NORDIC IONOSPHERIC SOUNDING ROCKET SEEDING EXPERIMENT (NISSE)

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ABSTRACT

The Nordic Ionospheric Sounding rocket Seeding Experiment (NISSE) is a student research project in the REXUS student rocket experiment program. The NISSE experiment flew onboard a sounding rocket, the REXUS 6, which was launched at the Esrange rocket range on March 12, 2009. In the NISSE experiment about 8.3 kg of water was to be released into the ionosphere at the REXUS 6 apogee altitude of about 95 km. The EISCAT UHF incoherent scatter radar system located in Northern Fennoscandia, was in action for detection and observation of the effects of the released water on the upper atmosphere. Although NISSE was only partially successful, we are motivated to present here the conceptual description of the experiment and discuss the experience gained from an educational point of view.

1. INTRODUCTION

In ionospheric chemical release experiments made by rockets, substances like barium compounds, water vapour, or just rocket exhausts, are released into the ionosphere and the effects are then observed and studied by using ground-based instruments and/or measurement devices onboard the rocket itself [e.g. 1 and references therein].

Since 1979, incoherent scatter (IS) radars have been utilized to study such man-made ionospheric modifications [2]. The released substance modifies the ambient ion composition both directly by solar photoionization and indirectly through ion chemistry. Consequently, local variations in plasma appear (e.g. local variations in electron density) affecting the backscattered radar signal measured by an IS radar.

Active chemical release experiments using an IS radar have been mostly carried out at F region heights (ionospheric upper altitude region extending roughly from 120 km to the magnetosphere) due to the fact that the most abundant F region ion species O^+ is highly chemically reactive causing transformation of release substance particles into molecular ions. Both rocket exhaust plumes and released ion clouds of proper substance have been observed and studied [2, 3]. In addition several measurements of exhaust gases of space shuttle orbital maneuver subsystem engines have been made [4–7]. To our knowledge, very few E or lower altitude region, termed here as upper mesospheric-lower thermospheric (UMLT) region, IS studies have been published so far.

The release of the dense neutral vapour cloud into the ionosphere will cause the cloud to expand rapidly and simultaneously to cool down due to adiabatic expansion in the low-pressure atmosphere. Condensation to tiny solid particles may occur due to the temperature drop, but eventually these particles re-evaporate and the gas is thermalized by the collisions with the ambient atmosphere. Then the cloud temperature approaches the background atmospheric temperature and the expansion is dominated by collisional, diffusive processes [8].

In the case of a liquid, the substance starts to evaporate as it gets in contact with the atmosphere due to the low pressure. However, only part of the substance is flash-evaporated at once. According to Bernhardt [9], the evaporation proceeds by a continuous solidification-evaporation process due to cooling and warming effects of adiabatic expansion and latent heat release of condensation, respectively, until the liquid vanishes [see details in 9]. By modelling flash releases of liquids, Bernhardt concluded that vapour yields of 60-70 % could be obtained for several chemicals including some used in the past experiments, except water, which has high heat of vaporization. For 10 l water at a temperature of 70 °C, only 19 % was transformed to vapour, at once, according to the model. The rest of the water was expected to first condensate to ice form [9].

Formation of ice may also occur in rocket motor exhaust plumes. Water vapour is a common exhaust product and rapid cooling in the expanding exhaust cloud may lead to condensation of small ice crystals [e.g. 4, and references therein]. If the background atmospheric temperature is low enough and condensation nuclei are available, this kind of condensation phenomenon occurs naturally for water in the ambient atmosphere. The extreme conditions required for the phenomenon are met in the UMLT region during summer months, with lowest mean temperatures of ~133 K at the mesopause at around 88

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km [10]. These conditions enable even the ambient dry air between 80-90 km altitudes to condensate to the highest naturally occurring cloud phenomenon, noctilucent clouds, seen only in twilight conditions [see review by 11]. Smaller subvisual ice particles (with radii smaller than ~20-30 nm) may get charged and form dusty plasma, and when turbulence is present it can create strong measurable backscattering signatures, known as polar mesospheric summer echoes (PMSEs) that are detected by VHF and UHF radars [12–14].

In wintertime, conditions are somewhat different. Strong mesospheric radar backscattering signatures have been recorded also during winter months (PMWEs) in sunlit conditions, but at lower heights typically at altitudes below about 75 km. The explanation of these PMWEs has remained unclear and under active research [15], since temperatures in the winter mesosphere are too high for water-ice to exist for longer periods of time [11].

However, visual ground observations have been made of artificial noctilucent clouds (ANLCs) forming during wintertime. In two separate cases, in mid-latitude atmospheric conditions in 23 February, 1971, and 18 March, 1972, Benech and Dessens [16] observed that the exhausts produced by a rocket accelerated in re-entering into the atmosphere initiated the formation of an ANLC. In both events, the cloud was formed at an altitude region around 80 km and existed for some tens of minutes. The upper parts of the cloud were estimated to reach about 92 km altitude. The horizontal sizes of the clouds were estimated to be ~20 km. The clouds were suggested to have formed in the way that first the water vapour released condensated to small ice crystals and then these ice particles, and perhaps also Al_2O_3 particles that were among the exhaust gas, acted as condensation nuclei for ambient atmospheric moisture. The total amount of released gases was very small. The rocket produced only 260 grams of H_2O, 520 grams of HCl, and 1600 grams of Al_2O_3 on a trajectory covering 10 km horizontal range and several tens of kilometers altitude range in the re-entry phase [16].

Simultaneous Lidar observations by Fricke et al. [17] during the Black Brant XII rocket experiment at Andøya, Norway on January 25, 1995, showed a formation of an aerosol layer about 12 min after launch at 82-90 km altitude. The slowly descending layer grew distinct and weaker, and split into a double layer. Then a separate layer developed at 75 km. The top layer faded at 66 min and the bottom at 83 min. The rocket exhausts consisted mainly of the same gases as in experiments observed by Benech and Dessens and it was concluded that the most likely candidate for condensation was water vapour. In this case the ANLC was heavily distorted by upper mesospheric winds and waves [17].

In the terms of ion chemistry, F region water releases have been observed to lead to electron density depletion due to the rapid water molecule charge exchange reaction with O^+, and subsequent recombination of the created H_2O^+ ion with the ambient ionospheric electron [e.g. 4]. In the UMLT region, where NO^+ and O_2^+ are the dominant ion species, the above reaction chain is not effective. However, it has been suggested by Forbes [18] that water vapour injection below 120 km altitude could cause reduction in ionization due to screening of solar Lyman-α radiation. Due to the fact that the dominant source of NO^+ ions at 70-90 km altitude is photoionization of NO by Lyman-α radiation and since H_2O is primarily dissociated below 120 km by Lyman-α radiation, the result would be reduced ionization.

An additional reduction of ionization could be caused by conversion of ambient NO^+ and O_2^+ ions to heavy water cluster ions, which have more rapid recombination times. The water cluster ions are naturally common below altitudes of 75-85 km where the water concentration is higher, but may exist higher up depending on the moisture level of the region [18].

By releasing chemicals e.g. water artificially at UMLT altitudes and measuring the possible subsequent local perturbations generated in the ambient atmosphere/ionosphere by an IS radar, we can study and get information about the properties of the upper atmosphere. To our knowledge, very few active chemical release experiments have been done using the EISCAT radars. Holmgren et al. [19] have reported EISCAT UHF measurements associated with cesium releases in the Tor experiment performed in October 1984 at Esrange. However, their results remained somewhat unclear since their EISCAT measurements did not succeed as planned due to a phone line breakdown between Esrange and Tromsø. After those days, besides more reliable communication lines, more advanced radar experiments i.e. radar modulation codes have been developed to enable better measurements compared with those in the early days of EISCAT.

In the water release project NISSE was conducted during 2008-2009 as part of the REXUS student rocket experiment program coordinated by the ESA Education Office. The REXUS 6/NISSE experiment was launched on 12 March, 2009, at Esrange. Unfortunately, the electronics of NISSE failed and the water was never released. However, all educational objectives were fulfilled.

In this paper we present the conceptual description of the NISSE experiment, since it may give inspiration to rocket engineers and scientists who may be planning to conduct similar-type experiments in the future. In section 2 the payload is described and in section 3 the launch conditions and EISCAT radar configuration are presented. In section 4 we shortly discuss educational experiences during the project and in section 5 a short summary and discussion are given.

Figure 1. A 3D CAD of the NISSE experiment. Left: Mounted inside the rocket modules; Centre: Without modules; Right: 12-l Airfix A12 tank by Flamco.

2. NISSE PAYLOAD

The NISSE payload consists of a commercial off-the-shelf 12-liter pneumatic actuator water tank and a water distribution system, mounted inside two REXUS rocket modules (∅ 356 mm) (Fig. 1). The water tank and the distribution system are attached inside the 300 and 288-mm long bottom and top modules, respectively. A rubber actuator inside the water tank makes up a part of the tank volume and is filled with nitrogen gas that pressurizes the water to 8 bar. With help of the actuator the tank is able to deliver approximately 8.3 liters (or kilograms) of water. The water tank is designed to operate under a maximum pressure of 10 bar on the ground, but is pressurized to 8 bar for that it can withstand the forces applied by the REXUS 6 rocket (Improved Orion) during the flight; the peak acceleration of ~19 g in the lift-off boost phase and the rotational frequency of 3-4 Hz, and also the vacuum of space.

The water distribution system is placed in the top module. It consists of a release valve and a divider with nine radial outward-aligned copper pipes (∅ 10 mm) leading out through the holes placed on the skin of the upper module. The pipes are placed in a plane perpendicular to the axis of the rocket. The release valve is connected to the tank and the filling system. The water is led from the release valve through a copper pipe (∅ 12 mm) to the divider. The release is performed by using two explosive bellows actuators (squibs) to open the valve by moving a piston that in its original configuration plugs the pipe. The total mass of the NISSE payload onboard the rocket, including 8.3 kg water, is about 28.3 kg.

Fig. 2 shows the system block diagram of the experiment. The service module (SM) onboard the REXUS 6 rocket contains the main computer, which is programmed to send the start-of-experiment (SOE) signal and to handle the data from the pressure and temperature sensors included onboard to monitor the experiment operation during the flight. The main computer also transmits the pressure and temperature

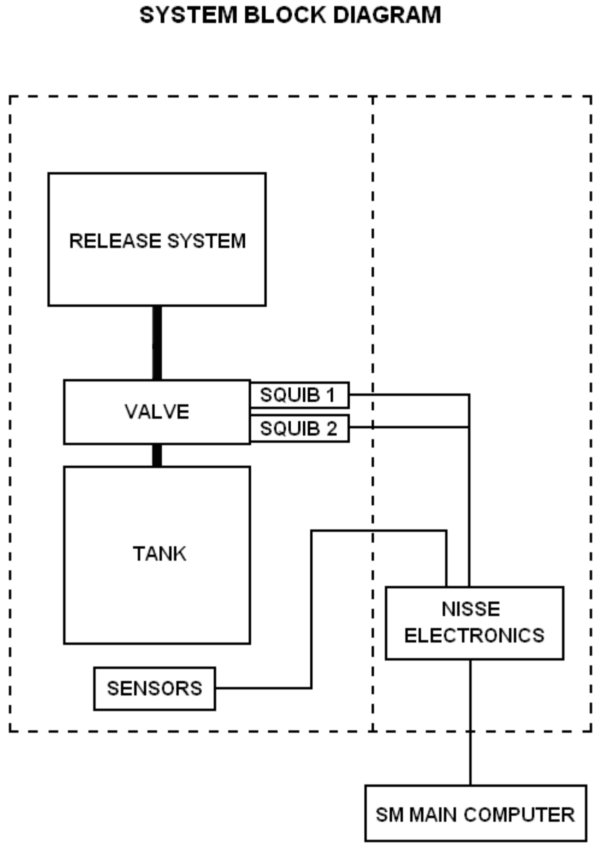

Figure 2. NISSE system block diagram. See details in text.

sensor data to the ground. On the SOE signal from the main computer the NISSE electronics is triggered to send a current through the squibs to ignite them.

The NISSE electronics is an RC-circuit placed inside a dedicated box in the experiment module above the NISSE payload. A baroswitch is placed in the circuit as a safety precaution. It ensures the capacitor is not charged until the rocket reaches an altitude of about 20 000 feet (~ 6 km) at which the atmospheric pressure has decreased to half of that on the ground.

On the activation of the squibs the valve opens and the water flows from the tank to the release system into the nine pipes, and ejects freely into space. The pipes are heated on the ground by warm air prior to launch to avoid freezing during the release. The bold lines in Fig. 2 show the water flow and the thin lines show the signal paths. The triggering is timed to occur four seconds before the nominal rocket apogee is reached due to the finite ejection time of the water (based on ground tests).

3. LAUNCH AND EISCAT MEASUREMENTS

3.1. Launch

The REXUS 6 rocket carrying the NISSE payload was launched at Esrange rocket range (67.9°N, 21.1°E) on Thursday 12 March, 2009, at 10:08 UT. The launch was conducted during quiet geomagnetic conditions (e.g. Esrange magnetometer data, not shown). The rocket reached an altitude of 89 km, which was about 7 km below the predicted nominal apogee altitude. The apogee was reached 143.9 s after lift-off. The mechanical construction of the payload withstood all forces acting on it during the flight, and came down in good condition with a parachute. Unfortunately, the NISSE electronics failed and no water was released – all water that went up came down within the payload.

3.2. EISCAT measurements

Despite the fact that the water was not released, it is worthwhile to have a closer look at the coordinated EISCAT measurements during the launch. Fig. 3 and Fig. 4 show the schematic illustration of the EISCAT configuration in 2D and 3D, respectively.

The tristatic EISCAT UHF incoherent scatter radar system [21] consists of a transmitter-receiver (TxRx) located in Tromsø, Norway and two remote receivers (Rxs) in Kiruna, Sweden, and Sodankylä, Finland. The UHF started operating at 09:00 UT, about an hour before the lift-off, and the measurements continued until 12:30 UT. The radar modulation used was manda, which is one of the standard UHF experiments suitable for UMLT altitude region measurements (see http://www.eiscat.se for further details). The range and time resolutions achieved by manda are 450 m and 6 s, respectively.

The UHF was scanning the expected water release volume derived from the REXUS 6 nominal flight trajectory. The scan pattern was a vertical scan of nine pointing positions of the radar beams' common volume. As seen along the Tromsø radar beam, the cross-section of the pattern forms a 3x3-square or three vertical columns (east, middle, west) surrounding the expected water release region. The centre position of the square, or the middle column, was placed at an altitude of 95 km at the position of the nominal apogee point of the rocket trajectory (somewhat below the nominal 96.4 km). The scan operated in such a way that the beams wiped down through all three positions along the middle column and up along the east column (as seen along the beam southwards from Tromsø) and then down along the middle column again and up along the west column. The scan pattern roughly covered the σ-volume and some of the 2σ-volume of the deviation in the rocket trajectory taken as guidance from the REXUS 3 data [20]. The radar pointing time in each direction was chosen to 30 s as a compromise of good time resolution and data quality. The total duration of one complete cycle was 360 s = 6 min, but the middle column positions were wiped twice. About 50 min before the lift-off the scan pattern was updated according to the latest predicted rocket trajectory data file and 30 min before the lift-off the radar was running again with an updated scan pattern. About 20 minutes before the lift-off the UHF radar was repointed and timed, in order for the scan pattern to start from the beginning (centre position) at the time of the water release.

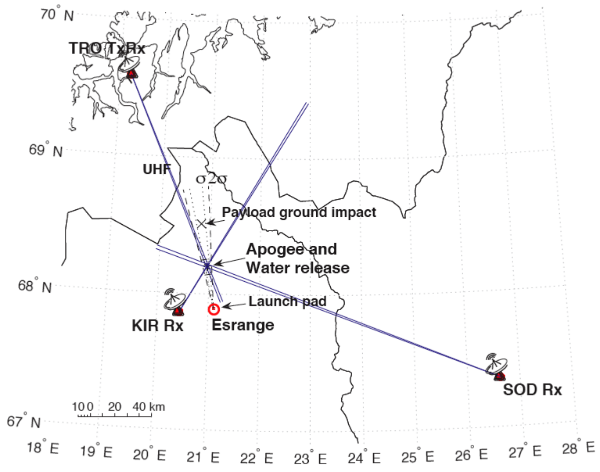

Figure 3. A schematic presentation of the REXUS 6/NISSE – EISCAT measurement configuration during the launch. The σ- and 2σ-deviations from the predicted trajectory of earlier REXUS 3 are marked by dotted and dashed sectors, respectively, and are shown just for example (taken from [20]).

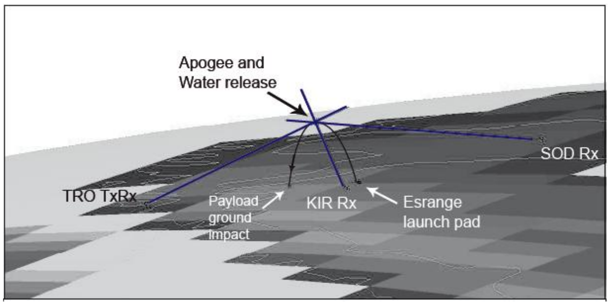

Figure 4. Same as in Fig. 3, but in 3D.

Besides the standard EISCAT measurement, the UHF raw data were sampled in real-time for the lag profile inversion data analysis [22].

Fig. 5. shows an overview of the electron density measurements during the launch measured by the UHF Tromsø antenna. In the analysis, time and altitude integration of 30 s and 2 km have been used, respectively. Before the lift-off, the electron density

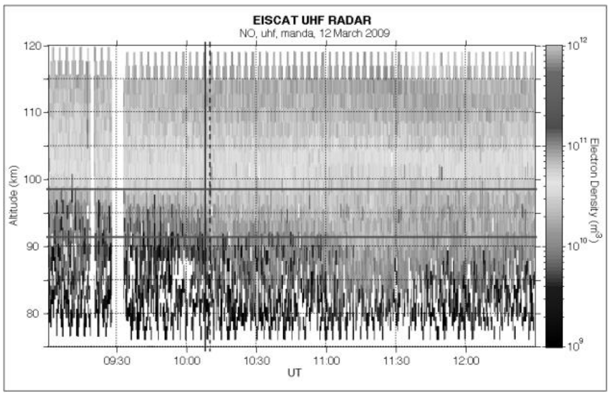

Figure 5. Electron density measurements during the REXUS 6 launch. The lift-off at 10:08 UT and the rocket apogee at ~10:10:40 UT are marked by vertical solid and dashed lines, respectively. The altitude region scanned by the tristatic intersection point is bounded by horizontal lines.

exceeded 10^{10} m^{-3} (a rough lower limit for detection) roughly around an altitude region of 90-94 km. From the lift-off onwards, the electron density started to increase also at lower altitudes and between 11:00 and 11:30 UT the 10^{10} m^{-3} –boundary was as low 84 km. Thus it can be concluded that at the lift-off and thereafter the prevailing ionospheric conditions were good enough for detection of possible disturbances generated by the water release. The data from the remote sites, however, turned out to be very noisy (not shown).

4. EDUCATIONAL NOTES

The project NISSE has taught the students involved a lot about teamwork, project management, rocket science and outreach. In addition they have learned something more about ionospheric physics, EISCAT and collaboration with international space organizations, like ESA and Eurolaunch (Deutsches Zentrum fur Luft- und Raumfahrt (DLR) + Swedish Space Corporation (SSC)). The students have gained experience and contacts that are not possible to get from usual studies at their universities and these will support their studies in space physics in the future.

The design of the experiment was done with the help of a retired rocket engineer, and in meetings with supporting engineers at the University of Bergen (UiB) the design was gradually adapted and the construction planned. Except for this, the NISSE student team did not undergo the usual supervisor-student interaction in studies, but worked as a group without a supervisor. All criteria had to be conceived by themselves. It was useful to learn how a group of scientists collaborate and seek help from experts (e.g. ESA, Eurolaunch and UiB) whenever needed. The fact that our group was scattered around the Nordic countries (Norway, Finland and Denmark), forced us to use all benefits of the modern Internet-based communication tools of today. Besides emails, especially instant messaging turned to be a very good tool for communication during the project. Writing several reports about the progress in different phases of the project improved documentation skills.

Although the project was scientifically only a partial success, all educational objectives were fulfilled.

5. SUMMARY AND DISCUSSION

NISSE, a challenging rocket water release experiment in the upper atmosphere onboard the REXUS 6 rocket, was conducted at Esrange on March 12, 2009. NISSE was planned, built and executed under guidance of experts from ESA, Eurolaunch and University of Bergen. In the NISSE experiment, about 8.3 kg water was to be released into the daytime atmosphere at the altitude of about 95 km in midday ionospheric conditions. Effects of the water release on the ionosphere were to be studied by observations of the EISCAT UHF incoherent scatter radar. However, due to the aforementioned electronics failure the water was never released. Another drawback was the lower rocket apogee altitude than predicted. Despite, as a student project, NISSE provided great experience about conducting a larger-scale international scientific project.

It could be argued that the amount of water (8.3 kg) would be too small to cause a measurable effect. As discussed in the Introduction, however, water injection could possibly cause reduction of the ionization due to screening of solar Lyman-α radiation and/or due to conversion of the ambient molecular ions to heavy cluster ions [18]. This would lead to a similar local decrease in electron density as water releases in the higher F region, but now for different reasons.

To estimate the effects of ion and neutral chemistry, we modelled the effects of the water release by using the comprehensive Sodankylä coupled Ion-neutral Chemistry model (SIC) [23, 24]. The modelling results of a 10-kg water vapour point release at an altitude of 95 km showed indeed a clear depletion in the background electron density. A 60 % decrease from the pre-release electron density values progressed to lower altitudes reaching 79 km in 15 min and lasted at least one and a half an hour (data not shown). However, the results surely overestimated the impact since the diffusion model taken from Bernhardt [25] was originally derived for F region expansions. In addition, neither aerosol formation (ice particles) nor transport by neutral winds was taken into account. Moreover, the modelling was made for a point release. In our experiment the water would have spread on a distance of a couple of kilometers along the trajectory.

Another scenario is that the life-time of the possible condensated ice particles would turn out to be long enough for further condensation to occur. These ice crystals could then act, together with other impurities in the region and in the released water, as condensation nuclei for ambient atmospheric moisture and induce a formation of an artificial noctilucent cloud, as has been observed [16]. If charged, these ice particles could lead to strong PMSE-like echoes that could be seen with the radar.

This kind of water release experiment at the UMLT region could be greatly improved by releasing as much water as possible by a detonation at the release altitude. Then the water would be in gaseous stage already at the beginning of the release and there would be no freezing risk in the release system. Another improvement is that the experiment should be conducted during summer months (end of May – beginning of August [13]). As discussed in the Introduction, in summer months the mesopause region (altitudes of 80-90 km) is cold enough for natural formation of the noctilucent clouds. An artificial water release would then have a greater probability to cause exciting effects measurable from the ground, like a noctilucent cloud and/or polar mesospheric summer echoes.

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