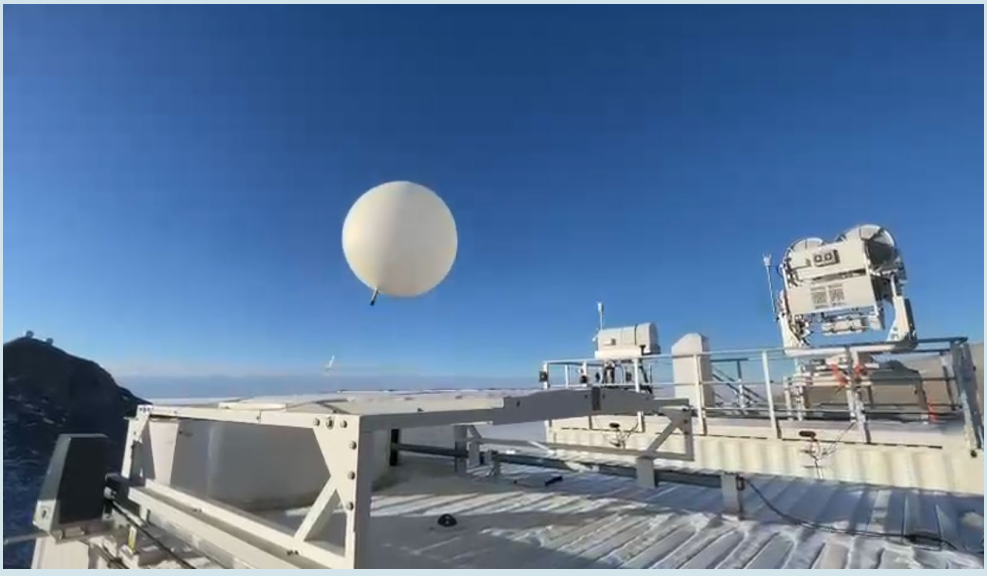

Annual report

Year 3: March 2024-February 2025

Troll Observing Network infrastructure project

Troll Observing Network

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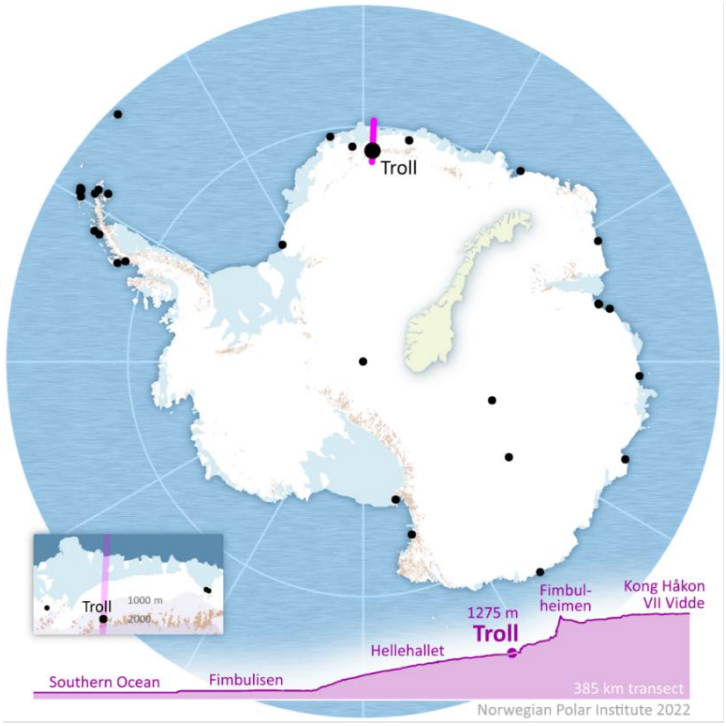
Photo frontpage: still image from video by Marius Bratrein, NPI. Weather ballon from ICO at Troll, January 2025.

Table of content

1. Introduction

The TONe consortium just completed its third year of implementing the Troll Observing Network (TONe). TONe is a comprehensive infrastructure network centered around Troll Research Station and focuses on the Dronning Maud Land (DML) region, a region of Antarctica with relatively little observational data available, thus contributing to the observation and data gathering effort required to gain new and needed knowledge for Antarctica and the Southern Ocean.



The Troll Observing Network provides long-term measurements within all compartments of the Earth System in a data poor region in data-poor Antarctica. Troll Research Station is at a unique location among other Antarctic stations through its location at the continental slope, far from the coast but not on the inland plateau.

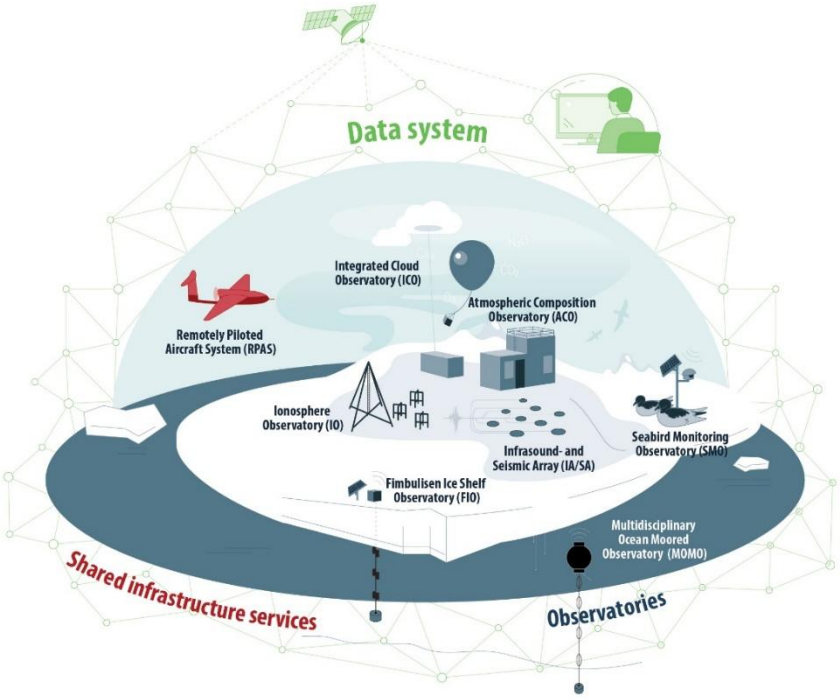
TONe includes observatories providing data that will greatly improve our understanding of space weather dynamics, atmosphere dynamics, solid earth structure and cryosphere dynamics, key global processes relevant to climate and sea-level change and the effects of global changes on marine ecosystems through eight distinct observatories:

- Ionosphere Observatory (IO)
- Integrated Cloud Observatory (ICO)
- Atmosphere Composition Observatory (ACO)
- Infrasound Array (IA)
- Seismic Array (SA)
- Fimbulisen Ice-shelf Observatory (FIO)
- Multidisciplinary Ocean Moored Observatory (MOMO)

- Seabird Monitoring Observatory (SMO)

TONe also includes a drone service (RPAS) that will enable collection of data over large parts of DML. Finally, TONe will ensure wide and free access to data from the observatories and drone service to the entire national and international research community, in the interests of serving society globally.

This is a report for the third year of TONe, covering activities from March 2024 to February 2025.



TONe consists of three components: the eight observatories, the shared drone infrastructure service and the data management system.

2. TONe activities for year 3 (March 2024 – February 2025)

In its third year, TONe has implemented another two observatories and the four previously established observatories have undergone further validation. This year's milestones include:

- Establishing NPI's integrated cloud observatory (ICO) at Troll
- Establishing UiO's digisonde to complete UiO's ionosphere observatory (IO) at Troll
- Purchase of the Windracer Ultra 2 drones for the TONe-drone service (RPAS)
- Proof of concept and collection of unprecedented observations from below Fimbulisen (FIO), along the DML coast (MOMO), from seabird colonies in DML (SMO) and new components in air composition (ACO).

The significant accomplishments achieved over the past year are the result of thorough planning, dedicated effort, and a consistently positive attitude from all parties involved in addressing the challenges that arose throughout the last years work. This collective effort encompassed the scientific personnel, technical staff, and the operational team at Troll, with valuable support from KSAT personnel and equipment. The successful execution of the extensive work carried out during

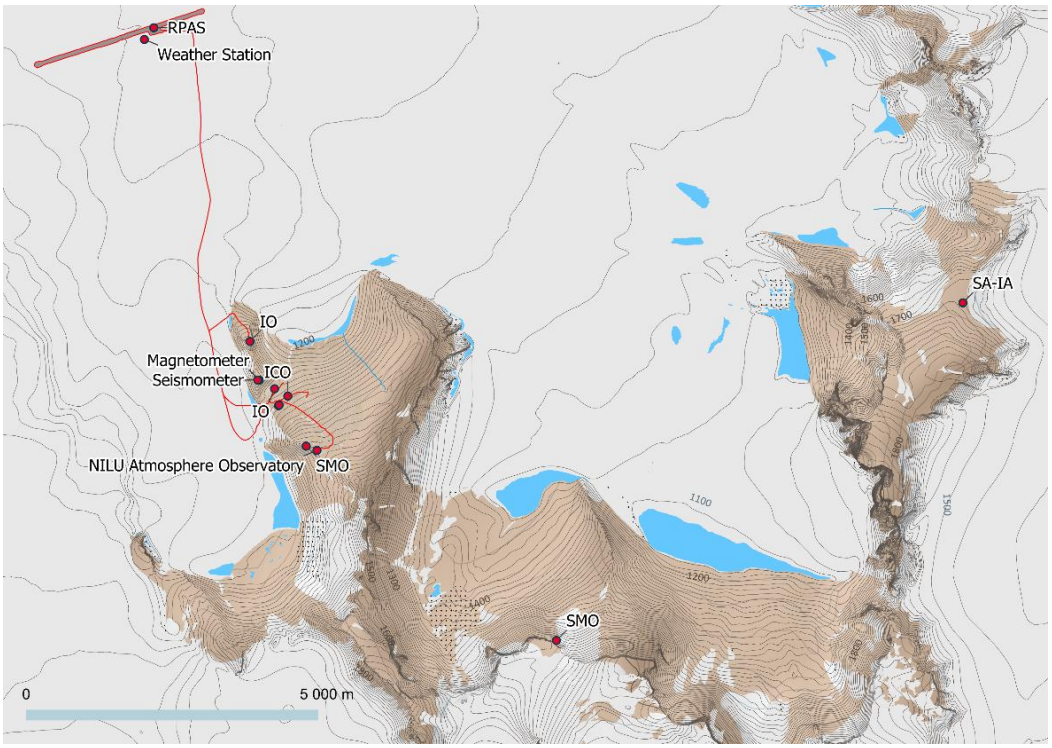
the brief summer season at Troll would not have been possible without the commitment and presence of the on-site teams.

A key aspect of TONe's administration is fostering effective collaboration and communication within the consortium. To support this, the TONe partner consortium holds monthly digital meetings to ensure regular dialogue and coordination. The third annual in-person partner meeting took place in Tromsø on 17–18 June 2024. The agenda featured an initial scientific insight into results from two of the established observatories (FIO and ACO), a presentation and discussion on the use of the RPAS service, and a progress update on TONe-DATA. In addition, the consortium explored strategies for promoting TONe, potential synergies with the Centre of Excellence "Center for Ice, Climate, Cryosphere and Climate" (IC3), and plans for building further on the observing network beyond the current implementation phase.

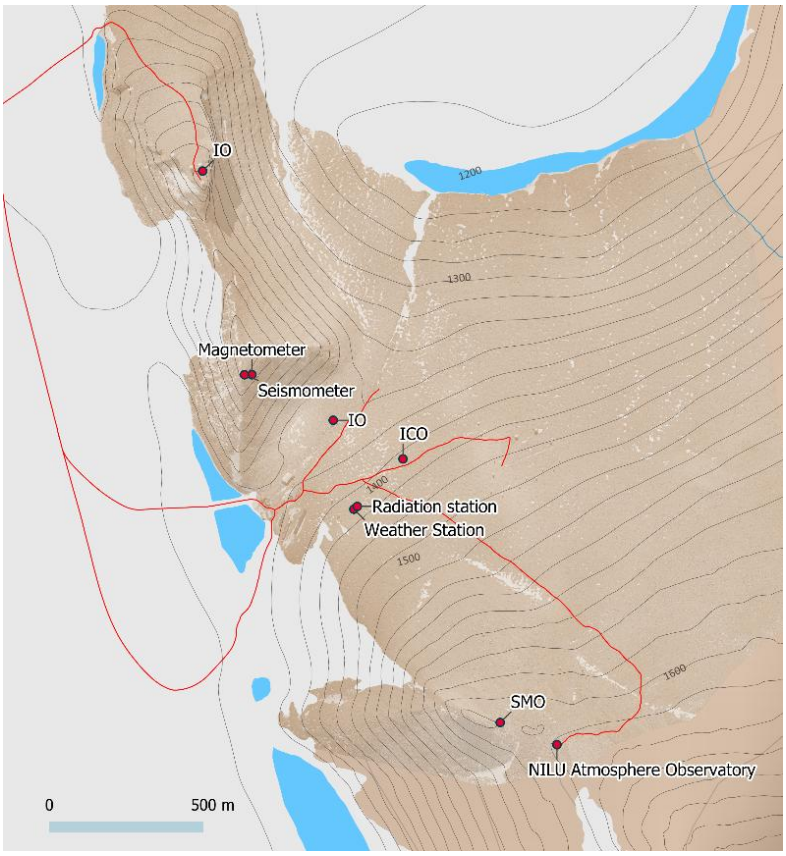
Details on the work and can be found in Section 3, details on outreach activities in Section 4, and a reference list in Section 5.

3. Summary of work and progress for the observatories, RPAS service and data management system

After this year's successful set-up of ICO and IO, the scientific landscape at Troll is changed. Below are updated maps of the research infrastructures – including both TONe observatories and additional science instruments.



Overview of the TONe infrastructures in Jutulsessen (abbreviations as in the TONe concept figure above, and in the text below). Research infrastructures established before TONe is also included. Figure: Even Birkeland, NPI.



Overview of the TONe infrastructures zoomed in at Troll Research Station (abbreviations as in the TONe concept figure above, and in the text below). Figure: Even Birkeland, NPI.

3.1 The Ionospheric Observatory (UiO)

The Ionospheric Observatory (IO) allows for studies of processes in the upper polar atmosphere, with the focus on its ionised part, the ionosphere. Within TONe, a digital ionosonde (digisonde) has been deployed at the Troll Research Station. The digisonde is an ionospheric radar that sends radio waves to the ionosphere and analyses the reflected signal. Reflection from the ionospheric layer depends on the wave frequency and ionospheric electron density. Thus, scanning through frequencies, the radar allows for studying and monitoring the ionisation profiles in the ionosphere, which is related to geomagnetic activity but also to forcing from below. Digisonde data is valuable for studying atmospheric gravity waves, which modulate the ionospheric density. The digisonde also allows for monitoring of the convection of variations in ionospheric plasma (electrons and ions) in the horizontal direction. This allows us to study the dynamics of ionospheric irregularities and state of the ionosphere over the station. Together with other instruments within the Ionospheric Observatory and at neighboring stations this allows for detailed studies of space weather phenomena and space weather effects over Dronning Maud Land. It will give an insight into processes related to variability of upper atmosphere, ionospheric plasma, geomagnetic activity and aurora and how they contribute to space weather effects.

In year 2024 and the Austral summer of 2024-25 the digisonde DPS4D has been installed at the Troll Research Station. The radar consists of an antenna mast of 18 meters that has been designed specifically for this location, as well as four receiving antennas and an instrument container. The digisonde arrived at Troll in season 2023-24 and it was secured for winter of 2024 and prepared for installation. The container housing the instrument was fabricated in year 2024 and sent to Antarctica by ship in the beginning of December 2024. The whole year was characterized by preparations for the installation of the instrument and the fieldwork. Two staff members from UiO were deployed to

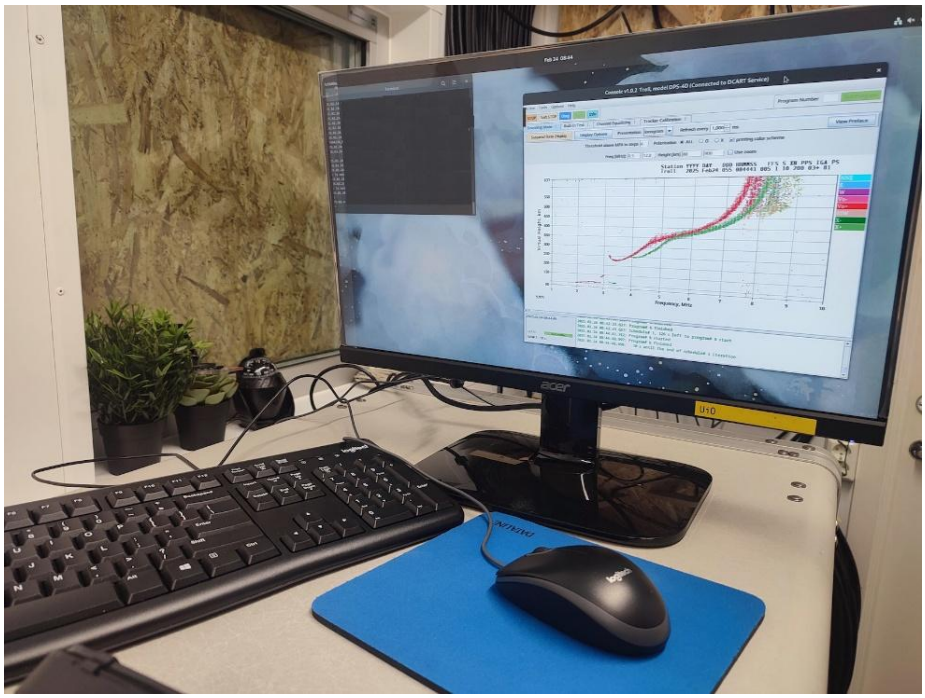
Troll in mid-December 2024 to work on the installation with the support of the personnel on the site. The work included preparations of the ground, road, foundations for the transmitter and receiver antennas, foundations for the observatory container, preparations of the cables. The transmitter antenna mast was erected according to the technical guidelines. The receiving antennas were installed after preparation of the ground in the first 1.5 months of the fieldwork. The container arrived at Troll in mid-January 2025. The instrument was thereafter connected, cables adjusted according to specifications and local conditions, and measurements started in the first half of February 2025. In the second half of February the instrument was prepared for the winter season. Initial tests were successful, and no major problems were detected.

The UiO instrument container arrived in the middle of January 2025 by ship and was transported to the station on sledges from the coast. Photo: Wojciech Miloch, UiO.

Installation of the transmitter antenna mast. Photo: Wojciech Miloch, UiO.

In Year 2025 it is foreseen to commission the ionosonde and monitor its performance. It is also planned to provide the direct flow of data to the local and international databases for ionosonde data to provide near-real time data from Troll. The plan is to incorporate the digisonde in the global network of instruments for ionospheric and upper atmospheric research. As only a handful of ionosondes exist in Antarctica, and only one digisonde in this part of Antarctica, this forms a unique dataset. This is of importance for space weather monitoring and forecasting services. The first

publications with the ionosonde data from Troll are also planned. Finally, it is planned to carry out maintenance of the digisonde in the Antarctic season 2025-26.



The digisonde was started successfully, and the first data was collected in February 2025. The typical data is shown on the screen. Photo: Wojciech Miloch, UiO.

The digisonde was prepared for the winter season in February 2025. Photo Wojciech Miloch, UiO.

The new digisonde infrastructure; from the left the four receiver antennas, the tall transmitter antenna mast and the instrument container. Photo: Jonas Birkeland Carlsen, UiO.

Publications related to the Ionospheric Observatory in 2024: Kotova et al. (2024), Miloch et al. (2024) and Pedersen et al (2024).

3.2 The Atmosphere Composition Observatory (NILU)

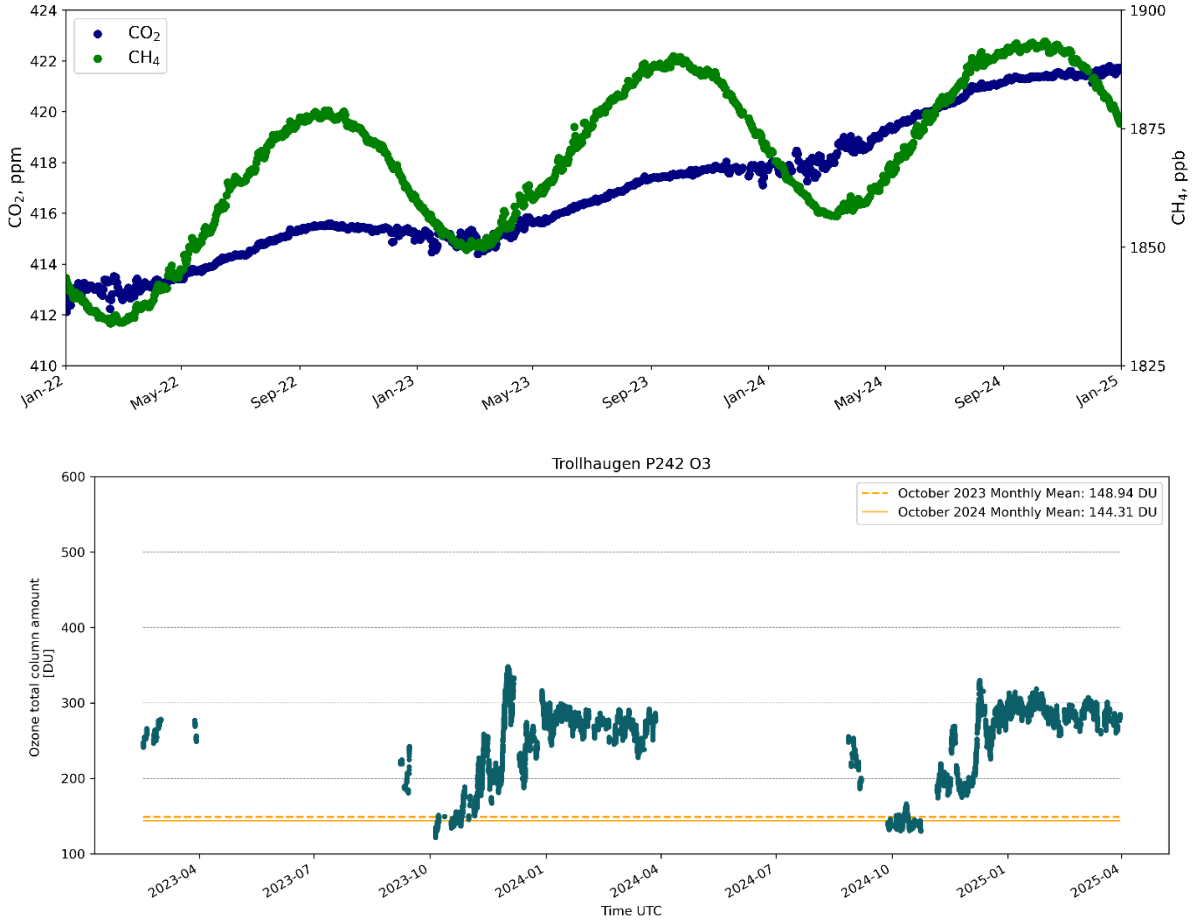
This observatory expands the existing atmospheric monitoring at Trollhaugen (1553 masl), located 1 km east of Troll and largely unaffected by local activities. Measurements began in 2007 and relocated to the current site in 2014. The program includes monitoring of contaminants, aerosols, greenhouse gases, trace gases, and UV/ozone, now enhanced with state-of-the-art instrumentation to better understand climate processes and ozone depletion. The three instruments, which are part of the TONe project, have all been installed and are in operation.

A CO2, CH4, CO monitor from Picarro was installed already in December 2021 and data are available from these first years (figure below). From March 2024 to February 2025, the primary focus has been on ensuring high-quality data using establishing guidelines. The high-pressure compressor system installed last year has been tested and is ready to fill cylinders as part of the calibration setup. Preliminary data for 2024 have been submitted to NOAA for comparison with observations at their South Pole station. Quality-controlled data will subsequently be submitted to the WMO World Data Center for Greenhouse Gases (WDCGG). Trollhaugen became a global site within the WMO GAW network in January 2025.

An aerosol particle sizer (APS), which measures aerosols in different size fractions, was installed at the beginning of 2023. In July 2024, the instrument's laser beam that counts the number of particles malfunctioned, requiring the unit to be sent with the first flight from Antarctica (in November) to the manufacturer in the UK for repairs. It was returned by NILU's maintenance staff, reinstalled in February 2025, and is currently operational again. Data are available from the WMO World Data Centre for Aerosols (WDCA) hosted at NILU.

A PANDORA spectrometer measuring vertical total column of different trace gases (O3, SO2 NO2 and formaldehyde) was installed in January 2023. This instrument is integrated into the "Pandonia Global Network" (PGN), and it is specifically used for routine validation of the Sentinel-5P satellite operated by the European Space Agency (ESA). The data are provided in near-real-time and are openly accessible. A snapshot is shown in the figure below.

During the annual maintenance trip to Trollhaugen in January–February 2025, NP personnel received training to ensure that instruments operate in accordance with standard operating procedures.



Upper plot: Daily mean concentration of the greenhouse gases methane (CH_4) and CO_2 measured at Trollhaugen. Lower plot: Observed concentrations (in green) of the ozone column (DU) measured at Trollhaugen, comparing the monthly mean concentrations in October (in orange) when the ozone layer is the thinnest.

3.3 Integrated Cloud Observatory (NPI)

The Integrated Cloud Observatory (ICO) is NPI's new observatory at Troll Research Station. It includes a system of instruments to measure atmospheric and cloud properties. Three instruments make measurements from the ground continuously: a cloud lidar, a microwave radiometer and a cloud radar. Combined, these give a real-time picture of the temperature and humidity in the atmosphere, cloud heights, thicknesses and physical properties (liquid, ice or mixed and particle size).

The lidar sends up a laser beam that gets scattered back by clouds and aerosols. It gives good measurements of cloud base height and thickness, if the clouds are not too thick, and has high vertical resolution. Because it measures the polarisation of the returned light it can also distinguish between liquid and ice clouds.

The radar sends out microwave radiation, which can see deeper into thick clouds and is more sensitive to cloud particle sizes. It also measures the doppler shift of the returned light, giving a measure of the particles' motion; if pointed up, this gives fall speed and turbulence measurements, and when pointed other directions it can measure horizontal winds. The radar can look in any direction, giving spatial information about the clouds in the area, up to about 15 km.

The microwave radiometer measures microwave light emitted by the atmosphere. It can retrieve temperature and humidity profiles and is very good at retrieving the total liquid water in clouds and the total water vapour in the atmosphere.

A radiosonde program provides daily in-situ data from weather balloons to help interpret the ground-based data and to help with weather forecasting. They measure temperature, humidity, pressure and winds up to 30 km above sea level. There are no other stations making similar measurements between the coastal region and the high plateau.

The cloud and atmospheric data will be used to understand the energy and mass balance in the region (the only Antarctic station on the coastal-to-plateau slope). The understanding of the cloud properties will also help improve the representation of these clouds in weather and climate models, currently a significant challenge. The radiosonde data are transmitted in real time to global weather forecasting services, and the cloud data are shared with the European network CloudNet.

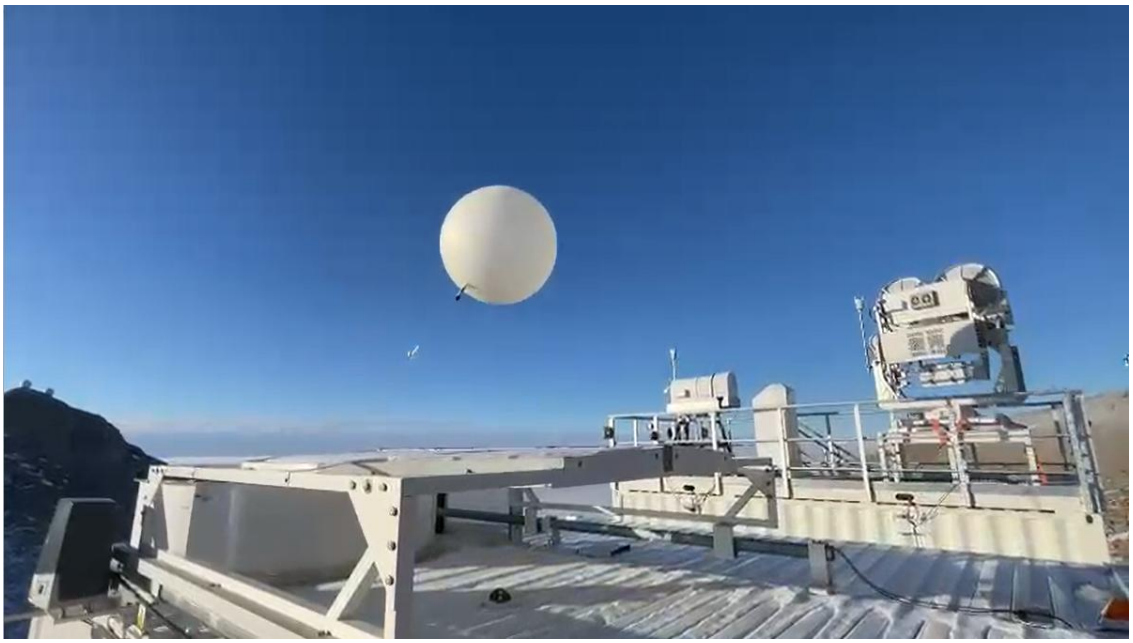
Over the last year (2024), all instruments were purchased (automatic radiosonde container, hydrogen generation container for the weather balloons, instrument and IT container, radar, radiometer and lidar). They were shipped to Troll where they were installed on a steel foundation installed last year. All equipment was connected to power and internet and is up and running with data flowing in real time. Five people from the project were deployed for over a month during the 24/25 field season, and countless personnel at Troll facilitated the installation, including those in the photos below.

Lifting the radiosonde container into place. Photo: Stephen Hudson, NPI.

Lifting the hydrogen container into place. Photo: Stephen Hudson, NPI.

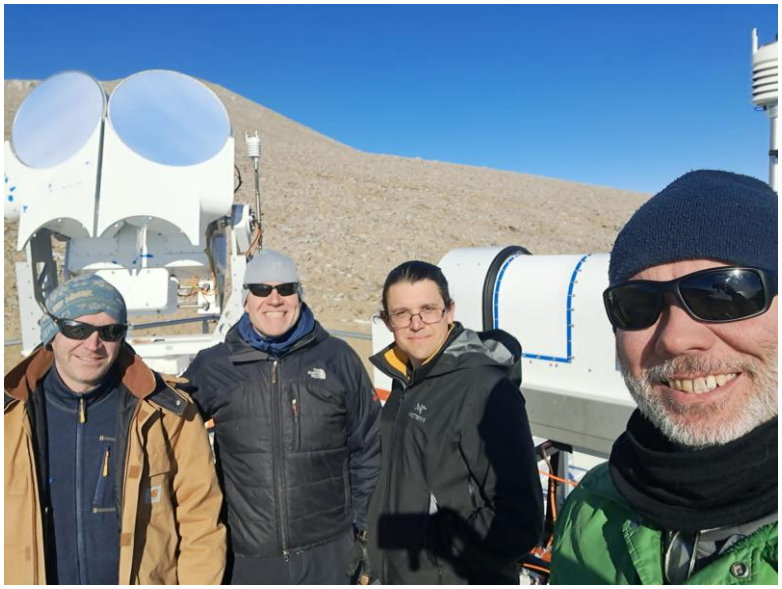
The completed station. The weather balloon container is on the left; the hydrogen container is in the middle and the instrument/IT container is on the right; the farthest right container is used for storage. Photo: Stephen Hudson, NPI.

As we are gathering data, we will start analysing it and sharing it with the community. We plan to write a data article first, then work on research articles publishing findings. We will also be working to secure funding for further research with the data.



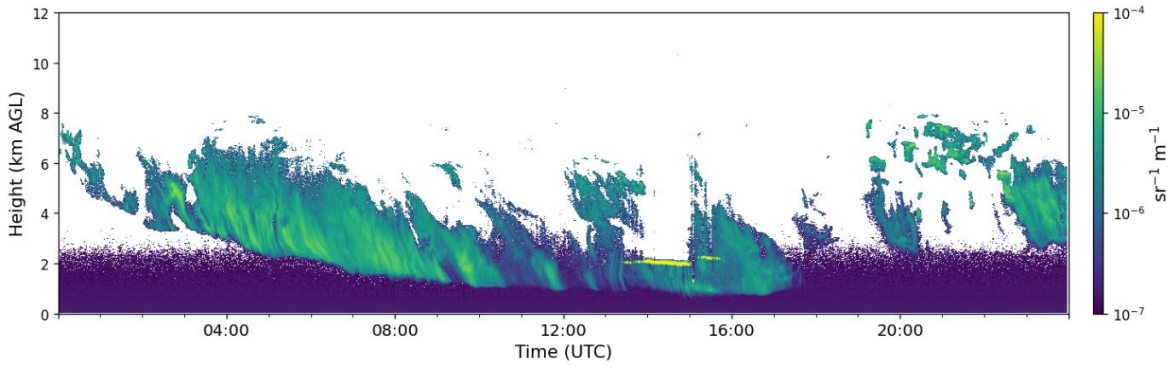
Launching the weather ballon. Photo: Marius Bratrein, NPI

The completed station and surroundings. Photo: Stephen Hudson, NPI.

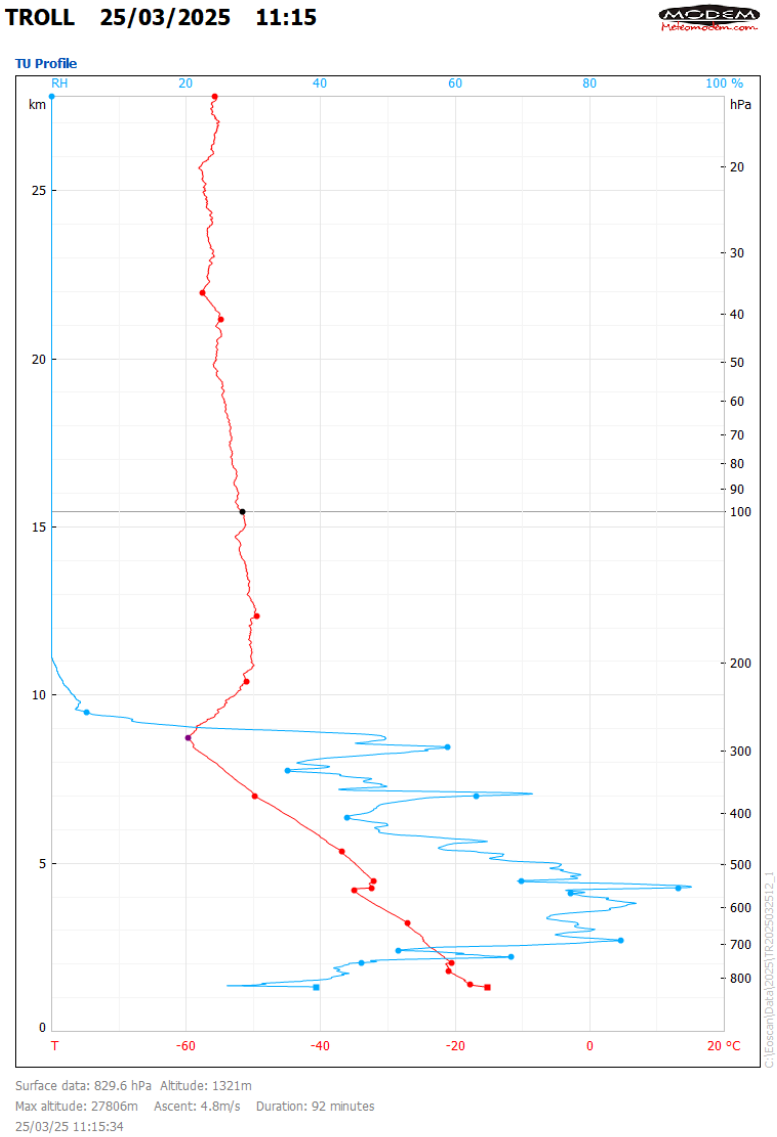


Team photo with ground-based instruments. Photo: Michael Town, ESR.

Ground-based data are available via CloudNet: https://cloudnet.fmi.fi/site/troll
Radiosonde data are distributed by Met.no to the World Meteorological Organisation.



Example lidar data; the greens and yellows show locations of clouds throughout the day on 21 March 2025.



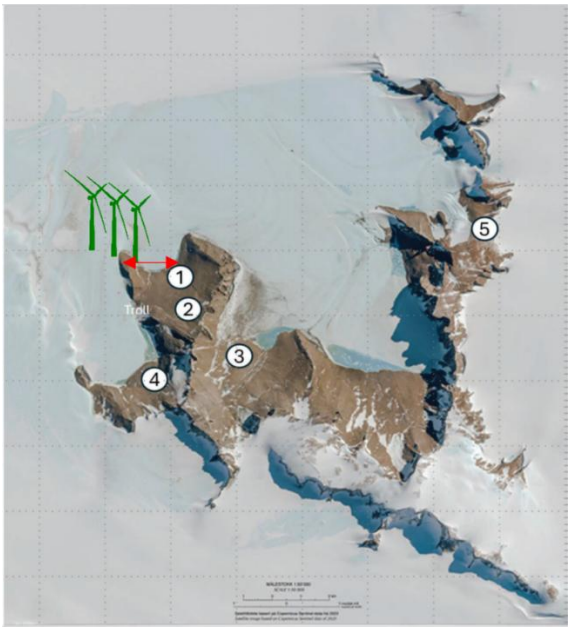
An example radiosounding showing temperature (in red, on the bottom axis) and humidity (in blue, on the top axis) from the surface to nearly 28 km above sea level.

3.4 Seismic Array and Infrasound Array (NORSAR)

The TONe Seismic Array (SA) focuses on the dynamics of the ice and solid Earth in DML. The new seismic array will upgrade the existing seismic station of NORSAR at Troll into a high-quality seismic observatory, not only compared to other stations in Antarctica but also in a global context. The array will record signals from all types of seismic events, including earthquakes, icequakes, iceberg calving, explosions and oceanic swell. The new seismic array will be able to record much weaker signals than the existing single station, and also measure the propagation directions and velocities of these signals. This additional information will be essential to associate observed seismic and infrasound signals with common sources and to locate them in the dynamic cryosphere.

The co-located infrasound array (IA) measures low-frequency pressure (sound) waves generated by atmospheric events, such as meteors, volcanoes, explosions and oceanic swell, as well as abrupt ice movements (icequakes). These waves can be used to analyse atmospheric dynamics and vertical coupling between different parts of the atmosphere. The propagation of infrasound waves in the atmosphere is influenced by weather conditions such as wind and temperature. This allows infrasound waves from known sources (such as storm systems, volcanoes and oceanic swell) to be used for analysing the state of the middle and high atmosphere.

The Norwegian Government plans modernize the Troll Research Station. The ambition is that a substantial amount of the required energy will be from renewable sources, amongst other from wind turbines. The size and location of the wind turbines would have a negative effect on the data quality from the seismic array, if the sensors were to be established at its originally planned array location in Mimelia. In 2024, the main focus of this work package has been to find ways to mitigate the negative impact of the planned wind farm at Troll. Early on, it became clear that the best solution would be to move the whole array away from the planned wind farm. A site survey in January 2024 led to the conclusion that locations (2) and (4) were not suitable and that location (3) could be a possible solution – see map below. After the site survey, NPI proposed to move SA and IA to Armlenet (location (5)), about 12 km away from the planned wind farm. The larger distance between the wind farm and the seismic sensors will minimize the impact of the noise from the turbines. However, the new location has additional challenges with respect to power supply and data transmission.

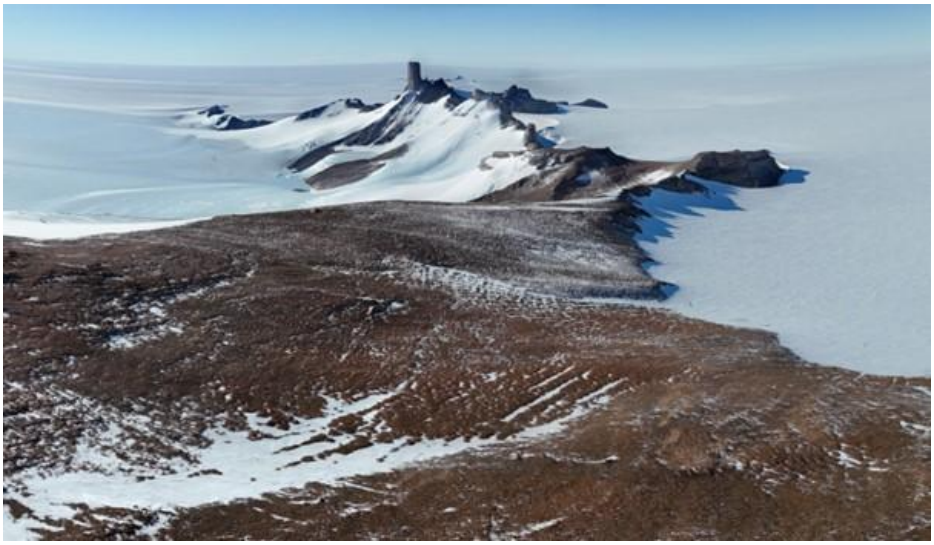


Map of the Troll area with the discussed possible array locations. 1: original location Mimelia; 2: revised location Mimelia; 3: alternative location Vassdalen, 4: alternative location Grjotøyra; 5: final location Armlenet.

Therefore, in November 2024, NORSAR and NPI conducted another site survey to investigate accessibility, underground conditions, data transmission via the 4G network, potential biological restrictions and possible array site locations at Armlenet. The site survey was very successful, and a site survey report has been produced.

In 2025, the main focus will be on re-designing, planning and purchasing of additional equipment needed to move the location of SA and IA from Mimelia to Armlenet. This includes designing an independent power supply and re-designing the data transmission to Norway. The new components will be transported to Troll in late 2025 / early 2026. The installation of the array is planned for the austral summer season 2025/26.

During the last year the TONe array plans together with an overview of about 12 years of research with data from the existing single seismic station at Troll were presented at several conferences, see overview in Chapt 4.1.

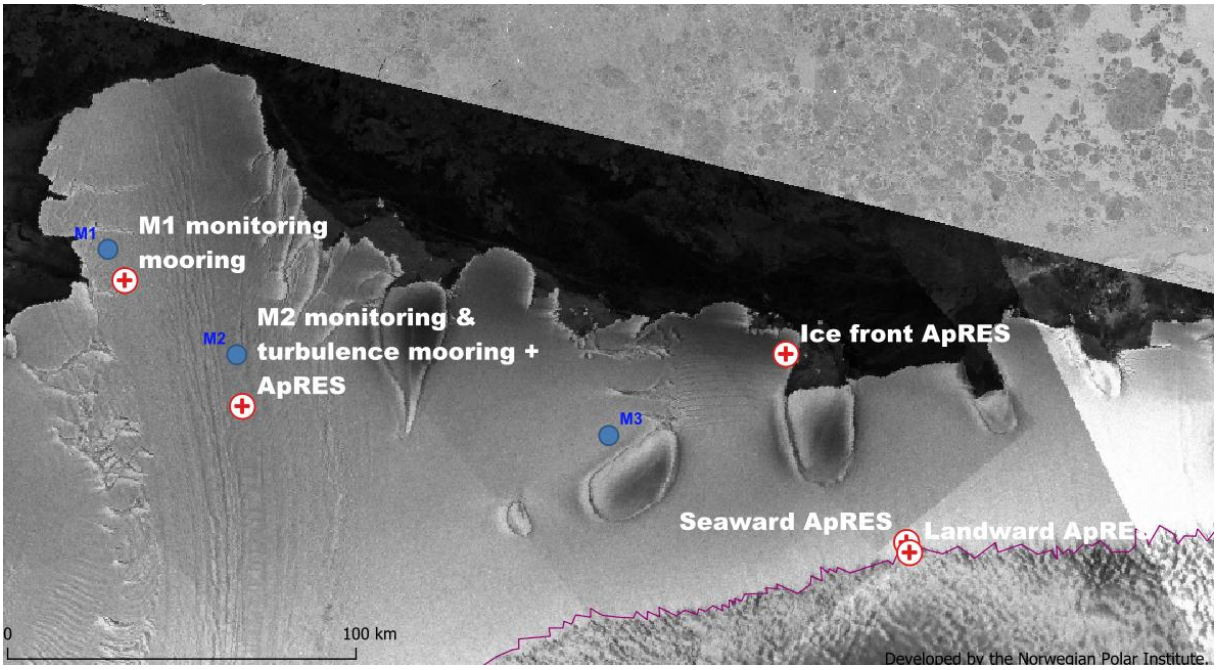


Drone photo of the proposed new array location at Armlenet. Photo: NORSAR.

Typical topography at Armlenet. Photo: NORSAR.

3.5 Fimbulisen Ice-shelf Observatory (NPI)

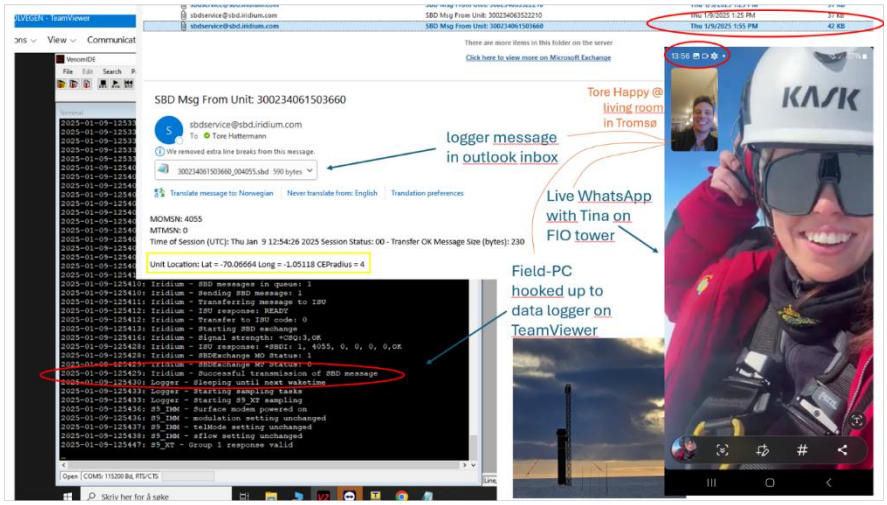
The Fimbulisen Ice-shelf Observatory (FIO) primary research sites on central and northern Jutulstraumen integrate cutting-edge oceanographic instruments monitors oceanographic conditions beneath the ice shelf and track changes in the ice shelf's surface and basal mass balance. In the 2023/24 Austral season, a major 50-day field campaign was successfully conducted to replace outdated instruments that were originally deployed in 2009. FIO contributes to understanding the coastal marine environment in the Atlantic sector of East Antarctica, the interactions between ocean currents and ice shelf melting, and the implications for global climate dynamics. The data will help refine global-scale climate models by providing precise measurements of ocean temperature fluctuations, ice shelf melting rates, and long-term environmental changes. Additionally, the observatory includes innovative under-ice acoustic navigation systems, which will support future autonomous glider missions under the ice shelf.



Overview map, showing the newly established (red) and old (blue) sites that are part of the Fimbulisen Ice Shelf Observatory.

This past year, the FIO drill sites on central Fimbulisen were revisited by small aircraft from Troll to download high-resolution data (too large for satellite transfer) on ice-ocean boundary layer turbulence and melt rate distribution around the M2 observatory. These concurrent temperature and velocity profiles under the ice base are unprecedented and will provide groundbreaking insights into ice shelf-ocean interactions.

The observatories M1 and M2 on central Jutulstraumen were further prepared for autonomous data collection, which will operate unattended for the next 4–8 years, transmitting long-term monitoring data remotely. Additionally, the old mooring site M3 was revisited to collect 3 more years of data after it had last been serviced in January 2022. This site will be maintained on an opportunistic basis as long as the instruments provide data, as it can easily be reached by ground based traverses associated with the Troll supply activities. In addition, threenew FIO melt rate radar (ApRES) sites were established near the grounding zone and the ice front on the eastern part of Fimbulisen. Conveniently situated along the Troll Research Station's resupply route, these sites will provide fresh insights into expanding the observatory to encompass also grounding line and subglacial processes.



Real-time confirmation of field data transfer during the service of the new M1 logger tower.

Data logger trench after removing three years of snow accumulation at the old mooring site M3. Photo: NPI.

Efforts have also been made to ingest and process the incoming near-real-time data transmitted directly from the FIO field sites via Iridium satellite communications. Currently, this process is being integrated with NPI's IT infrastructure and the TONe data portal and is expected to be completed by 2025, making the observatory fully operational. Leveraging synergies with iC3 and other ongoing research projects, data analysis and interpretation of the FIO observatory have begun. Additionally, project applications are being prepared to secure follow-up funding for utilizing TONe-FIO data and extending the observational work.

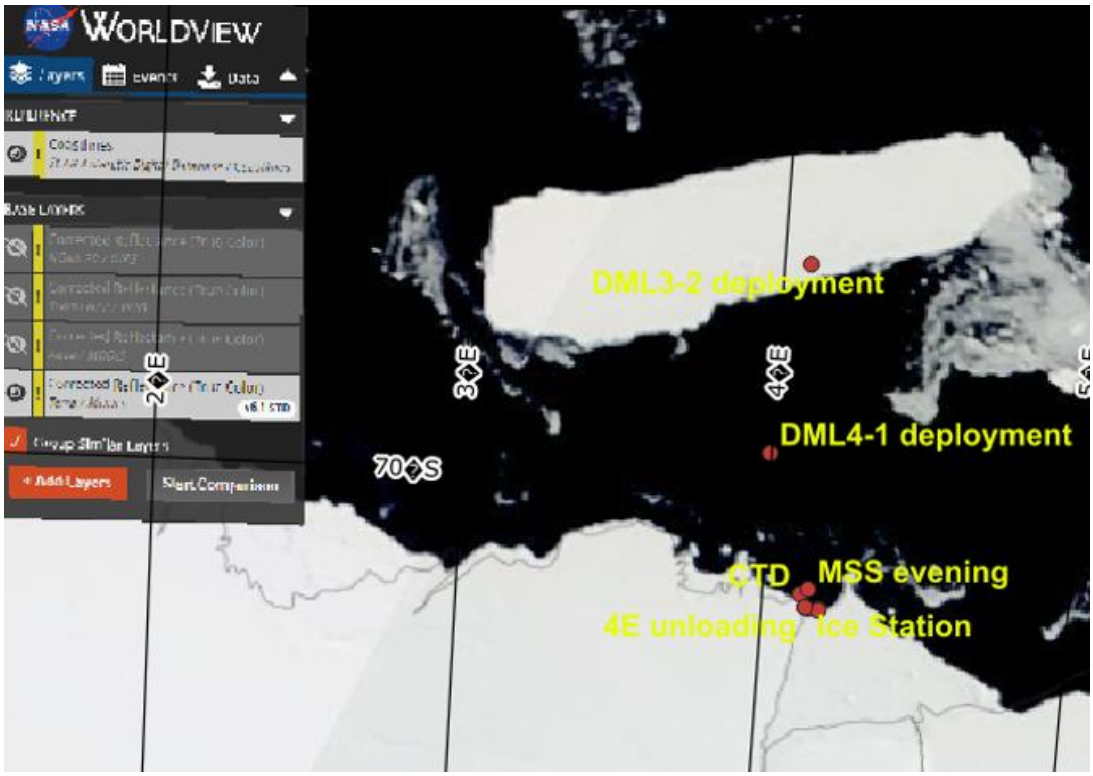
3.6 Multidisciplinary Ocean Moored Observatory (NPI)

The Multidisciplinary Ocean Moored Observatory (MOMO) consists of three oceanographic moorings strategically positioned at the Antarctic continental margin off Dronning Maud Land. MOMO aims to monitor oceanographic, biogeochemical, and biological parameters along the Antarctic Slope Front and the seasonal sea ice zone. MOMO will help resolve seasonal and interannual variability in the Weddell Gyre inflow, which plays a fundamental role in climate dynamics and the carbon cycle of the Southern Ocean and provide long-term time series for insights into the interactions between ocean currents, ice shelves, and biological productivity.

Most of the instrument procurement was completed in 2024 and the observatory were serviced in January 2025 using the Toll Supply vessel *Silver Mary*. A major milestone was the successful recovery of all three moorings, validating the novel weak-link technology designed to extend instrument strings closer to the surface. This advancement has enabled the collection of a new two-year hydrography and primary production time series, capturing data throughout the sea ice-covered season in the coastal Southern Ocean—a success that was by no means guaranteed, with a 60 km wide iceberg having been spotted to pass over one of the moorings in December 2023 (figure below).

An improved setup of the weak-link configuration based on the experiences from the recovery was incorporated on all three moorings that were redeployed, also including a novel chlorophyll sensor and an experimental sea ice thickness altimeter. Furthermore, the instrumentation of the deeper part of the mooring was extended with an additional active acoustic sensor for monitoring krill and other pelagic species, further expanding the observatory's biological research capabilities. In addition, a short (~100m tall) mooring was placed on the continental shelf to captures the properties and seasonal evolution in Rektangelbukta, where NPI has previously been monitoring the evolution of landfast ice in the past. These efforts have significantly enhanced MOMO’s ability to study ocean circulation, ice shelf melting, and ecosystem dynamics.

In the upcoming year, efforts will concentrate on processing and archiving the datasets in the Norwegian Polar Data Centre (NPDC), making them available for scientific analysis. Research will be driven by an iC3-financed PhD and postdoc projects, with findings integrated into larger data compilations such as e.g. provided by the OCEAN:ICE EU project. Additionally, proposals will be developed for the future maintenance and expansion of MOMO, including the development of network for acoustic navigation of autonomous underwater platforms (gliders, floats, AUVs) for operations under the sea ice and the ice shelf. The next scheduled servicing of the observatory is planned for early 2027, which may take place during a Southern Ocean voyage of *R/V Kronprins Haakon* or as part of the Troll Resupply cruise.



Satellite image showing a large iceberg on top of the DML3-2 mooring location in December 2023.

3.7 Seabird Monitoring Observatory (NPI)

The NPI's Seabird Monitoring Observatory (SMO) aims at providing key information on Antarctic seabird population status and trends. It allows a continuation and expansion of the ongoing seabird monitoring activities NPI has been performing in DML since 2011. The observatory consists of automatic time-lapse camera systems installed at two of the largest bird colonies in DML (Svarthamaren and Jutulsessen). A meteorological station has also been deployed at Svarthamaren to record continuously local weather conditions.

The first cameras have been installed in summer 2022/23, but the field season in 2023/24 indicated that most of them did not work properly. New ones from different manufacturers have been installed in 2023/24. Fieldwork conducted in January/February 2025 showed that most of these new cameras worked as planned and pictures were taken continuously (every 4 or 6 hours) all year long (with a gap during the dark season for those cameras relying on solar panels). A quick overview of the pictures taken by these cameras already provided new knowledge. It indicated that Antarctic petrels arrived very synchronously at Svarthamaren and Jutulsessen in mid-October before leaving also very synchronously for their pre-laying exodus two weeks later. To the best of our knowledge, this is the first data that have been gathered for that species at that time of their life cycle.

Antarctic petrel activity at Jutulsessen in October 2024. The left picture represents one area in the colony on the 22th of October when birds first visit the colony after the winter period. The right picture presents the same area a few days later when all Antarctic petrels had left the colony starting their pre-laying exodus (i.e. long foraging trip before coming back to lay eggs and start the breeding season). Photo: Sebastien Descamps, NPI

In addition, a time-lapse camera with 4G connection has been installed close to the Troll research station (on Trollhaugen) to monitor snow petrels in this area and in particular their breeding phenology. A camera with Iridium communication has also been installed at Svarthamaren (connected to the Iridium weather station) and one (low resolution) picture is sent daily via Iridium.

All these pictures, and the weather data from Svarthamaren, are available online via specific webpages (currently password protected). They will ultimately be imported automatically to, and be made publicly available on NPDC and the TONe web portal.

Time-lapse camera with 4G connection installed on Trollhaugen for monitoring snow petrels. Photo: Sebastien Descamps, NPI.

3.8 Remotely Piloted Aircraft System (RPAS) Service (NORCE)

The TONe RPAS (drone) service is set up to support the other observatories at Troll as well as being available as a service to the wider scientific community. The aim is to facilitate data collection in the DML region and contribute to bridge from local to regional scales. The drone service will have

Remotely Piloted Aircraft Systems with an effective range of about 800 km and endurance up to 8 hours. In addition, smaller electric multirotor and fixed wing drones will be deployed as part of the service. The drone service is set up to support research projects through data collection with advanced instrumentation that ordinary research projects otherwise would not be able to conduct on their own. Biennial deployments serving multiple projects will reduce costs for individual projects as well as reducing risk through the use of professional drone operators with experience of conducting drone operations in polar environments.

The Aircraft build and the radar system build started in the autumn 2024 and will be completed in April/May 2025. The other sensors have been ordered together with control and logging systems that will also be integrated in the airframe in spring 2025.

Left: TONe-RPAS under production in Southhampton, the VHF radar antennas can be seen under the wings. Right: Radar hardware installation in the fuselage. Photos: Andreas Tøllefsen, NORCE.

A shelter design is being worked on and the design will be completed in the spring of 2025.

Below follows a list of aircraft and sensor specifications for the TONe drone service as it will be implemented.

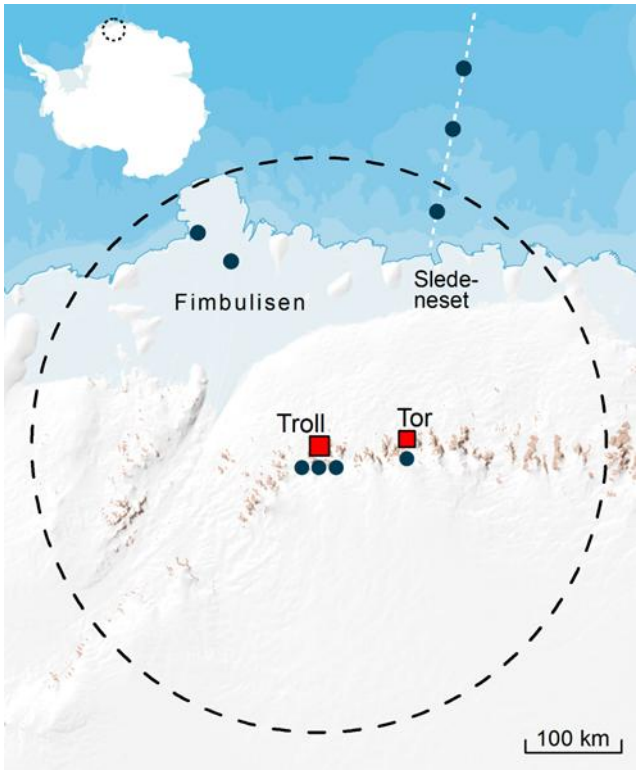
Aircraft Specifications

- Make and model: Two Windracer Ultra 2 drones
- Endurance: up to 800 km, 8 Hrs
- Payload capacity: 150 kg
- Broadband Satcom: Starlink
- Runway Requirements: 300 m

These specifications allow the drone service to cover large parts of DML from the Troll Station as illustrated below. The operational set up could allow for deployments from the shelf or from other stations in the region in the future.

Sensor Specifications

- VHF radar for bed topography/bounding line mapping/subglacial lakes
- UWB radar (2-6 GHz) for snow stratigraphy mapping
- NEO HySpex VNIR 1800 hyperspectral imager
- High resolution wide swath aerial camera system
- Meteorological sensors TPH
- Broadband radiometers



Effective area that can be reached from the Troll Station under near ideal weather conditions. Circle diameter is 600 km. Illustration: NPI.

With this configuration, the project anticipates the following applications linked to the TONe observatories:

- Cryosphere
  - Ice thickness and stratigraphy
  - Recent surface mass balance
  - Snow water equivalent
- Ocean
  - Sea-ice properties, ice fraction and albedo
  - Primary production, chlorophyll-A, algae
  - Sea surface temperature
- Atmosphere
  - Basic meteorological parameters in the boundary layer
  - Net radiation/broadband and spectral reflectance and albedo/heat fluxes
- Ecosystems
  - Seabird monitoring
  - Marine mammal survey

The plan for 2025 is to finish integration and complete training and testing before shipping one aircraft to Troll. The other aircraft will be used for further training and testing before first planned season in January 2027. Based on the training and testing NORCE will develop a software processing system and analysis tools to take the raw data from the sensors to calibrated and geolocated level-1 data files that scientist can use in their research analysis. The broadband satellite link will bring unique capabilities when it comes to providing data in near real time. However, the data rate of the

sensors is very high so a limited subset of the data will be transferred by satellite link from the aircraft or from Troll Station.

Windracer Ultra 2 drone. Photo: Rune Storvold, NORCE

Windracer Ultra as deployed by BAS at the Rothera Station in the 2023/24 season. Photo: Carl Robinson, BAS.

3.9 Data management system

The TONe data management system (DMS) is a distributed data storage and publication system with an online data portal for unified access to all TONe data.

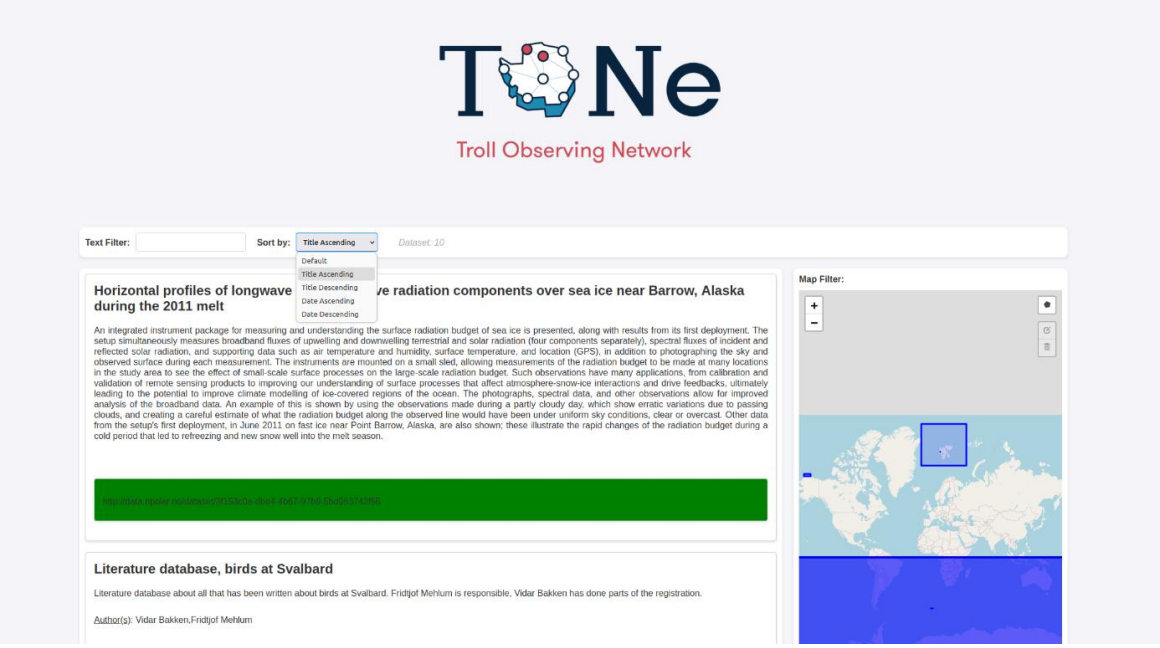
The DMS comprises local data and application servers at Troll Station, permanent data storage and management at the partner data centres in Norway, metadata management by NorDataNet – a national research infrastructure operated by the Norwegian Meteorological Institute - and the data portal to be hosted by NPI.

The four data servers for Troll Station were acquired in 2023. Following a redesign of the general ICT infrastructure at Troll Station the servers were reconfigured in Tromsø in the boreal summer of 2024 and shipped to Troll Station late in the year. They were installed and connected at Troll Station during the 2024-2025 summer. 2024 also saw the development of the TONe data portal, with

advanced search and filtering capabilities. The TONe data portal will harvest the TONe metadata set from NorDataNet and provide data access links directly to the data centres holding the actual data.

During 2025 the data pipeline will be implemented by setting up metadata harvesting through NorDataNet to the TONe data portal. The former is largely in place already, but a mechanism to identify and tag TONe datasets specifically must be tweaked and tested.

The TONe data portal is intended to be an integral part of the TONe web portal. We expect the TONe data portal itself to be operational within the year, depending on the TONe website progress.



Screenshot of a fully functional test implementation of the TONe data portal, showing filtering of dummy data from the Arctic. The visual design will change in the final version, and the search map will be in a south polar stereographic projection instead of the Mercator projection.

4. Outreach

Effective communication is a vital component of the TONe project. Guided by our communication strategy, the primary target audience has been identified as the broader scientific community. However, additional key stakeholders include decision-makers, Norwegian ministries and the Research Council of Norway, leadership within other research institutions and national Antarctic programs, as well as the general public.

A central priority for the TONe management is to engage both national and international research communities in utilizing TONe data, observatories, and services. Our user base includes researchers conducting fieldwork in Antarctica in collaboration with the TONe team, as well as those who remotely access and apply TONe data in innovative ways from their home institutions. Equally important is our commitment to demonstrating how the Norwegian research community contributes to advancing knowledge about Antarctica, particularly in outreach to the general public.

The TONe website (https://www.npolar.no/en/tone/) still remains the primary platform for disseminating project information. It provides comprehensive details on each observatory, the RPAS (drone) service, and the TONe data infrastructure. In early 2025, the website underwent a visual

update to enhance accessibility and user experience. Work on developing the TONe data portal is scheduled to begin later in 2025, further strengthening access to and usability of TONe resources.

The social media channels of the partner institutions—particularly on Facebook and Instagram—have been actively used to communicate TONe-related activities and developments to the general public. Although TONe previously maintained its own account on X (formerly Twitter), the NPI made the decision to discontinue the use of this platform, and TONe has followed suit. A summary of TONe's communication activities over the past year is provided below.

4.1 TONe Communication and Outreach Activities Year 3

Information about TONe in general and the individual observatories has been communicated widely the last year. Specifically, TONe has been presented at the following scientific conferences/workshops:

- Elin Darelius: Eleven tents, three holes and a bathtub: how to observe the ocean beneath a 400 meter thick ice shelf, Presentation at the Ocean Science bar, September 2024.
- Elin Darelius: Eleven tents, three holes and a bathtub: how to observe the ocean beneath a 400 meter thick ice shelf, Presentation at the University of Bergens GEO seminar, October 2024.
- Elin Darelius: Livet på isen: hvordan studere havet under 200 m tykk is. Presentation at UiB NT strategic seminar, December 2024.
- Elin Darelius: Hold hodet kaldt – feltarbeid på Fimbulisen, Antarktis. Presentation for UiB, February 2025.
- Tore Hattermann and Elin Darelius: "Femti dager, elleve telt og tre hull - Oseanografisk feltarbeid på Fimbulisen". Keynote presentation at the Antarktisseminaret, Tromsø, May 2024.
- Stephen Hudson et al.: Information on TONe with focus on TONe ICO at 1st General Assembly of the Norwegian Geophysical Society, Union Lecture, June 2024.
- Christina A. Pedersen et al: «Update on Troll Observing Network», oral presentation, Antarktisseminaret, Tromsø, May 2024.
- Christina A. Pedersen et al: «Troll observing network», poster presentation at Antarktisseminaret, Tromsø, May 2024.
- Christina A. Pedersen et al: Presentation on TONe at the SCAR Open Science Conference in Pucon, Chile, August 2024.
- Christina A. Pedersen et al: «Troll observing network», poster presentation at Framdagen in Tromsø, Nov. 2024.
- Johannes Schweitzer, Jon Magnus Christensen & Sindre Stokkan: TONe: Plans and Status of the Seismic and Infrasound Arrays. Antarktis Seminar 2024, Tromsø, 7.-8. Mai 2024 (poster).
- Johannes Schweitzer & Nadége Langet: How analysing icequakes can lead to a better understanding of glaciers. Antarktis Seminar 2024, Tromsø, 7.-8. Mai 2024.
- Johannes Schweitzer & NORSAR Colleagues: Using Seismic and Infrasound Data to Characterize the Dynamics in Ice Shelf Movements. Antarktis Seminar 2024, Tromsø, 7.-8. Mai 2024.
- Johannes Schweitzer & Nadége Langet: Seismic stations at Troll, Dronning Maud Land, Antarctica – Past and Future. 39th General Assembly of the European Seismological Commission, 22 – 27 September 2024, Corfu, Greece.

- Johannes Schweitzer & Pirli: The seismic station Troll in Dronning Maud Land, Antarctica – Presence and Future. Presentation at the 4th General Assembly, African Seismological Commission, Windhoek, Namibia, February 2025.
- Sabine Eckhardt et al.: Global relevance of atmospheric observations in the Antarctica. Oral presentation, Antarktisseminaret, Tromsø, May 2024.
- Stian Solbø, et al.: Troll observing network drone service, Presentation at the SCAR Open Science Conference in Pucon, Chile, August 2024.
- Wojciech Miloch et al: webinar for International Space Weather Initiative, United Nations office for Outer Space Affairs: "In-situ and ground based studies of plasma irregularities in the polar ionosphere", January 2024
- Wojciech Miloch et al., Ionospheric Plasma Structuring and Irregularities at High Latitudes, talk at 4th URSI Atlantic Radio Science Meeting, Maspalomas, Spain, May 2024
- Wojciech Miloch et al. Troll Ionospheric Observatory in Dronning Maud Land, talk at SCAR Open Science Conference, Pucon, Chile, August 2024.
- Wojciech Miloch et al., Ionospheric Plasma Irregularities in the Polar Regions, talk at SCAR Open Science Conference, Pucon, Chile, August 2024.
- Wojciech Miloch et al., Ionospheric irregularities at high latitudes: observations and models, talk at International Reference Ionosphere Workshop, IRI2024, September 2024.
- Wojciech Miloch et al., Studies of ionospheric plasma irregularities at high latitudes and status of the 4DSpace instrument network, invited talk at IMPC Workshop, Sao Paolo, Brasil, September 2024

TONe was also in the media, both in terms of by popular science articles written by members of the consortium, but also in the news media:

- NORCE Contracts for Windracers ULTRAs for Antarctic Missions at Windracer web Sept 2024; https://windracers.com/norce-contracts-for-windracers-ultras-for-antarctic-missions/
- Antarctic research station Troll acquires research drones with a range of 1000 km at NORCE web Sept 2024: Antarctic research station Troll acquires research drones with a range of 1000 km - Norce
- New Windracers drones for Antarctica- NORCE buys two ultra mk1s at Polar JournalOct 2024: https://polarjournal.ch/en/2024/10/03/new-windracers-drones-for-antarctica-norce-buys-two-ultra-mk1s/
- VG 24.03.2024: «Det er noe vi ikke har kontroll på». News article about TONe-FIO siting Tore Hattermann etc.: «Det er noe vi ikke har kontroll på»
- Report series on Ionospheric Observatory fieldwork and installation in the SCAR (Scientific Committee on Antarctic Research) newsletter and in various SCAR social media (Facebook, X, Bluesky), 24-28 February 2025.

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5.1 Publications

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Lindbäck, K., **Darelius, E.**, **Moholdt, G.**, Vaňková, I., **Hattermann, T.**, Lauber, J., & de Steur, L. (2025). Basal melting and oceanic observations beneath central Fimbulisen, East Antarctica. *Journal of Geophysical Research: Oceans*, 130, e2023JC020506. https://doi.org/10.1029/2023JC020506.

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5.2 Contributions to reports

Troll observing network – Status and progress in 2023, Njåstad og Pedersen, Fram Forum 2023: Troll Observing Network – status and progress in 2023 - Framforum

Information on TONe FIO and TONe MOMO in iC3 annual report: Hattermann et al. https://ic3.uit.no/news/annual-report-2024

Monitoring of greenhouse gases and aerosols in 2023. Annual report, Platt et al: https://hdl.handle.net/11250/3171271

5.3 Datasets

Hudson, S., **Bratrein, M.**, **Neely, R.**, **Town, M.**, & **Walden, V.** (2025). Microwave radiometer data from Troll Station on 31 March 2025. ACTRIS Cloud remote sensing data centre unit (CLU). https://hdl.handle.net/21.12132/1.43ec991131164a24

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Lunder, C., Platt, S. NILU, 2021-2024, Main greenhouse gases and carbon_monoxide at Trollhaugen, data hosted by EBAS at NILU, DOI: https://doi.org/10.48597/5EMN-3E4Y

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Troll Observing Network