose	UAS Manufacturer	Sensors
Thermal imaging	Snow appearance in darkness and poor light condition	DJI Matrice 300 RTK	DJI Zenmuse H20T thermal camera
Photogrammetry	Snow surface (and then volume) and appearance	D JI Matrice 300 RTK	DJI Zenmuse P1 with 35 mm lens.
Lidar (professional)	Snow surface (and then volume)	Self-developed (Field Group)	Hesai XT-32
Lidar (low cost)	Snow surface (and then volume)	DJI Matrice 300 RTK	DJI Zenmuse L1
GPR	Snow layering and depth	DJI Matrice 300 RTK	Radsys Zond Aero, 1 GHz shielded antenna
Remote photogrammetry	Visual inspection and surface models	DJI Matrice 3D (UAS) in a DJI Dock 2 (docking station)	Built-in camera (24- and 162-mm)

3.3 Software Used

To complete GEOSFAIR, a variety of software was used to conduct the UAS flights and to collect and process avalanche-related data. The software is listed in Table 5.

Table 5: Software used

Purpose	Software	Description
Flight planning and control	DJI Pilot	Flight control app for DJI enterprise UAS.
Flight planning and control	UgCS	UAS mission planning software with advanced photogrammetry, lidar and terrain following tools
Graphing	Prism	Statistical analysis and graphing software tailored for scientific research
Editing	Cloudcompare	Open-source 3D point cloud processing software for editing and analyzing point clouds
Programming	Python	Programming language
2D Maps and 3D models	DJI Terra	Mapping software for 2D and 3D reconstructions.
Data collection and processing	Pix4D	Photogrammetry software for creating maps and 3D models from UAS imagery
Data collection and processing	Metashape	Photogrammetry software for generating 3D spatial data from images
Data collection and processing	SiteScan	Cloud-based drone mapping software for data collection, processing, and analysis
Data collection, processing, and dissemination	QGIS	Open-source GIS software for data visualization, editing, and analysis
Data collection, processing, and dissemination	ArcGIS Pro	Professional GIS software for creating, analyzing, and sharing 2D and 3D maps

3.4 Meetings and Coordination

In addition to participating in GEOSFAIR activities as part of the work packages, the key personnel in the project held digital coordination meetings every second month throughout the project. Over the course of the project, the team also met in person at several locations, for example at fieldwork sites during demonstrations and at conferences. The team also held yearly meetings with the steering committee and the reference group.

3.5 Main Field Locations

Figure 5 and Table 6 presents the main field locations and the various field activities completed as part of GEOSFAIR. These include flight tests, vendor demonstrations, and data collection efforts. We include two spin-off projects (F7 and F8), which were conducted after the end of the GEOSFAIR project, because they were conducted while this report was written and had great relevance to the project purpose.

Figure 5: Main field locations in the GEOSFAIR project.

Table 6: Most important field locations

Field activity ID	Locations, date	Involved parties	Objective	Documentation
F1	Breiddalen and Grasdalen, Strynefjellet, April 2021	NPRA	Familiarization with UASs, sensors, and land survey equipment.	Youtube (DBBfSgJ6dRg)
F2	Trollstigen, Lidar on UAS, vendor test, October 2021	NPRA and seven vendors	Test lidar data collection accuracy/ repeatability in mountain environment.	NPRA report 825 (McCormack et al., 2022). Deliverable D3.2a.
F3	Fonnbu, Strynefjellet, March/April, 2022	NPRA, NGI, and SINTEF	Acquire snow surface data sets.	NPRA report 873 (Frauenfelder et al., 2022) and 996 (Dupuy et al., 2024).
F4	Fonnbu, 2023 (week 9 and 11)	NPRA, NGI, SINTEF, Montana State University	Acquire snow surface and snow layer data sets. Project meeting.	NPRA report 1011 (Tobiesen et al., 2024b).
F5	Grasdalen 2023 (over 22 days)	NPRA and Field	Acquire snow surface data sets over time to support site-specific avalanche warning services.	Haddad (2023), ISSW papers (McCormack et. al., 2023; Solbakken et al. 2024)
F6	Fonnbu (2024) in March (F6) and October	NPRA, SINTEF, NGI	Acquire snow surface and snow layer data sets. Project meeting.	NPRA report 1025 (Châtel, 2025)
–	Other trips to Ryggfonn and Fonnbu	NGI	Acquire snow pit data and visual snow surface observations.	regobs.no
–	Storlidalen (March 2022)	SINTEF, NPRA	First real-scale test of UAS-mounted GPR.	
F7	Ørskogfjellet, November 2024 to April 2025	NPRA	Proof of concept of drone docking system.	Spin-off project not reported yet except for paragraph 4.3.6 in this report.
F8	Haukelifjell (January to April 2025)	NPRA and Mesta AS	Proof of concept of remotely assisted drone operation in operation contracts.	Spin-off project not reported yet except for paragraph 4.3.7 in this report.

4 RESULTS

The findings from the GEOSFAIR activities are presented in this section.

4.1 State-of-the-Art Review

A state-of-the-art review, "Avalanche Hazard Assessment Supported by UAS" (McCormack et al., 2024), cited 114 publications and highlighted the effectiveness of UAS in monitoring avalanches. It also explored technological advances for supporting flights in harsh environments and for UAS operations by transportation agencies. Key findings included the following:

1. **Effectiveness**: UASs can provide detailed and accurate data for avalanche monitoring. Multiple studies documented photogrammetry (structure from motion (SfM)) and lidar used for snowpack data collection.
2. **Technological Advancements**: Advanced sensors and imaging technologies enhance hazard detection.
3. **Operational Challenges**: Harsh environments and steep terrain pose challenges for UAS operations, but new technologies (such as anti-icing and AI controlled flight) will help address these challenges.
4. **Recommendations**: Developing protocols for routine UAS operations, exploring AI for rapid decision-making, and utilizing autonomous flights—perhaps with UAS deployed sensors, and beyond line of sight (BLOS) operations for remote data collection—will support the advanced use of UASs by transportation agencies.

These findings underscore the potential of UASs to revolutionize avalanche hazard assessment and improve safety in avalanche-prone regions, and they emphasize the importance of staying updated with technological advancements.

See NPRA report 958 (McCormack et al., 2024a) for details. This report is a project deliverable beyond those mentioned in Table 3.

4.2 Questionnaire

A report from Reutz et al. (2022) presented the findings of a questionnaire-based survey distributed to personnel from national and regional road administrations in Norway. The aim of the survey was to evaluate the use of UAS for assessing roads exposed to landslides, rockfall, and avalanche hazards. In addition, the survey aimed to identify the challenges or barriers to data uptake. The recipients were identified as key people in their organizations addressing avalanche danger on the roadway. Results from 36 respondents to the questionnaire were summarized, along with some recommendations.

The survey revealed strong support for increasing the use of UASs across the organizations, with most participants eager to expand UAS data applications.

However, the survey also identified several challenges that hinder broader adoption. The most significant obstacle was the lack of certified UAS operators, with respondents noting that staff struggled to prioritize UAS certification because of busy schedules. The certification process was seen as time-consuming and complicated by varying regulations, depending on the drone size. If certification requirements and administrative tasks were simplified, respondents believed that drone use would increase. Another challenge involved handling the large volumes of data collected by UASs, most of which came from optical cameras. While UASs were primarily used to capture photos and videos, only a few respondents reported using terrain models. A lack of knowledge and training on how to fully utilize the data were also mentioned as barriers. Additionally, the survey indicated that most organizations had already developed or were in the process of developing operational manuals and procedures, with health, safety, and environmental (HSE) considerations factored into drone operations.

Overall, while obstacles remain, the survey concluded that there was a strong desire to increase UAS usage in the road sector, with a particular interest in optical and laser scanning data. Addressing the identified challenges could lead to more widespread use of UAS for road assessments.

See NPRA report 1002 (Reutz, et al., 2022) for details. This report corresponds to deliverable D3.1 mentioned in Table 3.

4.3 Vendor Test and Field Work

4.3.1 Preliminary survey at Strynefjellet, April 2021

As preparation for the project, a group from NPRA went to highway rv. 15 through Breiddalen and Grasdalen on the Strynefjellet mountain pass to familiarize the group with UASs, sensors, and land survey equipment and to make a GEOSFAIR informational movie (youtu.be/DBBfSgJ6dRg).

This activity corresponds to deliverable fieldwork F2 mentioned in Table 3.

4.3.2 Demonstration of lidar in Trollstigen; October 2021

Over three days (October 25-27, 2021), seven UAS vendors completed a series of flights with UASs carrying lidar at three pre-specified test sites close to the scenic

Trollstigen road (fv. 63) in Norway (McCormack et al., 2022). An analysis of the lidar data determined the following:

- **Accuracy**: Vertical root mean square (RMSE) with an accuracy of 1-2centimeters was possible.
- **Precision:** This was good on a survey scale, but the small-scale variability was considerable.
- **Mapping of snow surfaces**: The lidar returns of wet to dry new snow was good. Low point density (>30-50 points/square meter) seemed sufficient for snow depth calculation and change detection on even snow surfaces.

NPRA report 825 (McCormack et al., 2022) describes the details of this test. The report corresponds to deliverable D3.2a and covers fieldwork F2 mentioned in Table 3.

4.3.3 Fonnbu spring 2022: Sensor testing

On March 29 to April 1, 2022, the GEOSFAIR team at the research station Fonnbu in Stryn, Norway, performed a field test of UAS carrying different instruments. The overall purpose of the test was to evaluate the practical performance of UAS and sensors in field conditions, with a goal of assessing and monitoring snow avalanche hazards. The devices tested included the following:

- Photogrammetry to create detailed maps and 3D models of the terrain.
- Lidar to measure distances and create high-resolution topographic maps.
- Thermal imaging to identify snowpack conditions and potential weak layers.
- Multispectral imaging to analyze snow properties and vegetation cover.

Resulting geospatial datasets included 3D models (point clouds and elevation maps), multispectral and radiometric thermal images, and radargrams.

Various measurements and flights were carried out over pre-defined test areas. The UAS-based measurements were complemented by manually dug snow pit characterization. The sensors used during the test provided promising and detailed datasets about the snowpack characteristics and the surround terrain. In most cases, the UAS flight planning, communications systems, flight controls, and automated flights worked well. The use of each sensor also presented challenges which will be further explored. These challenges included equipment failures, difficulties operating UASs at altitude and speeds suitable for the collection of data and images, some manufacture-caused problems with the radar equipment due to low temperatures, and complex and time-consuming data processing.

See NPRA report 873 (Frauenfelder et al., 2022) for details. The report corresponds to deliverable D3.2b and covers fieldwork F3 mentioned in Table 3. The same fieldwork is referred to in NPRA report 996 (Dupuy et al., 2024), which corresponds to deliverable D1.1.

4.3.4 Fonnbu spring 2023: Additional sensor testing

Field work during two weeks in February and March 2023 in Fonnbu allowed, among other things, the GEOSFAIR team to gather extensive UAS photogrammetry and lidar datasets. Tobiesen et al. (2024b) described comparative studies of the repeatability and accuracy of the optical and laser data recorded with UAS-mounted sensors used during this test. For photogrammetry surveys, different sensors and different processing software were used and evaluated.

The overall conclusions and findings of this test were that both photogrammetry and lidar surveys may create accurate elevation models and orthomosaics when they are used on high-end survey drones with current available processing software. The research team concluded that this type of technology will be useful and valuable as a part of an integrated workflow for avalanche forecasting.

NPRA report 1011 (Tobiesen et al, 2024b) has more details. The report corresponds to deliverable D2.2 and covers fieldwork F4 mentioned in Table 3.

4.3.5 Fonnbu spring 2024 operational and data collection test

The GEOSFAIR team returned to Fonnbu for a week in March 2024 to further test UAS flights to gather photogrammetry and lidar data. The team found that the sensors provided usable data for snowpack analysis and avalanche monitoring. They also determined that, operationally, collecting effective data could result in aircraft crashes. These crashes required operations on foot to recover the aircraft and to avoid leaving equipment such as batteries in the environment. A second UAS provided usable reconnaissance concerning the crashed UAS. These tests highlighted that UAS flights, in rugged terrain can result in the possible loss of an aircraft and that a plan for recovery of the equipment may be prudent.

The test is documented in NPRA report 1025 (Châtel et al., 2025). The report corresponds to deliverable D2.3 and covers fieldwork F6 mentioned in Table 3.

4.3.6 Drone docking station at E39 Ørskogfjellet

As a spin-off project of GEOSFAIR, the NPRA conducted a pilot project using a drone station on E136 Ørskogfjellet during the winter of 2024/2025. The location was chosen because it had a suitable distance from the office locations in Molde (30 km), and because there was access to electricity and facilities that made it possible to test remote-controlled operations under winter conditions with low risk. The drone station was placed on top of a steel storage container to ensure stability and protection from human activity and snow plowing. The NPRA conducted tests with photo mapping from a distance and attempted to take off and land the UAS both with and without snow on the drone station. The tests showed promising results, although the limitations of a snow-covered drone station were evident.

Parallel to the testing at Ørskogfjellet, an application was sent to the Civil Aviation Authority of Norway to place operational drone stations at three locations, namely along the E6 through Drivdalen, Rv. 15 in Grasdalen, and E134 at Haukelifjell. These locations were approved by the Civil Aviation Authority.

In the spring of 2025, the first drone station was established in Drivdalen. The storage container was replaced with a movable trailer with its own pedestal for the drone station, airspace monitoring, a webcam, and communication via 4G/5G and necessary antennas (see Figure 6).

Further results of these drone docking stations are out of scope of GEOSFAIR and this report.

Figure 6: NPRA's first operational drone docking station in Drivdalen is a modification of the set-up used at Ørskogfjellet (photo: Halgeir Dahle, NPRA).

4.3.7 Operation contractor's data capture at E134 Haukelifjell

As a spin-off project of GEOSFAIR, the NPRA collaborated with the road operation and maintenance contractor Mesta AS from January to April 2025 to gain experience with remotely assisted UAS operations and to evaluate how data collection with UASs could be done by contractors when they are closer to avalanche-prone road segments than the NPRA's geohazard engineers. This was the case with the E134 Haukelifjell mountain pass, to which Mesta was closer than the avalanche forecasters, who were as much as 900 km away.

The goals for the pilot project were as follows:

1. **Document the snow surface** with a focus on avalanche deposits after artificially triggered avalanches with avalanche control measures in the Pepparsteinen and Austmannalia avalanche paths.

2. **Document naturally triggered avalanches** along the entire stretch from Ulvåa west to Austmannalia

3. **Document the snow cover** in general at the locations mentioned in points 1 and 2 under good lighting conditions (which improve as spring progresses).

Flights were conducted on six days, and all of them resulted in terrain models and orthomosaics based on photogrammetry. Data from Austmannalia (regobs 416552 and 420510) and Pepparsteinen (regobs 417269) were uploaded on regobs.no, a service provided by the Norwegian Water Resources and Energy Directorate (NVE). One model is shown in Figure 7.

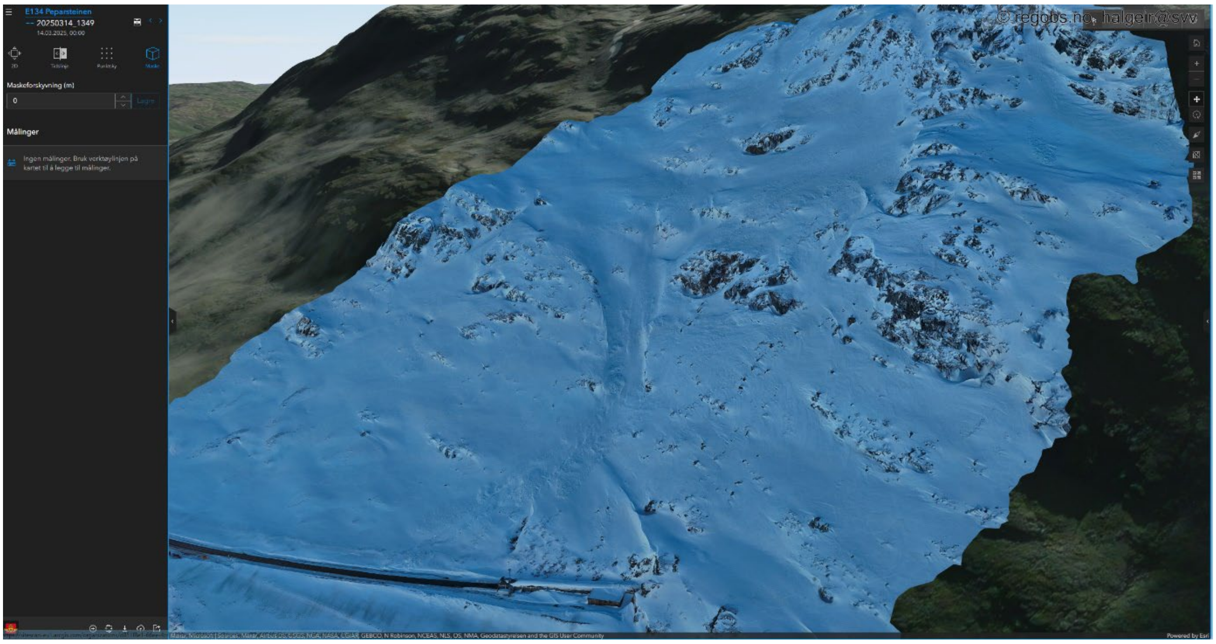

Figure 7: Snow cover model from March 14, 2025 (regobs 417269)

The following are some relevant observations:

- **Scope**: The scope was a bit excessive given the well-instrumented area and the stable snow conditions. Future use during more unstable conditions would be interesting.
- **Drones and pilots**: Drones and pilots stationed locally on the operation station (instead of one to three hours away) would improve cost effectiveness even more.
- **New insight**: The project provided valuable insights into avalanche areas without physical presence, aiding location-specific warnings.
- **Collaboration**: Collaboration between Mesta and the NPRA was beneficial and motivating, and the models had broader applications beyond warnings, such as snow distribution mapping for safety planning.
- **Overall**: The project was regarded as successful by both parties, and suggestions for drone needs in future contracts were recommended. The NPRA should suggest new standard specifications. The contractor found the experience educational and agreed that local stationing of drones and pilots is ideal.

4.4 Data Capture for Site-Specific Avalanche Warning

4.4.1 Repetitive lidar scans

Over a period of 22 days during winter 2023, repeated UAS lidar surveys were conducted in avalanche release areas along the mountain highway Rv.15 at Strynefjellet. A semiautomatic processing pipeline was developed to quickly make results available to avalanche forecasters by using a simple web application. Published results in the application included shaded snow surface relief, snow depth, snow depth changes over various time intervals, and snow surface inclination. Acquired data enabled precise detection of snow depth change and avalanche activity, providing valuable insights into snow accumulation patterns and expected avalanche sizes. The research team concluded that UAS lidar scanning in avalanche release areas is a viable method for generating high-resolution spatial data on snow depth changes that also works in poor weather and low-light conditions. More work is needed to ensure reliable measurements, ease interpretation of results, and better understand the impact on forecasted hazard levels. With future improvements, the methodology can contribute to improved site-specific avalanche warnings and increased safety for mountain highways.

These campaigns were presented at the International Snow Science Workshop in 2024 (ISSW 2024 O1.5, Solbakken et al., 2024). These activities correspond to fieldwork F6 mentioned in Table 3.

4.4.2 Data presentation

Results were presented to forecasters in a simple web application, where the user could select the date and type of result to be viewed. Available results were shaded relief, snow depth change over one to three days (see Figure 8), snow depth and snow surface inclination. The color scale for snow depth change was adjusted to account for expected measurement uncertainty, only showing changes larger than 10 cm.

4.4.3 Quantified impact of new data streams

Motivated by GEOSFAIR, Alexander Haddad performed a case study with 21 participants making avalanche forecasts based on traditional data and data from UASs, collected in GEOSFAIR (Haddad et al., 2023; Haddad, 2023). The case study approach illustrated how an organization could quantify the impact that a new flow of information could have on their forecasting team. This new information could be data that were always available and delivered in a new way (i.e., snow surface observations via remote sensing) or it could be for a new area of terrain. Interestingly, the lidar data in this case were not an entirely new data stream; rather, they provided a visible representation and context to windspeed data, precipitation data, and avalanche observations. Avalanche forecasting operations should be aware of the impact that new data additions have on the pool of observations available to a forecaster, or the impact of data delivery improvements or changes. This case study showed what is possible in assessing a new addition or changes to a professional forecaster's workflow.

The findings are further discussed in a presentation at ISSW 2023 (O4.07, Haddad et al., 2023) and Alex Haddad's masters' thesis (Haddad, 2023). The thesis corresponds to deliverable D4.2 mentioned in Table 3.

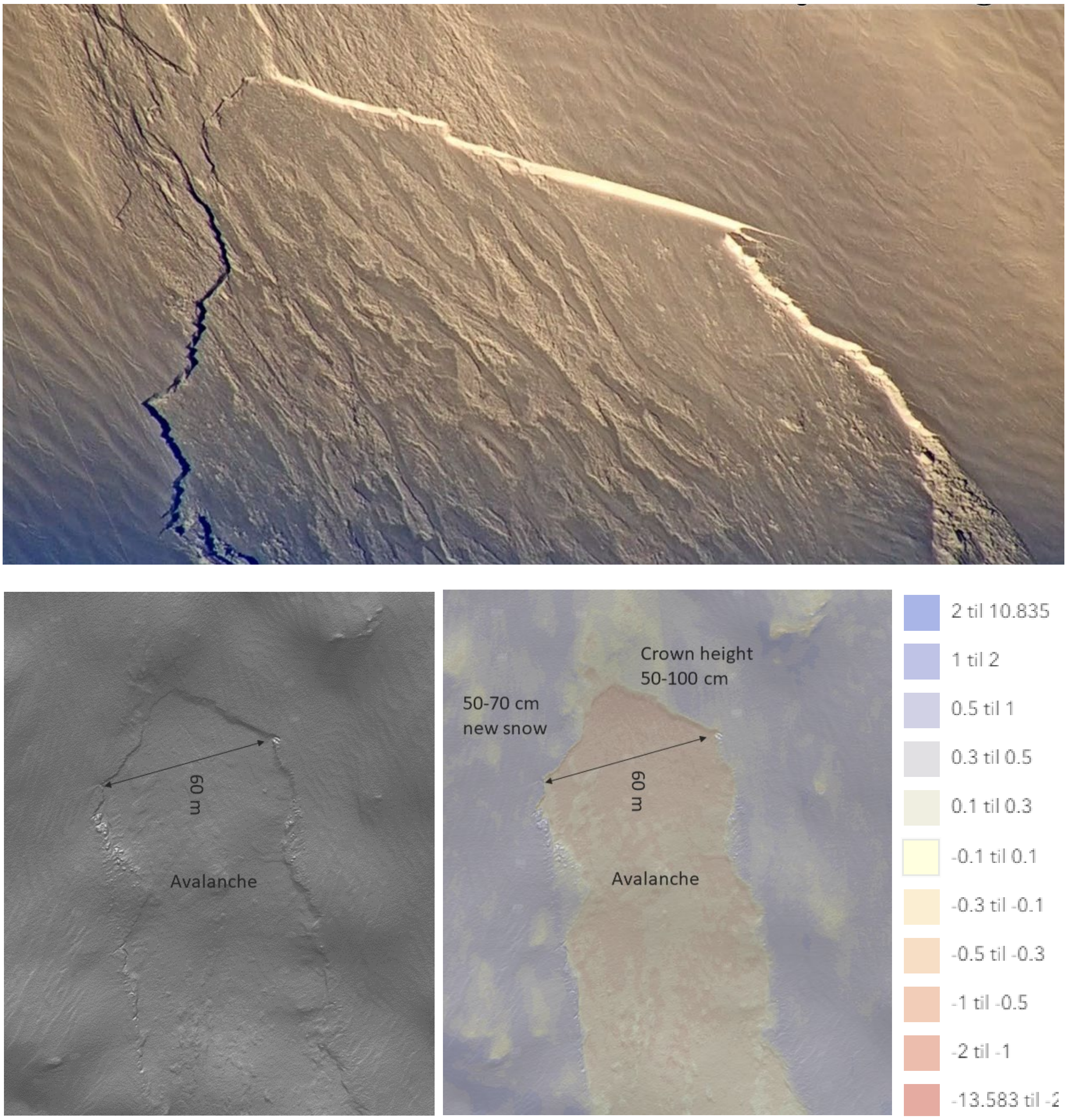

Figure 8: Upper: Photo of the crown. Lower left: Shadow relief of the snow surface based on lidar scan from February 21, 2023. Lower right: Change detection map where February 21 is compared with February 20. Details: regobs 330814

4.5 Guidelines and Recommendations

The GEOSFAIR project developed a series of guidelines and recommendations, which are summarized below.

4.5.1 Recommendations for sensor technologies

NPRA report 996 (Dupuy et al., 2024) provided optimal user-guided specifications for the UAS flight system, the associated sensors, and the logistical aspects necessary to forecast and monitor avalanches, as well as relevant snow parameters in adverse weather conditions. After an initial mapping of relevant snow and avalanche properties, it included some information about sensors being operationally used today and suggestions for other relevant sensors, including lidar, thermal, multispectral and optical cameras, GPR, and other lower technology readiness levels (TRL) technologies.

See NPRA report 996 (Dupuy et al., 2024) for details, which corresponds to deliverable D1.1 in Table 3.

4.5.2 Recommendations for acquiring photogrammetry and lidar data

NPRA report 991 (Tobiesen et al., 2024) described procedures and recommendations for acquisition of remote sensing data over snow surfaces. It included survey planning and data processing routines for high resolution terrain mapping using optical cameras and lidar scanning methods, using both commercial and open-source tools.

See NPRA report 991 (Tobiesen et al., 2024a) for details. This report corresponds to deliverable D2.1 in Table 3.

4.5.3 Recommendations for drone operations at avalanche-prone roads

Report 1024 (Solbakken et al. 2025) explored how road owners can best utilize drones in dealing with natural hazards. A few selected strategies were proposed:

1. **UASs and pilots**: Ensuring that road owners have UASs and pilots near exposed road sections.
2. **Quality**: Improving data quality.
3. **Use**: Increasing the use of UASs in active and organizational protection measures.

Focusing on these areas may not only lead to faster and better decisions after an incident but also provide entirely new opportunities for monitoring and early warning.

To describe the needs and requirements for UAS operations in avalanche and landslide areas, the NPRA operations should be classified on the basis of how they are practically carried out. Here are GEOSFAIR's suggestions:

- **On-site operations**: These operations are carried out entirely by personnel on site. This is the most common way to operate UASs today and requires the presence of individuals with the necessary pilot and technical expertise.

- **Remotely assisted operations**: The operation is performed by a pilot on site, with support from another pilot or specialist who is not present. This support ensures that the collected data meet professional needs and can include everything from verbal instructions during the operation to planning mapping missions and remote control of sensors.

- **Remote operations**: The flight is carried out by a pilot who is not present or automatically according to pre-programmed missions. The UAS and sensors are deployed in a docking station, and there is no need for a pilot or technical expertise on site.

See NPRA report 1024 (Solbakken et al., 2025) for details. This report corresponds to deliverable D4.4 in Table 3.

4.6 Master's Theses

Several master's theses have been initiated on the basis of data from GEOFAIR and in collaboration with research partners NGI, SINTEF, and associated universities including Ecole Polytechnique (France), Université Grenoble Alpes (France), Norwegian University of Science and Technology (Norway), Montana State University (USA), and the University of Oslo (Norway). Project staff in GEOSFAIR contributed to supervision of these theses. Information about the theses is shown in Table 7.

Table 7: Master's theses within the GEOSFAIR project (all of them completed)

Student	University	Title	Supervisors
Martin Châtel	Ecole Polytechnique (France)	Geophysical snow-mapping using Ground Penetrating Radar (GPR) borne by Uncrewed Aerial Vehicles (UAVs) (Châtel, 2024)	Bastien Dupuy (SINTEF)
Pauline Lorand	Université Grenoble Alpes (France)	Drone geophysics for natural hazards: ground penetrating radar surveys, processing and interpretation for snow (Lorand, 2022)	Bastien Dupuy (SINTEF)
Sigrid Helene Strand	Norwegian University of Science and Technology (NTNU)	Assessing the measurement quality of UAV-borne laser scanning in steep and snow-covered areas (Strand, 2023).	Hongchao Fan (NTNU), Trond Arve Haakonsen and Halgeir Dahle (NPRA)
Alex Haddad	Montana State University (MSU)	A framework for the quantitative assessment of new data streams in avalanche forecasting (Haddad, 2023)	Jordy Hendrikx (MSU)
Lisbeth Larsen	University of Oslo (UiO)	Weak Layer Prediction Using SNOWPACK – A Comparative Analysis of SNOWPACK Model Results with RegObs Observations near Fonnbu Research Station (Larsen, 2024)	Thomas Schuler (UiO) and Regula Frauenfelder (NGI)
Michelle Skogeng	University of Oslo (UiO)	Kartlegging av snøoverflater i skredutsatt terreng ved bruk av UAV-innsamlet lidar data (Skogeng, 2024)	Désirée Treichler (UiO) and Regula Frauenfelder (NGI)

4.7 Workshop (W1)

As part of an effort to disseminate and discuss project results a workshop named "Uncrewed Aerial Systems (UAS) in Avalanche Risk Assessment, Search, and Rescue" was held on September 27, 2024, in conjunction with the International Snow Science Workshop in Tromsø. Fifty representatives from 33 organizations attended presentations that covered UASs used in avalanche risk assessments, snow science, and search and rescue. The workshop participants broke into groups to discuss and report on the following topics:

- Field operations
- Data capture, processing and sharing

- Validating data from inaccessible terrain
- UAS fleet and pilot management
- Search and rescue
- Implementation of UAS technology

The workshop's findings are reported in Appendix B. This report corresponds to deliverable W1 Table 3.

4.8 Main findings

The key findings from GEOSFAIR are summed up in Table 8.

Table 8: Main findings in the GEOSFAIR project

Topic	Findings
UAS as sensor platforms	• Can carry a diverse range of sensors and cameras. • Stable and mobile platforms for data collection. • Able to fly to areas that are inaccessible to people.
Flight planning	• Important for effective and repeatable flights. • Good mission planning software available, which makes routine operations more feasible and can support flights operated by non-specialists. • Systematic flight paths and downslope movement save battery life. • For ground penetrating radar, a fly height of 50–100 m achieves a good balance between resolution and flight efficiency.
Flight operation	• Strong winds and icing on propellers reduce flight time and may lead to loss of control of the drone. • Requires advanced planning (e.g., charged batteries) and variable setup times. • Trained pilots are important. • Occasional aircraft loss is expected so a recovery plan is prudent.
Sensor capabilities	• Photogrammetry: Snow surface and volume data can be collected but limited to times of good visibility and good light and contrast conditions. • Thermal: Minimal benefits found, not much studied. • Lidar: Snow surface and volume data can be collected in most all lighting conditions, also in light precipitation. • GPR: High resolution snow height, information on layering and snow properties (density and wetness).
Mapping accuracy	• Snow surface with SfM: Better than 5–10 cm. For repeatable measurements, it is recommended to use the same equipment and processing procedure and software. • Snow surface with lidar: Depends on the lidar quality. Our best measurements are estimated to +/- 10 cm. • Snow stratigraphy with ground penetrating radar: Approximately 10 cm vertical resolution in automatic processing mode.
Data processing and presentation	• Each sensor system requires different processing software. • Processing time varies depending on sensors, software, and user familiarity with software. • Staff training on software use is important. • The software is improving over time.
Next steps	• Both UASs and sensor technology are rapidly advancing and should be monitored for relevant developments. • Improved computing power and new tools for data processing (e.g., AI) will likely increase the timeliness and value of UAS-collected data.

4.9 Future Projects and Activities

The following is a list of projects and activities suggested or prompted by GEOSFAIR findings. This list can be used to generate follow-up projects and applications for GEOSFAIR.

- (Semi-)autonomous and remote avalanche monitoring, focusing on a handful of drone garages and AI control ("auto-GEOSFAIR", or "remote-GEOSFAIR").
- Expansion of scope based on avalanche findings in GEOSFAIR to a multihazard perspective ("multihazard GEOSFAIR").
- UASs as an integrated part of new technology, including ground-based technology ("multi-tech GEOSFAIR").
- Investigation of the decision objective of using UASs ("DECSIONAIR")
- Exploration of the use of "drone garages" for remote and autonomous UAS operations.
- Evaluation of the use of UAS technology by NPRA winter maintenance contractors at Haukelifjell (pilot project together with Mesta AS).
- Testing of UAS technology and sensors in more diverse locations and in varied weather conditions.

5 DISCUSSION

5.1 Status of Knowledge Needs

This chapter reviews the knowledge needs introduced in paragraph 2.1 and presents insights provided by the project.

5.1.1 Roadside avalanche monitoring

How will UASs provide data in support of roadside avalanche monitoring?

As documented in NPRA report 1024 (Solbakken et al., 2025), UASs are currently mainly used by the NPRA to collect single images and video. However, the use of UASs for terrain mapping with photogrammetry and lidar is increasing, and the mapping methods are evolving toward more streamlined, onsite operations. More operations are also being performed remotely assisted or remotely controlled (see details in paragraph 4.5.3).

5.1.2 Replacement or enhance existing tools

Will UASs provide data replacement or just enhance existing tools that the NPRA currently employs?

To discuss how UAS operation could replace or enhance existing methods, it is relevant to revisit how helicopters have been used for geohazard applications as presented in chapter 1.2, Figure 1, and Table 1 and to distribute the total costs for relevant geohazard applications, presented in a pie chart in Figure 9.

UASs can replace applications for site-specific and local surveys and inspections (purpose 1, 2, and to some degree, 3). In some cases, UASs can also be used for preventive avalanche release (purpose 8), replacing a portion of mobile avalanche release systems (using helicopters) and to some extent supplementing stationary, remote avalanche control systems (RACS) (Tveit and Bøckman, 2024). Although this activity is limited today, this can change if regulations and costs change in support of UAS use.

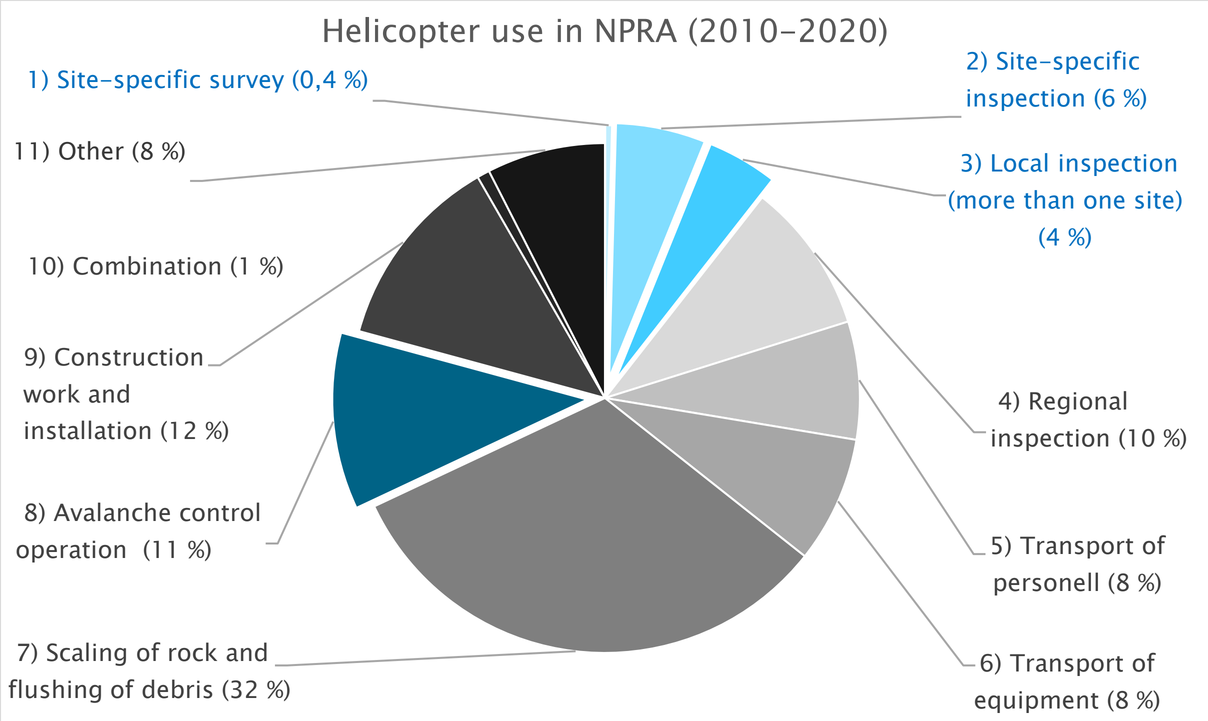

Figure 9: Distribution of helicopter costs for different geohazard purposes (2010-2024). If we assume that UASs and helicopters cover the same application area only on site-specific or local inspection and surveys (blue sectors), it will affect approximately 10 percent of total helicopter costs.

Figure shows that site-specific and local surveys and inspections accounted for approximately 10 percent of the NPRA's helicopter costs between 2010 and 2024. A large portion of this activity could be replaced by UAS operations. However, more interestingly, if geohazard engineers are certified and have access to drones, then the number of avalanche paths subject to survey or inspections should increase considerably. So rather than replacing existing data collection, UASs will contribute to the enhancement and supplementation of present data.

It is expected that up to 90 percent of the required helicopter use for geohazard purposes will remain, even with the introduction of drones. This is because UAS flights can only partially replace regional inspections, transport of people, rock scaling, flushing, and construction and installation work.

In summary, the proportion of helicopter flights replaced by UAS operations will only constitute a small part of the benefits of UASs for geohazard purposes. More relevant, UASs will open new opportunities and enhance activities for which the NPRA currently lacks data. The cost-benefit of UASs should be measured on the basis of whether the NPRA achieves better and faster decisions, less uncertainty, and shorter road closures.

Stated differently, if the NPRA did not introduce UAS usage, new data needs would increase helicopter use considerably.

5.1.3 Useful and timely coverage

Will UASs provide useful and timely coverage in locations of avalanche hazard?

UASs are useful for reviewing and assessing avalanche hazards. Assuming that UAS pilots and the aircraft are available, they can be quickly flown over areas of interest. In many cases UASs can be deployed more quickly than crewed aircraft and are less sensitive to poor weather. In addition, UASs can be flown over areas where it would be dangerous for crewed helicopters.

The experience from 22 days of lidar scanning campaigns described by Haddad, (2023), Haddad et. al (2023), Humstad et al. (2023) and Solbakken et al. (2024) (see also field activity F5 in Table 6) proved that measurements could be carried out during mornings, between 9:00 and 11:00 AM, after which the incoming data could be processed and presented to forecasters through an online portal before noon. This updated snow information could be included in a site-specific avalanche warning for the road published by 14.00.

The data were both useful and delivered on time, but one could argue whether the benefits were worth the cost of collecting the data. A technological shift toward remote operations and drone stations could reduce costs and improve the cost-benefit ratio.

5.1.4 Challenging terrain, lighting and weather

Can UASs be used operationally in steep terrain and in a range of lighting and weather conditions?

GEOSFAIR and other NPRA UAS projects have demonstrated that UAS can be flown in steep rugged mountain areas and in inclement weather. In addition, it is possible to collect data in a range of lighting conditions using lidar and, in some cases, SfM (Structure from Motion).

UAS usage in mountainous conditions runs the risk of occasional aircraft loss, but this is likely acceptable given the overall needs of an avalanche program.

5.1.5 Remote and autonomous operations

Can UASs be operated remotely and fly autonomously to gather data?

UAS can be flown remotely assisted in collaboration with an onsite crew and remotely from drone garages. This was done in two spin-off pilot projects performed between the end of the GEOSFAIR project and before this report was published (see field activities F7 and F8 in Table 6).

Both projects showed that data could be used for remote geohazard assessment. The technology is already in place. When this report was written, both national regulations and the NPRA's certifications allowed for more development of remote data capture.

5.1.6 Technology and decision-making

How can new technology successfully and economically be integrated with the current decision-making processes within NPRA?

Figure 10 shows the NPRA's updated natural hazards decision making system based on the findings from the GEOSFAIR project. The changes due to GEOSFAIR drone inspection and data collection inspections are noted in the flow chart. UASs provide information to support hazards assessment by NPRA geohazard engineers or the NPRA's road operations contractors.

The path for integrating UAS technology into the NPRA has been discussed in the preceding sections and involves replacing and enhancing previous data collection methods that have largely been completed by helicopter. This new approach will have economic benefits by reducing operational costs while also supporting quicker and better decisions that benefit society as a result of shorter roads closures and more travel predictability. This technology can also move toward more remotely assisted and remotely controlled data collection, reducing business costs for the NPRA.

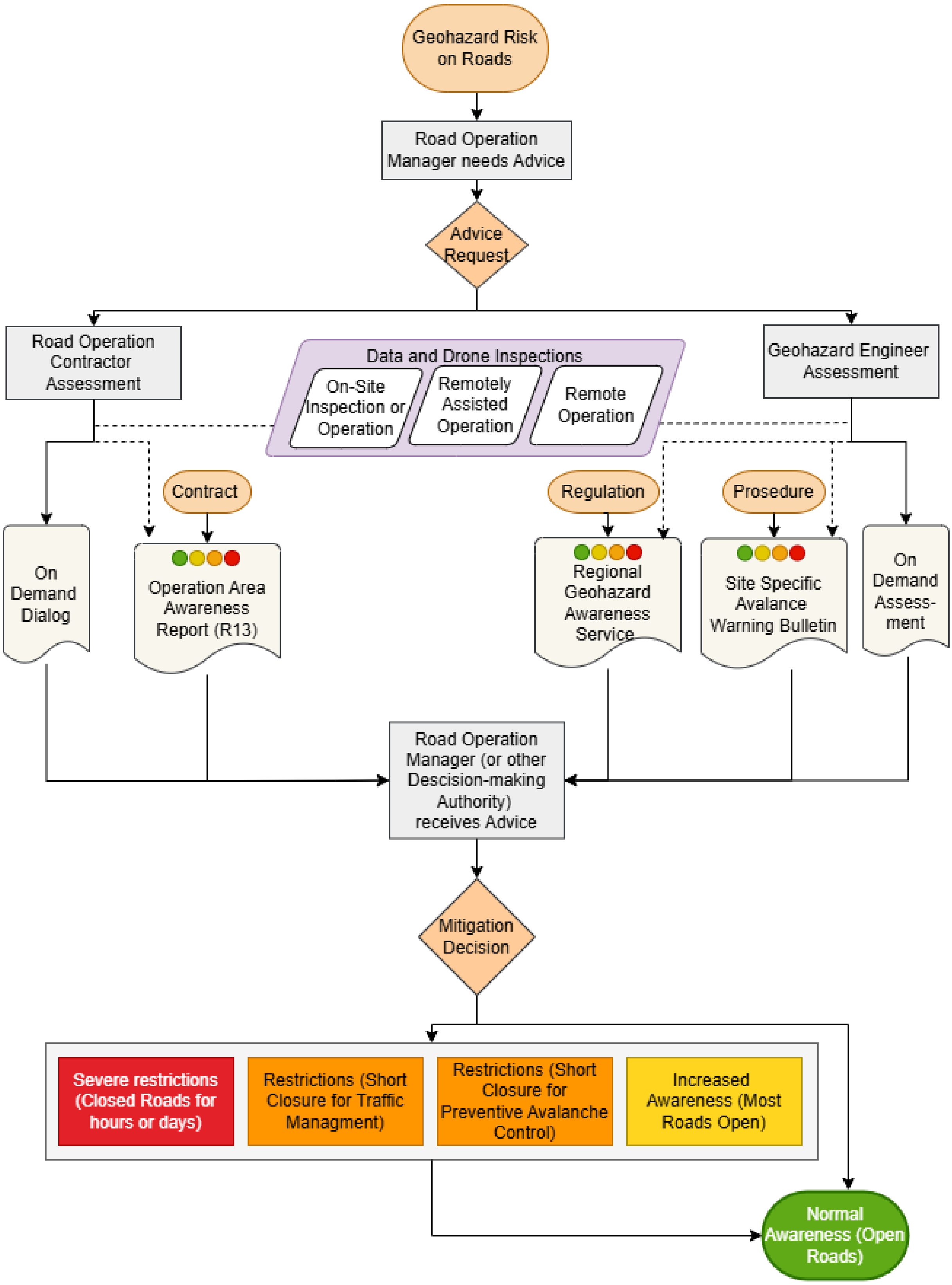

Figure 10: Updated decision-making system after the GEOSFAIR project with purple boxes that includes new definitions of UAV applications for geohazard purposes.

5.2 Comparison with Objectives

5.2.1 Primary objective

Paragraph 1.4 refers to the main objective for GEOSFAIR:

> *(to) develop effective methodologies for integrating uncrewed aircraft systems (UASs) and UAS-collected data into the present NPRA decision support system for geohazard risk assessment, considering both decision-making requirements and UAS aircraft, sensors, and software specifications.*

Although the primary focus was on snow avalanches, applications to other geohazards were considered by the project. General UAS application to geohazard risk assessment and decision-making procedures is seen in an organizational context in Figure 10.

5.2.2 Secondary objectives

The four verifiable secondary objectives (chapter 1.4), could be said to be achieved through these key points:

1. **Suitable UASs were identified and evaluated**: A goal of GEOSFAIR was to identify and evaluate UAS (aircraft, sensors, and software) that are suitable for NPRA's geohazard applications. Through field tests and supplier demonstrations, we have found that for all practical purposes, and if we disregard research tasks, the Norwegian Public Roads Administration can manage with off-the-shelf drones, sensors, and software. The equipment used in this project (see chapters 3.2 and 3.3.) reflects examples of equipment that has proven useful for geohazard purposes.

2. **Requirements were specified**: Requirements for adoption of UASs by decision makers within the NPRA and by other road owners are specified in NPRA report 1024 (Solbakken et al., 2025); see chapter 4.5.3.

3. **Testing was conducted under realistic field conditions**: Tests of UASs and of UAS-collected data under realistic field conditions and evaluation of results are discussed in filed reports; see chapter 4.3.

4. **Software and tools were developed.** The project developed a web application (the GEOSFAIR snow info viewer) that provided usable information to avalanche forecasters. It has not yet been implemented into the REPONS geohazard tool (chapter 4.4.2 and lower part of Figure 7), but it will work as a guide for further development.

5.3 Comparison with Plan

If we compare the original plan as shown in Appendix C with the adjusted plans (chapter 2.3) and what was carried out, there were minor changes. The project group changed its composition, and more field activities and milestones were added. Less hardware development was done than initially planned, but there was more testing of off-the-shelf products and different combinations of drones and instruments than planned. Some activities were rescheduled, and some products were merged.

5.4 Answers to Research Questions

We refer to the research questions discussed in paragraph 2.2.

5.4.1 Meaningful information (RQ1)?

The question was whether UAS-based tools can be used to deliver meaningful information for operational avalanche risk evaluation and mitigation.

The answer from the project is yes, UAS-based tools can indeed provide valuable information for operational avalanche risk evaluation and mitigation. Key points consist of high-resolution imagery and topographic data, real-time monitoring for decision-making, accessibility to remote or hazardous areas, cost effectiveness in comparison to traditional methods, and integration with other technologies such as geographic information systems (GIS) and predictive models to enhance the accuracy of avalanche risk assessments.

5.4.2 Enhanced or accelerated decision-making processes (RQ2)?

The question was "Can the adoption of UAS and UAS-based measurements demonstrably enhance or accelerate the NPRA's risk-based decision-making processes?"

GEOSFAIR demonstrated that UASs and UAS-based measurements can both enhance and accelerate NPRA risk-based decision-making processes concerning natural hazards. The activities as part of this project collected usable data that supported NPRA staff as they made decisions related to avalanche risk.

5.5 Impacts and Effects

Table 9 has details of the improvements resulting from the GEOSFAIR project activities, as well as the resulting impacts to the NPRA's operations and mission and snow science in general.

Table 9: Impacts and effects of the GEOSFAIR project

Improvements	Impacts
More data, better data	Use of UAS provides more (larger areal coverage and more regular inspections) and better (higher resolution) data.
Increased staff safety	Reduced need for staff to travel along avalanche-susceptible roads.
Emission reduction	Reduced crewed helicopter flights and more sustainable conduct of inspections. Roads open more quickly or are not closed, resulting in more efficient travel (less vehicle idling and fewer travel detours).
Better snow science data	The GEOSFAIR findings will benefit other organizations, both in avalanche management and water resource management.
Increased overall utility and automation of UAS	GEOSFAIR will develop easy-to-use workflows that will support non-specialists operating UAS. This will create spin-off applications and provide additional value for the UAS industry.
Strengthen the technical capacity of other road owners	According to the new Roads Act §10, NPRA has had, since 2020, a special responsibility to ensure safety and preparedness for the entire road network, which includes supporting other road owners. GEOSFAIR will strengthen the NPRA's ability to fulfill this role.

5.6 Outcome from Support of the Research Council of Norway

This section summarizes feedback on the project outcomes given by NPRA to the company *Samfunnsøkonomisk Analyse AS*, which mapped the results and outcomes on behalf of the Research Council of Norway (RCN).

The NPRA concluded that the project's partners were crucial for the project's success, including the NPRA, NGI, SINTEF, universities, other companies and vendors, and an international network. Key contributions included capacity for R&D activities, expertise in specific fields, and knowledge of applying for public funding.

Furthermore, the NPRA concluded the following:

1. **Project importance**: The project was considered important at the application stage and remains important for the future.
2. **If RCN did not support GEOSFAIR**: without funding from the Research Council, the project activities would likely have been conducted at the same time but on a much smaller scale, at a slower speed, without the strong connection to decision-making processes, and without the scientific framework that NGI and SINTEF contributed.

3. **Research and development (R&D)**:
    - **Use of results**: R&D results are being used by research institutions, but the usage by private and public sectors is uncertain. The results have been widely shared in written form and through experience sharing.
    - **Improved products, services and processes**: The project resulted in the launch of new or improved products/services, delivery of more sustainable and higher quality products/services, implementation of new and improved business processes, and reduced costs or reduced cost increase.
    - **Research and development awareness**: The project increased the awareness of the benefits of R&D, increased competence in conducting R&D projects, and established new national and international collaborations.
    - **Initiation of more research and development (R&D)**: The project led to the initiation of new R&D projects and follow-up projects, and it reduced greenhouse gas emissions and energy consumption. No doctoral degrees came out of the project.
4. **Outcome**: The project contributed to increased safety, reduced emissions, and improved public services.
5. **Implementation**: The ease of implementing R&D results was as expected.
6. **New investments**: No major investments have been made as a direct consequence of the project, but they are expected soon as we believe that drone docking stations will be more common.
7. **Patents**: No patents are expected

Overall, the NPRA is very satisfied with the project's success.

6 CONCLUSION

6.1 Major Outcome

GEOSFAIR demonstrated that uncrewed aircraft systems (UASs) are not only effective sensor platforms but also providers of critical, actionable data for snow avalanche forecasting and monitoring. This capability positions UASs as important tools for roadway-owning agencies, supporting them in making informed decisions when managing snow avalanches and natural hazards. In addition, the project produced comprehensive tools and documentation designed specifically for roadway agency staff that will ensure that UAS technology can be safely and efficiently incorporated into operational workflows for the management of avalanche and other natural hazards.

6.2 Strengths of the Methods

A key strength of the project was the active engagement of NPRA staff, whose daily responsibilities directly involve collecting and analyzing snow and avalanche data. Their involvement ensured that the research was grounded in real-world operational needs. Moreover, the numerous field tests—conducted under realistic conditions—validated not only the UAS and sensor performance but also the robustness of the deployment methodologies. With experts developing approaches for sensor deployment and data processing, the project demonstrated that UAS and sensor technologies can be integrated into routine operations by roadway-owning agencies.

6.3 Weaknesses of the Methods

Despite the advances, challenges remain. Keeping pace with rapid developments in UAS and sensor technologies proved to be a constant challenge, as those developments sometimes outstripped the pace of testing. Ongoing issues were flight regulations that constrained the full scope of testing, as well as environmental factors—such as adverse weather conditions, variable lighting, and steep terrain—that continued to pose operational restrictions. The project also encountered limitations associated with the relatively few tests on autonomous flights, which are critical for fully realizing operational independence.

6.4 Contribution to Science

This research established an effective approach for evaluating the application of UAS technology to snow avalanches and other natural hazards—a methodology that is likely to remain relevant as sensor and UAV capabilities continue to evolve. Beyond enhancing operational decision-making, the study supported the accumulation of valuable data, leading to a better understanding of snowpack dynamics and avalanche behavior. These insights have far-reaching implications, benefiting sectors such as water resources management, hydrology, and climate research.

6.5 Further Work

Opportunities for future research and development include the following:

- **Autonomous Flight Operations**: Developing and testing autonomous flights from dedicated drone garages.
- **Technological Integration**: Integrating UAS operations with complementary systems, such as ground-based sensors, to create more robust monitoring networks.
- **Diversified Testing Locations**: Expanding field tests to include diverse geographic and climatic conditions.
- **Cross-Hazard Application**: Applying insights and methodologies from this study to other natural hazards, such as landslides.
- **AI Integration**: Exploring the use of artificial intelligence both in the control of UAS operations and in the advanced analysis of sensor data.

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APPENDICES

APPENDIX A: Publications and dissemination form GEOSFAIR

APPENDIX B: Report from final workshop at ISSW 2024

APPENDIX C: Project plan submitted to the Research Council of Norway (March 2021)

APPENDIX D: Roles and procedures in the decision-making system of NPRA

APPENDIX E: International Reference Group of GEOSFAIR

APPENDIX F: Steering committee of GEOSFAIR

APPENDIX A: Publications and dissemination from GEOSFAIR

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APPENDIX B: Final workshop at ISSW 2024

"International Snow Science Workshop" 2024:

Workshop: Uncrewed Aerial Systems (UAS) in avalanche risk assessment, search, and rescue.

September 28, 2024

Content

1 Overview

The workshop "Uncrewed Aerial Systems (UAS) in avalanche risk assessment, search, and rescue" was held in conjunction with the International Snow Science Workshop in Tromsø, Norway in September 23–27, 2024 (ISSW 2024). The UAS workshop took place at the Tromsø Campus of The Arctic University of Norway on September 28th.

It was jointly organized by the Norwegian Public Roads Administration (NPRA), the Norwegian Geotechnical Institute (NGI), SINTEF, and NORCE. This summary is written by the workshop organizers from these organizations.

1.1 Purpose of the Workshop

The goal of the workshop was to explore innovative applications of Uncrewed Aerial Systems (UAS) in the context of avalanche risk assessment, avalanche control and prevention, as well as for search and rescue. The workshop constituted also the final seminar of the GEOSFAIR project[1].

1.2 Agenda

The workshop started with a series of presentations (see Section 2), relevant to UAS used in avalanche risk assessments, snow science, and search and rescue. This was followed by breakout groups who explored and reported out on the following six topics:

1. Field operations
2. Data capture, processing and sharing
3. Validating data from inaccessible terrain
4. Drone fleet and pilot management
5. Search and rescue
6. Implementation of drone technology

1.3 Participants

There were 50 attendees from the following organizations:

- Alaska Department of Transportation & Public Facilities (USA)
- Alpine Solutions and Canadian Mountain Holidays (Canada)
- Avalanche Commissions Tyrol (Austria)
- Avalanche Warning South Tyrol (Italy)
- Codelco, SMI (Chile)
- Drone Amplified (USA)
- Fachhochschule Graubünden (Switzerland)
- Funäsfjällens Lavinskola (Sweden)

[1] (https://www.vegvesen.no/en/fag/fokusomrader/forskning-innovasjon-og-utvikling/pagaende-programmer-og-prosjekter/geosfair/

- Futuradar GmbH (Switzerland)
- Geoformer igp AG (Switzerland)
- Icelandic Meteorological Office (Iceland)
- IVAQ Technologies S.L. (Spain)
- Lavinprognoser (SEPA) (Sweden)
- Norwegian Geophysical Institute (Norway)
- NORCE (Norway)
- Norwegian Polar Institute (Norway/Antarctica)
- Norwegian Public Roads Administration, NPRA (Norway)
- Norwegian University of Science and Technology (Norway)
- Norwegian Water Resources and Energy Directorate (Norway)
- Orica (Australia)
- Politecnico di Milano (Italy)
- POLS Engineering (Iceland)
- RECCO (Sweden)
- Rescue Services of Lapland (Finland)
- Redcross Avalanche Group (Norway)
- Sam Production (Sweden)
- SINTEF (Norway)
- SLF (Switzerland)
- Stellaire AS (Norway)
- The Finnish Association of Fire Officers (Finland)
- UiT The Arctic university of Norway (Norway)
- Vail Resorts (USA)
- Washington State Department of Transportation (USA)

Figure 1. Workshop participants came from 12 countries and four continents.

2 Presentations

The following presentations were held prior to the group work:

- *Tore Humstad, NPRA and GEOSFAIR project manager, Norway:* provided an overview of the goals of the workshop and of the GEOSFAIR project in general. He noted the NPRA's more recent focus on safely keeping roads open and explained how to access GEOSFAIR reports and publications.
- *Andreas Tøllefsen, NORCE, Norway:* presented on UAS and autonomy in an avalanche context. NORCE has multiple UASs and experience addressing flight limitations and operation challenges due to harsh weather. They suggest new levels of flight autonomy, using tools such as machine vision and real time lidar, will improve UAS operations.
- *Rolf-Ole Rydeng Jenssen, NORCE, Norway*: presented the SnowDrone which is being tested to fill the gap between ground-based and aircraft snow measurements. This UAS uses UWiBaSS (Ultra-Wideband Snow Sounder) radar to measure snow depth and stratigraphy.
- *Emil Solbakken, NPRA and GEOSFAIR, Norway*: reported on field tests to examine repeated UAS Lidar scanning to support avalanche forecasting. The finding determined that lidar can be successfully used for this application in many weather and lighting situations, but noted challenges related to weather that causes icing. Drone stations equipped with lidar will make such data collection much more efficient, both with regard to costs and time.
- *Bastien Dupuy, SINTEF and GEOSFAIR, Norway*: presented on the use of Ground Penetrating Radar (GPR) on UAS for avalanche forecasting. A series of field tests determined that GPR did result in usable quantifiable data consistent with hand dug snow pits. The study also provided operational recommendations such as for flight speeds and heights and noted that crashes are a possibility.
- *Sean Salazar, NGI and GEOSFAIR, Norway:* covered a series of tests in real world conditions exploring low-cost UAV Lidar. The effort gathered high quality and useful data, with a high level of reliability including in bad weather. Limitations for operational use were also determined relating to data gaps and errors and as flight safety concerns.
- *Halgeir Dahle, NPRA and GEOSFAIR, Norway*: presented on Drone in a Box (UAS garages for remote operations). They are commercially available from several vendors. There are still unanswered questions relating to how much area an autonomous UAS can effectively cover, flight regulations and charging times.
- *John Stimberis, Washington State Department of Transportation, USA*: covered the use of UAS for avalanche programs in Washington State, USA, which they have been doing since 2008. The use of this technology includes photography, evaluating snow volumes in avalanche catchments and testing the delivery of explosives for artificial release. The benefits include lower operational costs and greater operational agility but are limited by regulations, lack of trained staff, and weather.
- *Diego Sánchez Franco, IVAQ Mountain Rescue Drones, Spain:* discussed his company's UAS designed to detect up to four avalanche beacons. They are still in development and ultimately plan on having the UAS perform autonomous searches.

- *Ralph Blumberg, Drone Amplified, USA:* presented their commercially available UAS designed to drop explosives to trigger artificial avalanche release.
- *Patrick Dryer, Alaska DOT & PF, USA*: present their avalanche program and UAS response capabilities. The agency has an active UAS program with more than a hundred aircraft with a variety of different sensors as well as automated processing capabilities to support their operations including emergency responses. They are successfully using drone docks.
- *Harvey Goodwin, Norwegian Polar Institute, Norway:* highlighted their successful use of surface mounted ground penetrating radar on tracked vehicle and snowmobile used to detect crevices in the snow roads in Antarctica.

3 Takeaways

The main takeaways from the presentations can be summarized as follows:

- *General:*
  - Various attendees presented on topics such as UAS autonomy, lidar scanning, ground-penetrating radar, and drone-in-a-box systems. Highlights included advancements in sensor technology and the operational challenges faced in harsh weather conditions.
  - In general, UAS, as aerial platforms, are increasingly capable of flying in the conditions that support snow science and avalanche operations.
  - The operation of sensor technology has advanced to the point where usable data can be collected for avalanche risk identification, monitoring, and mitigation. This includes information from camera observation, and data from photogrammetry, lidar and ground penetrating radar.
- *Field Operations:* UAS technology provides fast, efficient mapping and data capture. However, limitations include the need for certified pilots, weather impacts, and high operational costs. Future improvements are expected in regulations, battery life, and broadcasting capabilities.
- *Data Capture and Processing:* Current technology allows for effective data collection and processing using software like DJI Terra and ArcGIS. Challenges include high software costs, connectivity issues, and multi-step data processing. Future advancements aim for full automation flights and better integration with civil aviation authorities.
- *Validating Data from Inaccessible Terrain:* UAS technology helps validate data in difficult-to-reach areas. Limitations include complex airspace regulations and harsh weather. Future tools are expected to improve airspace control and automated approvals.
- *Search and Rescue:* Drones enhance visual searches and IR camera usage, but face challenges like noise, limited radio range, and weather conditions. Future developments include autonomous drones with multiple sensors for improved search and rescue operations.
- *Implementation of Drone Technology:* Benefits include the availability of commercial off-the-shelf sensors and UAVs. Challenges involve complex airspace operations, weather

constraints, and political uncertainties. Future expectations include better integration into airspace and more diverse data sources.

- Despite identified challenges, the benefits of using UAS presented during the workshop suggests that new and innovative use of UAS in the avalanche world will occur in the near future.

4 UAS Group Work Summary

After the presentations, the workshop participants broke into six groups to discuss five topics:

1. Field operations (logistics, weather, personnel, light…)
2. Data capture, processing and sharing
3. Validating data from inaccessible terrain
4. Drone fleet and pilot management
5. Search and rescue
6. Implementation of drone technology

Each group had these topics to discuss during their work:

- Advantages of today's technology/methodology
- Limitations of today's technology/methodology
- Expectations for future technology/methodology
- Further work
- Other comments

The following summarizes the groups' discussions.

4.1 Field Operations

The advantages of current UAS technology in field operations include the ability to provide a fast, cheap, and efficient way to frequently obtain overviews and map areas. LiDAR technology allows for quick data capture, processing, and sharing of information.

However, there are numerous limitations, such as the need for certified pilots due to strict regulations, the impact of weather and lighting conditions on operations, and the high costs associated with frequent flying to maintain proficiency.

Future expectations include better regulations, user-friendly processing tools, longer battery life, and improved broadcasting capabilities. There is also a need for more pilots and stricter licensing requirements. Further work involves integrating UAVs into emergency response plans and practicing regularly.

4.2 Data Capture, Processing, and Sharing

In data capture, processing, and sharing, it is certainly feasible to collect usable information, as seen in workshop presentations. There are advantages of today's technology include the use of easy-to-use software like DJI Terra and ArcGIS, and the ability of drones to operate in various weather conditions and altitudes.

Limitations include closed systems and high license costs for software, connection problems for telemetry, regulations that limit operations in remote areas and high altitudes, and the multi-step nature of data processing, which should be automated. In addition, weather reduces UAS's capabilities.

Future expectations involve full automation of data capture and processing, improved regulations, better integration with civil aviation authorities, and the use of AI and high-performance computing for data analysis and interpretation. Further work should enhance dialogue with pilots in helicopters (or other crewed aircraft) and improve data sharing. Photogrammetry in combination with real-time data transmission to the cloud are also important aspects to consider.

Drones can be considered a game-changer for mapping and data collection, providing significant advantages in field operations.

4.3 Validating Data from Inaccessible Terrain

The advantages of current technology for validating data from inaccessible terrain include the ability to activate pre-defined danger areas through NOTAMs and the use of improved tools for flight planning and approvals. However, limitations include complex airspace regulations and the need for approvals, as well as harsh weather conditions that limit drone operations.

Future expectations involve improved tools for airspace control and automated approvals, and better integration of drones with other airspace users. Further work should focus on developing protocols for safe drone operations in controlled airspace. Software like FlightHub2 and FlytBase can be used for mission planning (with peer review) enhancing the overall efficiency and safety of drone operations.

4.4 Drone Fleet and Pilot Management

Pre-defined danger areas for flights can be activated through NOTAMs. SafeSky, combined with remote ID, informs other airspace users about drone operations. Tools like AirData automate approvals, pre-flight checklists, and flight logging. NINOX Drone (Norway) alerts others about flight plans and seeks permission in controlled airspace. FlightHub2 and FlytBase software facilitate peer review before approving and monitoring remote missions.

In drone fleet and pilot management, the advantages of current technology include the use of visual and thermal imaging for various applications, livestreaming capabilities, and remote operation via 5G. However, limitations include strict regulations, high costs for training and certification, harsh weather conditions, and the need for experienced pilots.

Future expectations involve the establishment of remote operation centers, improved training systems, more support from authorities, and better incident reporting systems. Further work should seek permissions for drone-in-a-box operations and improve insurance policies. The use of DJI, Skydio and other equipment for various operational needs is also highlighted as a significant advantage in mitigating natural hazards.

4.5 Search and Rescue

For search and rescue operations, drones provide significant benefits for visual searches and IR camera usage. Distributed drones in local stations enhance safety for rescue personnel. However, limitations include noise issues, limited radio range, challenging BVLOS flights, weather conditions, and the need for multiple UASs for different use cases.

Future expectations involve the development of search tools for Recco/avalanche beacons and IMSI catchers, better airspace control, and equipment designed specifically for UAS SAR missions. Further work should improve procedures for manned/unmanned teaming and instant avalanche mapping. Possible technology includes autonomous drones perhaps with multiple sensors and capabilities, which could enhance search and rescue operations.

4.6 Implementation of Drone Technology

The implementation of drone technology benefits from the availability of commercial off-the-shelf (COTS) sensors and UAVs, and the general acceptance and understanding of the technology. There are low hanging fruits such as using Structure from Motion (SfM) with low cost and low weight UASs as well as already available tools and knowledge.

Limitations of the UAS technology include data capture at different altitudes and climates, UAS technology and operation in a complex airspace with multiple operator such as manned helicopters. Other limitations are related to weather constraints, political uncertainty, integration challenges, and the immature nature of the industry, particularly regarding battery energy density.

Future expectations involve the development of drone-in-a-box systems for easy data delivery, portable and plug-and-play systems, better integration into airspace, and more diverse data sources. Further work should focus on more research on aircraft and sensors, increasing the weather envelope, and better computational resources. Collaboration between public agencies and private actors is essential for better implementation, and business models and tender strategies must allow for more drones.

4.7 Plenum discussion summary

The UAS related technology and equipment develops fast. Tasks that were impossible or hard to perform are now routine, such as high-quality terrain models acquired in BVLOS flights.

Regulatory and airspace restrictions do not develop as fast as technology develops. This limits the deployment and operational flexibility.

DJI is the major manufacturer for UAS systems for users attending the workshop. Political issues may reduce the legal use of DJI products. It may be a good policy not only using one manufacturer.

4.8 Final note

Establishing a kind of international society or group for use of UAS in avalanche subjects may be important to further develop the technology and integration. This workshop may have been the first step towards the establishment of such an environment. It was stated that a workshop may be held annually, physically at each ISSW and virtually in the year between. NPRA and the GEOSFAIR team will look into this and may be a facilitator for the next virtual workshop in 2025.

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ISSW and Tim Dassler facilitated this workshop at UiT. Thanks for all help.

Appendix

Workshop agenda

Saturday 28. September 2024

Time	Theme/title	Presenter	Affiliation
08:30	Welcome and introduction	Tore Humstad/Ed McCormack	GEOSFAIR
08:50	Autonomy of UAS	Andreas Tøllefsen	NORCE
09:05	SnowDrone - Drone-borne radar system for snow measurements	Rolf Ole Rydeng	NORCE
09:20	Acquisition and use of LiDAR data in avalanche forecasting	Emil Solbakken	GEOSFAIR
09:35	**Pause**		
10:05	Low-cost UAS-LiDAR: assessing repeatability and accuracy	Sean Salazar	GEOSFAIR
10:20	Ground penetrating radar on UAS, 2	Bastien Dupuy	GEOSFAIR
10:35	Drone docking station	Halgeir Dahle	GEOSFAIR
10:45	Use of UAS on American highways	John Stimberis	WSDOT
11:00	Short presentations	Diego Sanchez Franco	IVAQ Technologies
		Ralph Blumberg	Drone Amplified
		Patrick Dryer	*Alaska DOT& PF*
		Harvey Goodwin	Norwegian Polar Institute
11:30	**Lunch served at Campus**		
12:30	**Group work** Themes: 1. Field operations 2. Data capture, processing and sharing 3. Validating data from inaccessible terrain 4. Drone fleet and pilot management 5. Search and rescue 6. Implementation of drone technology		
14:00	**Pause**		
14:30	Wrapping up the workshop	Tore Humstad/Ed McCormack	GEOSFAIR
14:45	Workshop ends		

APPENDIX C: Original Project Plan (2021)

Project plan submitted to the Research Council of Norway, March 2021.

GEOSFAIR: Geohazard Survey from Air – remote decision support with focus on avalanche applications

1 Challenges and needs

Society's reliance on transport networks has grown extensively, amplifying adverse impacts of network disruptions. Linear infrastructure, such as road and rail networks, pipelines, and power grids are especially sensitive to catastrophic disruption[1]. In Norway, roadside geohazards pose a serious threat to the transportation network and road users every year. Roadway closures, due to avalanches, landslides, and rockfall occurrences, incur high economic costs and greatly impact the reliability of Norway's critical transportation network[2,3].The Norwegian Public Roads Administration (NPRA), as well as county and municipal road-owning agencies have the responsibility to maintain important routes through mountainous, avalanche-prone corridors[4,5]. According to public strategies[6,7] and responsibilities[8,9], the NPRA must facilitate efficient and predictable transportation to maintain accessibility for people and goods throughout the country. Keeping roads open during the winter therefore requires the operation of programs to continuously monitor avalanche conditions, to assess risk, and to enable mitigation measures (such as occasional artificial releases). The large size of the road network and its increasing use has led to augmenting mitigation costs over the past decades, which led to a stronger focus on risk mitigation measures. The NPRA has spent up to 1.3 billion NOK annually to protect national and county roads from geohazards in the past years[10–12]. These numbers illustrate the urgent need for cost-effective and innovative methods for future geohazard risk assessment and risk mitigation measures along the network.

To maintain a satisfactory preparedness level against geohazards along roads and infrastructure, detailed knowledge of conditions in exposed areas is necessary. Systems for monitoring and forecasting are required, which involve the collection and evaluation of data using a range of methods. While avalanches are only one of the relevant geohazards, they stand out as the most dependent on the weather and can lead to rapid changes in the risk situation. In comparison to other geohazards, avalanches cause more frequent traffic restrictions and repeatedly occur along the same paths. Current avalanche hazard assessment efforts by the NPRA involve visual observation (on foot, skis, snowmobile or from manned helicopter), hand-dug snow pits, and stationary sensors, combined with weather station information. Because it is challenging and often dangerous to collect data by physically visiting an avalanche release area, conditions are often evaluated based on observations from the road, or by extrapolation of weather data. With the presently used monitoring strategy, many mountain roads remain closed for lengthy periods to ensure the highest level of safety for road users and maintenance staff. Keeping infrastructure closed or decommissioned for service may lead to severe societal and financial consequences, as there is often little or no road redundancy[13]. Compounding the problem are climate changes that result in more severe, more frequent, and less predictable geohazards[14,15], emphasizing the need for better proactive monitoring and risk mitigation.

Today's cost situation, in combination with the current and future risk picture, form the backdrop for the GEOSFAIR project application. Based on updated governmental goals for transportation[16], the NPRA has identified the following specific research and innovation areas which will constitute significant value creation if improved: *(1)* Utilization of new, automated technology to survey terrain, while reducing costly manned helicopter flights and manual tasks; *(2)* Improve accuracy and reliability of data that are collected; and *(3)* Implement structured digitalization strategies to remotely monitor sites and to improve preparedness and decision-making ability. Combining the rapid developments in unmanned aircraft systems (UAS), with automated digitalization methods, new technologies for advanced data capture, and critical decision support tools will result in considerable cost savings and safety improvements for the NPRA and other road owners with similar challenges (e.g. the county administrations).

Following this argument chain, the **primary objective** of GEOSFAIR is *to develop effective methodologies for integrating unmanned aircraft systems (UAS) and UAS-collected data into the present NPRA decision support system for geohazard risk assessment, considering both decision-making requirements and UAS aircraft, sensors, and software specifications.* Within the scope of this project, avalanche risk assessment will be the focus. Four verifiable secondary objectives, each of which address a specific challenge, will help to achieve the primary objective, as described within Table 1.

Table 1. *Secondary objectives (SO) that verifiably address the challenges and needs of GEOSFAIR.*

Secondary objectives (SO)	***Challenge addressed by SO***	***Verification of SO***
SO1. Identify and evaluate UAS aircraft, sensors, and software that are suitable for NPRA's geohazard applications.	Useful data needs to be collected remotely in realistic field conditions (varying terrain/weather).	Systematic evaluation of available/emerging UAS aircraft, sensors, and software to determine recommended specifications.
SO2. Specify requirements for adoption of UAS by decision makers within the NPRA and other road owners.	National requirements for preparedness and safety. Implementation of new workflows, protocols, and training.	Iterative gathering and consolidation of requirements to create guidelines for operation and implementation.
SO3. Testing of UAS and of UAS-collected data under realistic field conditions (and first evaluation of results).	Operate in realistic conditions; timely evaluation of data. Validation within NPRA workflows and decision-making processes.	Feasibility study and careful design of test arrays; critical evaluation and independent validation of the results.
SO4. Develop software and tools that provide usable information and allow rapid integration and support in the decision-making process.	Address data processing issues (e.g. large data sets, but rapid analysis required). Ensure confidence in road closure, reopening, and maintenance decisions. Integration/interface with current data support systems. Address organizational barriers against successful implementation.	Work with existing NPRA data tools, e.g. the geohazard web portal *RESPONS*[17]. Develop method to document how new tools shorten the duration of road closures without jeopardizing safety. Develop implementation guidelines; integrate practitioner and decision-maker input in all project activities.

2 Excellence

2.1 The innovation

2.1.1 Innovation concept:

Today's avalanche monitoring efforts by the NPRA are time- and personnel-intensive and result in limited observations. Regional overviews of snow conditions during upcoming or ongoing avalanche cycles are largely not feasible. To combat these constraints, the NPRA has sought to use UAS in routine operations; however, previous applications of UAS have been limited to narrow research tasks in ideal conditions using advanced, but often impractical, data capture methodologies. Nonetheless, as the national body responsible for key tasks, such as implementing national preparedness systems and assessing road hazard and traffic information, the NPRA must aim to benefit from further developments in UAS technology and build organisational-level competence.

Consequently, the innovation to be realised within GEOSFAIR includes the systematic evaluation of the practical use of UAS and data gathered by UAS in support of routine roadway administration decisions. The novel aspects of the project include exploration of new and emerging sensor technologies, including UAS-based ground penetrating radar (GPR) and directly georeferenced photogrammetric survey techniques to identify critical snow parameters, such as snowpack thickness, detailed surface topography, weak layers and recent avalanche debris. Another innovation for the NPRA and other road-owning decision makers will be the potential for semi- and fully autonomous implementation of UAS technology. Automation will be critical to supporting rapid and more effective assessment of site conditions by non-expert staff, subsequently enabling a faster and more confident decision-making process. Thus, adopting UAS in routine operations has the potential to reduce the economic impacts of premature or extended road closures, while also reducing personnel exposure to dangerous conditions.

2.1.2 Knowledge needs

While a range of UAS-borne sensors have been utilized for research purposes – including light detection and ranging (LiDAR) sensors[18,19], GPR sensors[20], and various cameras[21,22] – the feasibility of using these sensors for operational decision-making processes has yet to be verified. With the emergence of advanced digitalization methods that facilitate machine-to-machine communication and increasingly efficient data management, there exists a large, albeit underexploited, potential for improvement of current workflows. GEOSFAIR therefore aims to explore how UAS technology can be integrated into critical avalanche monitoring needs of the NPRA and subsequent decision-making processes. GEOSFAIR will be guided by the need to develop knowledge about which UAS (aircraft, sensors, and software) can realistically and routinely address the NPRA's needs. GEOSFAIR will therefore address a number of urgent knowledge gaps and associated questions, for example: *(1)* How will UAS provide data in support of roadside avalanche monitoring?; *(2)* Will UAS provide data that replace or just enhance existing tools that the NPRA currently employ?; *(3)* Will UAS provide useful and timely coverage in locations of avalanche hazard?; *(4)* Can UAS be used operationally in steep terrain and in different light and weather conditions?; *(5)* Can UAS be operated remotely and fly autonomously to gather data?; *(6)* How can new technology successfully be integrated with current decision-making processes within NPRA?

2.2 R&D activities

2.2.1 R&D objectives

The primary objective of GEOSFAIR is to develop effective methodologies for integrating unmanned aircraft systems (UAS) and UAS-collected data into the present NPRA decision support system for geohazard risk assessment, considering both decision-making requirements and UAS aircraft, sensors, and software specifications.

The **anticipated results (AR)** of the proposed innovation reflect each of the aforementioned SO of the project and are stated as follows:

AR1. *Specifications and guidelines for UAS aircraft, sensors, and software that are suitable for the NPRA's geohazard applications, with an emphasis on avalanche monitoring;*

AR2. *Consolidated requirements for adoption of UAS by the NPRA and other road owners;*

AR3. *Performed, assessed and reported field test of UAS and of UAS-collected data under realistic conditions;*

AR4. *Software and tools that transfer usable and meaningful information about avalanche hazards to decision-makers at the NPRA and beyond.*

2.2.2 R&D challenges, design and scientific methods

Small unmanned aircraft have seen significant technical advances in the past decade and have become increasingly capable, more affordable, and easier to operate. In addition, these aircraft can complete missions autonomously using pre-determined flight plans. UAS can be equipped with cameras and compact sensors that collect snow data more quickly and more safely than by traditional means. A series of preliminary tests, arranged and overseen by some of the GEOSFAIR project members, indicated that UAS have the potential to support avalanche management[23–25], but additional research is needed to determine specifications for the most suitable UAS technologies (aircraft, sensors, and software) and requirements for implementation in existing decision support systems to make the technology operationally applicable for the NPRA and other road-owners. International efforts have evaluated the use of UAS for collecting snowpack data[26] and as input for avalanche risk assessment[27,28]. However, these studies have collected data in ideal conditions, and to the best of our knowledge, no research has explored the use of UAS to collect avalanche-related data in bad weather and in rugged terrain. And none have developed a decision support framework resulting in UAS-collected data quickly and routinely to be used by avalanche staff from roadway operating agencies to support decisions to open or close roads.

In direct response to the state-of-the art outlined above, the research strategy and activities within GEOSFAIR will focus on two main research questions (RQ):

RQ1. *Can UAS-based tools be used to deliver meaningful information for operational avalanche risk evaluation and mitigation?*

RQ2. *Can the adoption of UAS and UAS-based measurements demonstrably enhance or accelerate the NPRA's risk-based decision-making processes?*

3 Impact

3.1 Potential for value creation

GEOSFAIR will challenge the industry state-of-the-art by establishing a methodology for UAS-assisted risk assessment in road transportation corridors. Value creation is foreseen in at least nine distinct areas: *(1)* **Increase the number of site visits for better coverage**: UAS have the potential to reduce the time needed to assess an avalanche site and the number of locations that staff can inspect will increase; *(2)* **Enable remote inspections of inaccessible areas**: Due to steep terrain and staff safety requirements, many avalanche release areas are inaccessible and must be assessed from a distance. The use of UAS will allow for more effective remote inspections; *(3)* **Provide more, and more accurate data:** The use of UAS can provide the NPRA staff with better or higher quality or resolution data; *(4)* **Reduce risk to the traveling public:** Avalanches releasing onto roads can create life threatening situations due to vehicles and people being swept off of a road or simply due to vehicle collision with avalanche debris on the road. The results of GEOSFAIR will reduce these hazards; *(5)* **Reduce manned helicopter flights**: Any ability to replace manned flights with UAS usage will result in considerable cost savings. In addition, substituting manned flights with UAS will decrease the carbon footprint of such reconnaissance trips, and lead to a more sustainable conduct of inspections; *(6)* **Better snow science data**: GEOSFAIR will explore the use of aerial sensors to provide information about snow volumes, surface properties, snow depth and layering. These findings will benefit other organizations, that must monitor avalanche risk and those who may need to track snow cover information, e.g. for water resource management and flooding hazards; *(7)* **Increase the overall utility and automation of UAS:** This project seeks to develop easy-to-use mission planning, automation, and data processing workflows that could be adopted by the NPRA. Planning and execution of flights and data handling (collection, analysis and presentation) must be partly automated; *(8)* **Support sustainability**: Globally, a number of countries are impacted by road closures due to avalanches or the threat of avalanches, which reduces transport network reliability and results in detours, and inefficient travel patterns. GEOSFAIR supports a more reliable transport network that uses less energy and reduces the release of pollutants; *(9)* **Strengthen the technical capacity towards other road owners**: According to the new Roads Act §10[5], the NPRA has since 2020 a special responsibility for ensuring safety and preparedness for the entire road network, which includes supporting other road owners. Consequently, the NPRA must make professional capacity, tools, and methods available to eleven counties and one state-owned road company. This project will strengthen the NPRA's ability to fulfill this role.

Benefits to the public sector and other end users: GEOSFAIR will benefit public and private sector organizations, who are required to monitor avalanche risk, as well as roadway users that depend on safe transportation infrastructure (county administrations, mountain municipalities, the Norwegian state enterprise *Nye Veier*, railroad authorities, and the freight industry). Moreover, GEOSFAIR will benefit the UAS industry by increasing the applicability of UAS technologies for operations in extreme conditions and providing incentive for possible new markets (e.g. remote and automated mapping and geohazards monitoring). GEOSFAIR will also promote advances in snow science research, by developing additional methods of collecting snow information.

National and global development and sustainability challenges: GEOSFAIR responds directly to the NPRA's desire to evaluate technology to support more rapid and effective roadside avalanche hazard monitoring and forecasting, as stated in the *2018–2029 Norwegian National Transport Plan*[8]. GEOSFAIR also addresses recommendations put forth in the White Paper no. 15 to parliament (2011-2012), entitled *How to live with hazards – about floods and landslides*[29]. Furthermore, the activities of GEOSFAIR will contribute to UN sustainability development goal (SDG) 9*: Industry, innovation and infrastructure – Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation* (Targets 9.1, 9.4, 9.5) and SDG 13: *Climate action – urgent action to combat climate change and its impacts* (Targets 13.1–13.3). Moreover, GEOSFAIR will contribute to meeting other national and international development and sustainability challenges. Specifically, the activities of GEOSFAIR will promote: *(1)* improved reliability of the transportation network; *(2)* increased resilience of the network to geohazards and climate change effects; *(3)* reduced emissions due to travel disruptions and detours; *(4)* reduced emissions from manned helicopter flights and NPRA maintenance vehicle used for site visits; *(5)* additional observations to record and track impacts of climate change; and *(6)* increased safety of both road maintenance staff and the travelling public.

3.2 Utilisation of results

3.2.1 Plan for the realisation of the innovation

GEOSFAIR, if to be successfully realised, must ensure that data captured from UAS will support actions by roadway managers. In this way, the NPRA and the project team aim to support the development of a future industry standard. The project will sponsor yearly NPRA seminars at the end of each project year (as described in the WP-4 activity), to discuss, improve, and streamline this process, enabling new input and realignment of the project plan. Ideally, these seminars will continue beyond the GEOSFAIR project period.

Additional steps will ensure that the innovations of GEOSFAIR are realised. UAS pilots within the NPRA will be trained prior to the project, and equipment will be purchased, so that the NPRA team is ready to participate in the planned field demonstrations. This will enable NPRA staff to use the results and methods from GEOSFAIR to provide feedback on further developments and improvements (e.g. updating UAS operations guidelines). NPRA staff will develop estimates of the number of road closures that are caused by geohazards, which will subsequently be used to prepare analysis on how UAS will affect a roadway's expected availability in an effort to document the value of the GEOSFAIR project to NPRA staff. Similarly, the results from field demonstrations with NPRA staff will be used to decide how avalanche control should be performed (e.g. from fixed masts or helicopters).

Data management is a critical component of GEOSFAIR. The NPRA will establish an application programming interface (API) to capture selected data from UAS. The aim is to integrate UAS-collected field data with other geohazard data from existing stationary instruments, including doppler radars, infrasound detection and geophones, that feed into NPRA's *RESPONS*[17] geohazard web portal. The NPRA's IT and geodata staff will support the development of the APIs and databases. Data from fixed detection systems running at the GEOSFAIR test sites of Lavangsdalen and Strynefjellet will be collected throughout the project both to validate the UAS field demonstrations, but also to explore decision-making capabilities using data from multiple sources (i.e. a full-scale, instrumented road network). Given the importance of avalanche data management, findings from the field demonstrations will also be shared with the public national geohazard database *RegObs*[30] for further use by other public and private avalanche services (e.g. NGI's local avalanche warnings for Strynefjellet and the Norwegian Water Resources and Energy Directorate's regional bulletins for the Lyngen and Jotunheimen mountain regions).

With GEOSFAIR, the NPRA is taking the necessary steps to realizing these innovations and will contribute to pushing the limits of UAS and remote sensing applications in operational geohazard assessments. While GEOSFAIR will focus on avalanches, the methodology and findings of the project will be of value beyond avalanche applications and can be transferred to the monitoring of other natural hazards, such as rockfalls, landslides and debris flows, and will be usable for stakeholders outside of the NPRA (e.g. county administrations). The risk factors that may impact the realisation of GEOSFAIR are outlined in Table 3.2.1.

Table 3.2.1. *Risk factors and mitigation measures.*

Risk factor	Risk level	Mitigation measures
The NPRA receives political guidance to prioritise operations over research and development, potentially impacting project support (organisational risk)	Low	Modify project schedule, team, or budget, if necessary
UAS-obtained data does not provide usable information to the NPRA (implementation risk)	Low	Explore a wide range of best-available technologies and draw upon prior experience with UAS at the NPRA
Insufficient snowpack or extremely bad weather during planned field tests (weather-related risk)	Low – Medium	Two planned field-testing seasons; possibility to relocate testing sites to alternate locations
Civil Aviation Authority of Norway (Luftfartstilsynet) restricts the NPRA's ability to operate unmanned aircraft (regulatory risk)	Medium	Contact Luftfartstilsynet early in effort; request flight waivers and authorization for UAS flights
COVID-19 will have continued impacts during project period (health risk)	High	Project team will use remote connections and will conduct field work using best disease control advice

Ethical and gender perspectives: GEOSFAIR reflects the aims of the RCN to ensure that Norway is prepared for future societal challenges, especially as related to safe and reliable transportation networks, given the stress of a changing climate. The GEOSFAIR consortium will maintain a high quality of research that reflects the ethical standards set by the RCN. Several partners in the consortium have already established good working relationships through previous research collaborations and new relationships among researchers will be fostered. The content of the GEOSFAIR research does not have a prominent gender dimension. Project management-wise, at least two out of the four work packages will be led by women. As far as possible, women and men will be equally represented in the project steering group and in the research team.

3.2.2 Dissemination, sharing and exploitation

Potential for sharing and exploitation in other segments of the public sector: GEOSFAIR will expand the utility of UAS in the public sector by documenting the applicability to the NPRA's use case. Other public sector actors, including railway authorities may also benefit from the methodologies developed in GEOSFAIR. Beyond geohazard monitoring for the transportation sector, UAS are becoming increasingly common for a wide range of aerial survey needs and will be adopted by public agencies over time. GEOSFAIR's knowledge on how to use this technology in difficult conditions and without direct human piloting (i.e. autonomous operations) could benefit search and rescue operations, remote inspections of infrastructure (e.g. power lines, radio masts, dams), disaster relief, remote surveillance, analysis of agricultural crops, and many other uses not yet imagined. Furthermore, GEOSFAIR's contribution to the field of snow science should have impacts beyond the project and will benefit public agencies responsible for resource management, flood control, recreational use of snow, and numerous other potential users.

Dissemination plans: A project website will be established to share the most important GEOSFAIR findings with external stakeholders and the broader public (e.g. examples of remotely-captured data and results, that will be provided to roadway authority staff to support roadway closure/opening decisions). The dissemination activities will further include (cf. also Section 4.1.1): *a)* inviting NPRA staff (and staff from other relevant authorities and public bodies) and vendors to participate in the planned field tests; *b)* freely available download of established guidelines on the NPRA publications website[31] and the aforementioned GEOSFAIR project website; and *c)* organization of a public stakeholder workshop arranged at the end of the project. GEOSFAIR results will be communicated more broadly through publications in industry-targeted communication outlets (e.g. *Nordic Road and Transport Research*, or *Teknisk Ukeblad*). Project outcomes will also be promoted outside of Norway through Open Access, peer-reviewed academic journals (cf. description of deliverables provided in Section 4.1.1) and through presentation at national and international conferences (e.g. the 2021 Unmanned Nordic Conference in Oslo, and the 2022 and 2024 International Snow Science Workshops, in USA, and Tromsø, respectively). All project research communication will adhere to the FAIR principles[32]. Each work package will provide an opportunity to involve master students in the supporting research. All members of the GEOSFAIR consortia have long-established contacts within the main Norwegian universities, as well as with leading international universities. Most members of team routinely support and advise masters students. The project team anticipates that the innovative and exciting nature of the GEOSFAIR project, involving UAS, sensors, and avalanches, will be very attractive to students.

4 Implementation

4.1 Project plan for the R&D project

4.1.1 Main activities of the R&D project

GEOSFAIR will be divided into four work packages (WP), each with respective tasks that are outlined as follows.

WP-1: Hardware – aircraft platforms and sensors. The aim of WP-1 is to provide optimal user-guided specifications of the UAS flight system, the associated sensors and logistical aspects required to forecast and monitor avalanches and relevant snow parameters in harsh conditions.

R&D category: Industrial research. **Partners:** SINTEF (leading, Irene Jensen); NGI & NPRA (contributing).

Scientific content: *Task 1.1: Identification of UAS requirements:* This task will explore UAS (aircraft and flight control software) that are able to routinely operate in the challenging environments required for avalanche assessments (e.g. sub-zero temperatures, in winds above 10 m/s, and in rain or snow). The aircraft must have sufficient endurance to cover large areas, while carrying the required sensor payload (link to Task 1.2), and still be able to return to a safe landing site. The UAS should be portable to allow for transportation in standard NPRA vehicles and to allow roadside takeoff and landing. Finally, the UAS should be able to fly pre-determined routes autonomously. *Task 1.2: Recommendations for sensor technologies:* This task will explore UAS-mounted sensors that can provide information about snowpack and avalanche conditions by investigating *(1)* surface sensing methods, *(2)* subsurface scanning methods, and *(3)* weather parameters (wind speed, direction, and temperature). Surface sensing methods should provide information about snow depth and distribution, cracks, cornices, convex slopes, anchors, trigger points, and avalanche activity. Surface mapping will involve the use of high-resolution, and possibly infra-red, cameras and LiDAR. Subsurface scanning may be based on GPR to record snowpack thickness, internal structure of the snowpack (weak layers) and snow properties (hardness/density, water content). The investigation of the optimal GPR system will require determining limitations related to UAS payload and autonomy (link to Task 1.1) and the ability to fly close to steep surfaces (link to Task 2.1). To satisfy the goals of both Tasks 1.1 and 1.2, a thorough evaluation of the current state-of-the-art and emerging technologies in the market will be conducted. *Task 1.3: Optimization of flight logistics and data acquisition:* This task will define recommendations for hardware systems to optimize repeatability of aerial surveys. Specifically, the task will investigate and describe an innovative concept for how/where/when to execute UAS flights (e.g. UAS base mounted on a truck, central UAS garage) and will involve defining flight paths, spatial coverage, and the urgency and the frequency of surveys. Specifications on the automation of survey planning, the spatial coverage of the UAS system, and the recording of data will be proposed.

Anticipated R&D results: D1.1: Report describing operational specifications for the NPRA (year 2, Q3); P1.1: Scientific publication describing specifications for hardware (UAS aircraft, sensors, flight control) required for avalanche applications (year 3, Q1).

WP-2: Software – mission planning, automation, and processing workflow. The aim of WP-2 is to provide optimized software guidelines and testing environments to prepare for autonomous flight and data recording as well as automated data processing and interpretation workflows.

R&D category: Industrial research. **Partners:** SINTEF (leading, Bastien Dupuy); NGI & NPRA (contributing).

Scientific content: *Task 2.1: Automation of mission execution:* This task will investigate how to automate flight missions and how to create efficient surveys tailored to the given environment. This will include autonomous UAS flight and data acquisition testing, based on the sensor types that are specified in Task 1.2. Flight execution will be tested in a simulated environment to optimize autonomous flight patterns and data collection in challenging conditions without risking the loss of expensive equipment. *Task 2.2: Partial automation of post-mission data processing and interpretation:* This task will focus on making the recorded data usable by road operators. The workflows for processing sensor data, such as three-dimensional photogrammetric reconstructions or GPR image interpretation, will be optimized and standardized. As sensor technologies are developing rapidly, other emerging sensor types will also be considered during the project timeframe. *Task 2.3: Rendering, mapping and data translation:* This task will focus on developing an "easy" way to import data that have been generated in Tasks 2.2 and 3.2, including geotagged terrain visualizations, into the NPRA's *RESPONS*[17] web tool.

Anticipated R&D results: D2.1: Guidelines for autonomous flight control (year 2, Q1), link to D1.1; D2.2 (linked to D3.2): Specific (repetitive) field tests (link to WP-3) (year 3, Q1); D2.3: sensor data interpretation: flexible machine-learning-based software model (year 3, Q3); D2.4: Guidelines for workflow allowing to plug recorded and processed data into the NPRA's API (year 3, Q2).

WP-3: Application – field demonstrations and interpretation of results. The aim of WP-3 is to first consolidate the requirements for application of UAS into NPRA operations, followed by testing of UAS under varying field conditions, while considering the UAS specifications that were derived in WP-1 and WP-2. Data gathered by UAS will be interpreted and validated using conventional instrumentation and methods. This WP will also take advantage of the NPRA's existing industrial knowledge on advanced technology and intelligent transportation systems[33]. In short, WP-3 has to ensure that there exists a tight connection and interaction between the 'data producing WPs' (WP-1, WP-2) and the integration of the data (WP-4).

R&D category: Industrial research. **Partners:** NGI (leading, Regula Frauenfelder); SINTEF & NPRA (contributing).

Scientific content: *Task 3.1. Consolidation of requirements:* The NPRA's requirements concerning data to be captured by UAS will be consolidated and formulated as guidelines. These guidelines will then be tested in field trials and results will reflect back on guideline formulation, which will be iterated (closely linked to Tasks 3.2 and 2.1). Cost guidance for UAS equipment and operation will be developed. *Task 3.2. Field testing:* Together with the project team, the NPRA will test selected UAS-sensor systems (aircraft, sensors, software) in a series of field trials prior to and during realistic winter conditions at locations including NGI's avalanche research station at Strynefjellet[34] and in the E8 Borealis national laboratory for new technology in Lavangsdalen[35] (Fig. 4.1.2). In addition, a vendor technology demonstration will take place in project year 2. As described in Section 2.2.2, GEOSFAIR project members have organized two such tests in the past and therefore expect a good response from the industry.

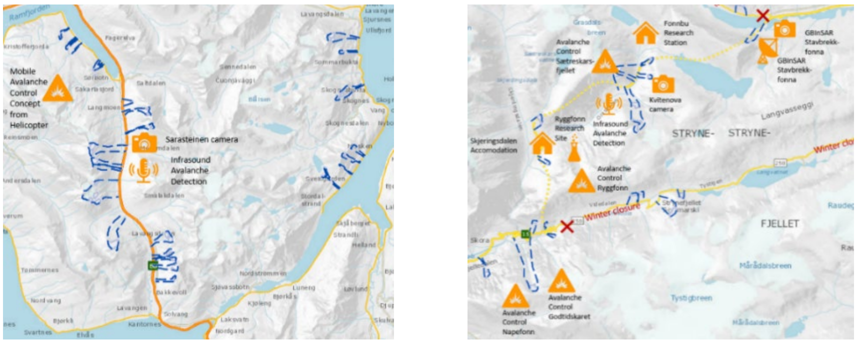

Figure 4.1.2. *(Left panel): Lavangsdalen in Troms county, part of the E8 Borealis national laboratory for new technology; blue outlines symbolize selected roadside avalanche paths, orange symbols are existing NPRA and county instrumentation.*
(Right panel): Strynefjellet area in Vestland county; orange symbols are existing NPRA and NGI instrumentation.

<u>Task 3.3. Interpretation and validation</u>: UAS sensor data will be compared to and validated by data collected using conventional instrumentation and hand-dug snow pits. The outcome of this step will be used by avalanche experts from the NPRA and NGI to assess the feasibility of UAS-obtained results for integration and implementation at the NPRA. This task is the crucial link between the WP-1 and WP-2 activities and the WP-4 activity, thereby ensuring direct collaboration between technologists and decision makers.

Anticipated R&D results: D3.1: Guidelines on NPRA (and other users') requirements for adopting UAS data in decision-making processes (year 2, Q1); D3.2: Field testing reports, Strynefjellet and Lavangsdalen sites (year 3, Q4); P3.1: Scientific publication summarising field test results and validation (year 4, Q2).

WP-4: Integration – enhanced decision support. The aim of WP-4 is to investigate and pilot how the outcomes of WP-1, WP-2 and WP-3, i.e. the aerial systems and the sensor data output, can be integrated into the NPRA's decision support processes. The results shall be easily understandable and usable for routine operations by NPRA staff and be available to other organizations concerned with avalanche hazards. This WP will also detail the extension of the project findings to natural hazards other than avalanches.

R&D category: Industrial research. **Partners:** NPRA (leading, Tore Humstad; international adviser, Edward McCormack); NGI & SINTEF (contributing).

Scientific content: *<u>Task 4.1 Decision support philosophies:</u>* The existing decision support system will be compared to decision support philosophies of comparable organisations at the national and international level, and conclusions be drawn on the pros and cons of the existing system. *<u>Task 4.2 Data management and utilisation:</u>* This task will investigate how new types of data can be integrated into operational avalanche hazard assessments. The aim is to develop a decision support framework describing how methods and data from GEOSFAIR can be applied in common avalanche hazard situations, supporting the consolidation of requirements and the interpretation and validation tasks in WP-3. The task will also address how UAS sensor data and data end products developed in WP-2 efficiently can be collected, stored and accessed within relevant data systems. This work will be connected to ongoing development of the *RESPONS*[17] geohazard web portal and API-based methods for collection of sensor data. *<u>Task 4 3. Organizational requirements:</u>* Based on consolidated UAS specifications and requirements as determined by WP-3, this task will address how competency and equipment can be distributed both geographically and organizationally (within the NPRA and county road administrations) to make relevant UAS surveys available when and where needed. Resulting guidelines will form the basis for further training and implementation plans. *<u>4.4 Uptake for other geohazard applications:</u>* This task will analyse if and, eventually, how the findings from GEOSFAIR can be applied to assess other natural hazards that impact roadway operations, such as rock falls, debris flows, and floods.

Anticipated R&D results: D4.1: Use cases and initial decision support framework (year 1, Q3); D4.2: MSc on decision support philosophies (year 2, Q2); D4.3: Databases and APIs ready for use (year 2, Q3); D4.4: Guidelines for training and implementation (year 3, Q3); P4.1: Scientific publication describing data flow, data management and revised decision support framework (year 3, Q4).

Milestones and project timeline: GEOSFAIR will measure progress using the following milestones, as illustrated in Figure 4.1.2. **M1.1:** UAS aircraft and sensor specification (2022, Q1); **M2.1:** Validation of autonomous flights (2022, Q2); **M3.1:** Vendor test, first winter (2022, Q2); **M3.2:** Additional testing, second winter (2023, Q2); **M4.1:** Demo of data integration into NPRA decision support system (2023, Q2); **D1:** GEOSFAIR project report (2024, Q2); **W1:** Project workshop for stakeholders (2024, Q2); **P1:** Scientific publication describing project outcomes (2024, Q2).

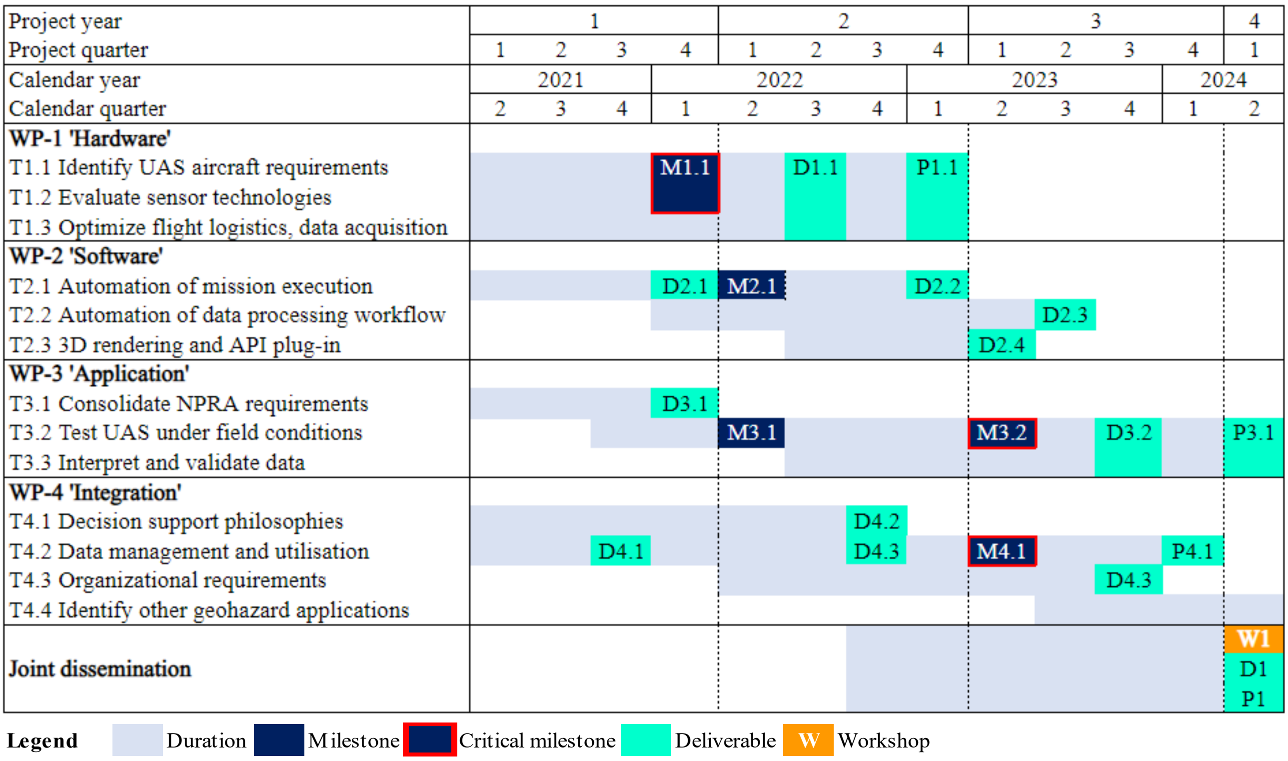

Figure 4.1.2. *Gantt chart depicting the project timeline, milestones and individual task duration.*

4.1.2 Project organisation, cooperation and strategy clarification

The NPRA will manage GEOSFAIR, which includes administrative oversight of the project. The designated **Project Manager (PM)**, Tore Humstad, is a senior principal engineer and trained geologist and avalanche forecaster at NPRA with more than 15 years of experience in the field of geohazard mitigation and avalanche hazard management. The PM has demonstrable experience in designing, planning, managing and implementing research and industry-related projects in the areas of geohazard mitigation. His main field of work in NPRA is avalanche monitoring, warning and preparedness systems. A Steering Committee (SC), consisting of representatives from each project partner, will be formed at project start-up and will act as the decision-making body of GEOSFAIR. The SC shall ensure that objectives, intentions and progress milestones are fulfilled. Project and SC meetings will be scheduled a minimum of twice per year and additional meetings will be organized as needed. When applicable, these meeting will be conducted online and/or online access will be made available to remotely located project members. The PM will appoint an external reference group to facilitate discussions among partners, other stakeholders and researchers, and to provide input to the project and its preliminary results.

The PM will be supported by **Prof. Dr. Edward McCormack** who will act as an international adviser (IA) to GEOSFAIR, assisting with research design and result up-take and implementation. The IA is a former chief engineer at the NPRA, and a professor in the Civil and Environmental Engineering Department at the University of Washington (USA). The IA is also an associate professor (Prof. II) at the Norwegian University of Science and Technology. In both capacities, the IA specializes in transportation technology evaluation. In 2008, the IA was one of the first researchers to explore the use of UAS for roadside avalanche monitoring by transportation agencies. Since then, the IA has conducted a series of tests in North America and for the NPRA to explore the use of sensors and cameras on UAS platforms to support avalanche monitoring by roadway-owning organizations.

SINTEF is one of Europe's largest independent contract research organizations. The research groups taking part in GEOSFAIR belong to SINTEF *Industry* and SINTEF *Digital*. While mobile and autonomous sensor systems and platforms constitute a priority area, SINTEF pushes the boundaries of autonomous UAS and robotics combined with geophysical measurements and geoscientific research. SINTEF will contribute to GEOSFAIR with expertise in UAS technology, lightweight sensors, and digitalization workflows. The involved groups have experience with participating in, and leading projects involving multi-disciplinary research, and are currently carrying out a strategic internal project involving development of UAS and sensor technologies. During this project, SINTEF's ambition is to continue developing its expertise in UAS systems, sensors and associated software and workflows. The expertise obtained in GEOSFAIR will be very valuable for SINTEF to develop future projects in the natural hazards fields, both with Norwegian public and private sectors, and internationally within EU programs.

The **Norwegian Geotechnical Institute (NGI)** is a leading center for research and consulting within the engineering-related geosciences, with expertise in geohazard analysis and modelling, as well as in natural hazard risk assessment and risk management. NGI has a long history of co-developing applied research with stakeholders through Joint Industry Projects and EU research projects. NGI will contribute to GEOSFAIR with its expertise in geohazards and avalanche science, as well as with in situ and remote sensing methods for UAS data validation. By making NGI's avalanche research stations at Strynefjellet available to GEOSFAIR, NGI's role will be crucial for validating field trials and for developing practical methodologies that can be adopted by the NPRA and other stakeholders. The expertise gained, and methods developed in GEOSFAIR will be highly relevant for other geohazard mapping and risk management applications and for other infrastructure, e.g. railroads. Furthermore, NGI foresees that GEOSFAIR will provide new opportunities for research of international quality, such as in the new Horizon Europe program, and will stimulate further collaboration with public sector partners.

5 References

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APPENDIX D: Roles and procedures in the decision-making system of NPRA

Road Operation Manager: This role involves overseeing the maintenance and operational activities of the national road network. Responsibilities include managing contracts with contractors, ensuring road safety and functionality, planning and prioritizing maintenance work, and implementing measures to handle seasonal challenges like snow removal and drainage

Road Operation Contractor: Contractors are responsible for executing the maintenance and operational tasks as specified in their contracts with the NPRA. This includes activities such as road repairs, snow removal, and other maintenance tasks to ensure the roads remain safe and functional

Geohazard Engineer: This role can be filled by a geologist, geotechnical engineer, or hydrologist. The primary responsibility is to assess and mitigate risks related to geohazards such as landslides, rockfalls, and avalanches. They conduct geological surveys, analyze terrain stability, develop preventive measures, and provide expert advice to ensure the safety of road infrastructure

Decision Authorities for Road and Traffic Management: The NPRA has established routines that enable the handling and follow-up of incidents around the clock. The ones responsible have the necessary mandates to make decisions related to road closures and openings, as well as the implementation of detour routes, etc. This role involves making critical decisions regarding road and traffic management. It can include the Road Operation Manager and operators at Traffic Control Centers. They are responsible for managing traffic flow, responding to incidents, and ensuring the overall safety and efficiency of the road network

APPENDIX E: International Reference Group of GEOSFAIR

An external reference group (RG) was established to facilitate discussions among partners, other stakeholders and researchers, and to provide input to the project and its preliminary results.

The RG consisted of the following members:

- Dave Gauthier, BGC Engineering Inc., Toronto, Canada
- Frederic Pourraz, Université Savoie, Annecy, France
- John Stimberis, Washington State Department of Transportation (WSDOT), Seattle, USA
- Kristin Martha Hàkonardottir, Verkís Consulting Engineers, Reykjavik Iceland
- Marc Adams, BFW, Innsbruck, Austria
- Markus Landrø, NVE, Gol, Norway
- Thomas Oomen, Michigan Technological University, Houghton, USA
- Yves Bühler, SLF, Davos, Switzerland

Appendix F: Steering committee of GEOSFAIR

A Steering Committee (SC), consisting of representatives from each project partner, was formed at project start-up and acted as the decision-making body of GEOSFAIR. The SC ensured that objectives, intentions and progress milestones were fulfilled.

The SC consisted of these members:

- James Strout, technical expert, NGI
- Bengt Holter, research director, SINTEF Digital
- Trond Michael Andersen, head of technical department, NPRA
- Petter Bakke, head of geodata department, NPRA

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