PIONEER PROJECTS

UAV DEPLOYMENT AT REUNION ISLAND FOR TCCON CALIBRATION AND SHIP EMISSION MAPPING

CONTRACT - BR/121/PI/UAV_Reunion

FINAL REPORT

30/12/2016

Promotor

Alexis Merlaud, Royal Belgian Institute for Space Aeronomy BIRA-IASB,
Avenue Circulaire 3, 1180 Bruxelles, Belgium

Authors
Alexis Merlaud (BIRA-IASB)
Martine De Mazière (BIRA-IASB)
Filip Desmet (BIRA-IASB)
Mahesh Kumar Sha (BIRA-IASB)

Published in 2018 by the Belgian Science Policy Office
Avenue Louise 231
Louizalaan 231
B-1050 Brussels
Belgium
Tel: +32 (0)2 238 34 11 – Fax: +32 (0)2 230 59 12
http://www.belspo.be

Contact person: Georges JAMART
+32 (0)2 238 36 90

Merlaud A., De Mazière M., Desmet F., and Sha, M. K., **UAV Deployment at Reunion Island for TCCON Validation and Shipping Emission Mapping**. Final Report. Brussels : Belgian Science Policy Office 2018 – 40 p. (BRAIN-be - (Belgian Research Action through Interdisciplinary Networks))

TABLE OF CONTENTS

SUMMARY

Context

The Royal Belgian Institute for Space Aeronomy (BIRA-IASB) has been involved in atmospheric research at Reunion Island (21°S, 55°E) since 2002, using in particular ground-based infrared and UV-visible spectroscopy. Reunion Island is located 800 km to the East of Madagascar, in the Indian Ocean. It is one of the few places in the southern tropical latitudes where atmospheric observations are performed. BIRA-IASB operates there two Fourier Transform Infrared (FTIR) spectrometers (one at sea level, the second one on a mountain observatory at 2200 m altitude) and a MAX-DOAS instruments at the harbour.

These measurements of atmospheric composition take place in the framework of international networks such as the Network for Detection of Atmospheric Composition Change (NDACC) and Total Carbon Column Observing Network (TCCON). The FTIR operated at sea level is part of TCCON, which measures the total column abundances CO_2, CH_4, N_2O (three important greenhouse gases) and CO from the solar radiation in the near infrared recorded by the spectrometer of the type Bruker IFS 125HR. The TCCON network has very stringent requirements for high precision and accurate measurements of these gases. The precision requirement for CO_2 is 0.25% (~1 ppm), for CH_4 is 0.3% and for CO is 1%. This stringent requirement is necessary to fulfil one of TCCON's main objectives: to provide essential validation resource for the measurement of greenhouse gases from space (e.g. with the research satellites OCO-2 and GOSAT).

TCCON requires calibrating the FTIR instruments at each station to the World Meteorological Organization (WMO) scale to include them as official network instruments. This calibration implies performing synchronous measurements with a well calibrated instrument above the TCCON station. This was done for other TCCON sites by flying over the site and making profile measurements of the targeted gases with a traditional aircraft equipped with in-situ gas analysers which were calibrated to the WMO scale. These reference measurements were then used to calibrate the TCCON data to the WMO scale. This solution would be very expensive at Reunion Island due to the remote location of the island. A recently developed technique, the AirCore seems to offer a cheap solution. AirCore consists of a tube which is brought to a high altitude (30 km) by a balloon and filled with ambient air during its descent. The collected gas is then passed within few hours after landing (typically between 0 – 4 hr) through a PICARRO gas analyser to get the vertical profile of the atmosphere. A delay in the recovery of the AirCore is related to the loss of resolution of the retrieved vertical profile of the gases in the atmosphere. At Reunion Island however, the AirCore launched on a simple balloon could easily fall in the ocean or inland cliffs which are very difficult to access easily upon its decent after the cut-off from the celling altitude. To overcome this issue and have quick access to the AirCore upon its landing, we would thus need a way to bring back the AirCore close to its launch site, or in another defined place on the island. This could be achieved by a homing parachute system.

Beside these activities in ground-based infrared spectroscopy, BIRA-IASB is involved in airborne research using UV-VIS spectroscopy. This technique is useful to study the distribution of short-lived anthropogenic species, in particular NO_2 and SO_2. Several instruments have been

developed and tested on board aircraft in the last years. In 2012, the Small Whiskroom Imager for atmospheric compositioN monitorinG (SWING) was developed and first tested from an ultralight aircraft in Belgium. This payload was designed for a dedicated Unmanned Aerial Vehicle that was developed in parallel within collaboration with the "Dunarea de Jos" University of Galati, Romania, and its spin-off Reev River Aerospace (RRA).

The project presented here merged the two aforementioned activities. The rationale for this clustering was that a unique industrial partner (RRA) offered us to solve the UAV-related issues for both activities (UAV developments, getting the flight approvals, and piloting on site). The initial plan was thus to organize a single campaign at Reunion Island, for the two different activities, which are linked by their general topic (atmospheric chemistry) and technique (measurements from unmanned airborne platforms).

Objectives

The objectives of the project were divided in two categories following the two aforementioned activities:

1) TCCON calibration of the Reunion Island station using an AirCore system attached to a homing parachute system. The AirCore would be released at 30 km altitude from a helium balloon. The homing parachute system, which should be developed during the project by our industrial partner (RRA), would bring the AirCore back in a predetermined 2x2 km^2 area. The AirCore collected air column would then be analyzed using a PICARRO in-situ gas analyzer owned by BIRA-IASB and already operating on the Reunion Island. This experiment would reveal the vertical distributions of CO_2, CH_4, CO, and H_2O above the station, enabling us to calibrate the ground-based FTIR instrument and be a fully certified TCCON station.

2) Demonstration of the measurements of ship-emitted NO_2 and SO_2 with the SWING payload onboard its dedicated UAV. The UAV would be operated by the industrial partner and launched from the main harbor at Reunion Island, from where it would fly up to 3 km altitude above the exhaust plumes of ships. We could then map at a high spatial resolution (200 m), the NO_2 and SO_2 fields, which would demonstrate a technique that could be used in the medium-term future for operational monitoring, as sulfur emissions from ships are regulated.

Conclusions

The BRAIN-be Pioneer project "UAV_Reunion" ended up by giving mixed results. Although, neither of the two initially proposed objectives was fully met, nevertheless several important experiments were performed within the project which enabled us to redirect our activities in more successful paths while keeping the science objectives in focus.

We have not performed any airborne campaign on Reunion Island within the time of the project. Investigations on the approval systems for UAV indicated that getting the flight approvals would not have been straightforward. Note that the regulatory framework for UAV operations in Europe is fragmented and that different laws apply for instance in Romania and in France.

Regarding the AirCore activity, two test campaigns were performed in Sodankyla, Finland, in July 2014 and June 2015. Two techniques to bring back the AirCore were tested: a parafoil and a flying wing. None of them showed appropriate performances. As an alternative mean to calibrate the TCCON instrument, we have successfully used a calibrated Bruker EM27/SUN spectrometer, both at Sodankyla and at Reunion Island. The results of these measurements should lead to the official recognition of the calibration of our TCCON experiment at Reunion Island in 2017.

Regarding the SWING activity, we have decided to change the target area after investigating the ship traffic at Reunion Island. Indeed, the latter appeared too sparse to be sure to get interesting data in a campaign timeframe of a few days. Therefore, we have investigated the area of Constanta, Romania, which is one the main harbour of the Black Sea. In the meantime, two versions of the SWING instruments were successfully deployed in the AROMAT campaigns in Romania and Germany, first on a UAV (September 2014), then on a Cessna (August 2015 and April 2016). We could in particular map the NO_2 field above Bucharest and Berlin and the SO_2 exhaust plume of a power plant. A major advantage of taking part in these campaigns was the possibility to validate SWING data with larger airborne instruments. The UAV flight above Constanta harbour has not been achieved at the time of this report but we have performed in July 2016 a promising test flight in the Antwerp area from the BN-2 of the Royal Belgian Institute for Natural science.

Keywords

Unmanned Aerial Vehicles; Reunion Island; TCCON; AirCore; Calibration; Greenhouse Gases vertical profiles; Miniature instruments; Pollutant Mapping

RESUME

Contexte

L'institut royal d'Aéronomie Spatiale de Belgique (BIRA-IASB) est impliqué depuis 2002 dans la recherche atmosphérique à l'Ile de la Réunion (21°S, 55°E). L'IASB y effectue en particulier des mesures spectroscopiques à partir du sol, dans l'infrarouge et dans l'UV-visible. L'Ile de La Réunion est située à 800 km à l'Est de Madagascar, dans l'Océan Indien. C'est l'un des rares endroits situés à la fois dans l'hémisphère Sud et sous les tropiques où sont réalisées des observations atmosphériques. L'institut d'Aéronomie y exploite deux spectromètres infrarouge FTIR (le premier au niveau de la mer, le second à 2200 m d'altitude), ainsi qu'un spectromètre UV-Visible de type MAX-DOAS, installé au port.

Ces mesures de composition atmosphérique s'inscrivent dans le cadre de réseaux internationaux comme le *Network for Detection of Atmospheric Composition Change (NDACC)* et le *Total Carbon Column Observeing Network (TCCON),* qui mesure la colonne totale de gaz comme le CO_2, CH_4, et le N_2O (trois gaz à effet de serre importants) ou le CO, à partir de la radiation solaire enregistrée dans le proche infrarouge par un spectromètre FTIR de type Bruker IFS 125 HR. Le réseau TCCON a des exigences très élevées pour la précision des mesures de colonne de gaz. La précision requise pour le CO_2 est ainsi de 0.25% (~1 ppm), de 0.3% pour le méthane, et de 1% pour le CO. Cette exigence élevée est nécessaire pour que le réseau TCCON remplisse un de ses principaux objectifs : fournir une base solide de validation pour les mesures de ces mêmes gaz depuis l'espace (par exemple à partie des satellites de recherche OCO-2 et GOSAT).

Le réseau TCCON requiert, à chaque station, la calibration des instruments FTIR à l'échelle de l'Organisation Météorologique Mondiale (OMM). Ceci est obligatoire pour inclure officiellement une station dans le réseau. Cette calibration implique de réaliser des mesures simultanées avec un instrument bien calibré au-dessus de la station TCCON. Ceci a été réalisé pour d'autres sites TCCON en les survolant avec un avion traditionnel équipé d'analyseurs de gaz in-situ, calibrés à l'échelle WMO. Ces mesures de référence ont alors permis de calibrer les données TCCON à l'échelle OMM. Cette solution serait très onéreuse à mettre en place à l'Ile de La Réunion, à cause de l'isolement de l'ile. Une technique récemment développée, l'AirCore semble offrir une solution peu couteuse. L'AirCore comprend un tube qui est amené à une haute altitude (30 km) par un ballon, ce tube se remplit avec l'air ambient pendant la descente. L'air ainsi collecté est alors analysé avec un instrument Picarro dans les quelques heures qui suivent l'atterrissage de l'AirCore. Ceci permet d'avoir les profils verticaux de l'atmosphère. Un délai dans la récupération de l'AirCore implique une diminution de la résolution verticale des profils de gaz dans l'atmosphère. Cependant, un AirCore lancé depuis l'Ile de la Réunion pourrait facilement retomber dans l'océan ou sur une falaise inaccessible. Pour pallier ce problème, il faudrait un accès rapide à l'AirCore après son atterrissage. Nous aurions alors besoin d'un moyen pour ramener l'AirCore près de son site de lancement, ou d'un autre endroit prédéfini sur l'Ile. Ceci pourrait être réalisé avec un système de parachute téléguidé.

A côté de ces activités en spectroscopie infrarouge, l'IASB est impliqué dans la recherche aéroportée en utilisant la spectroscopie UV-visible. Cette technique est utile pour étudier la distribution spatiale d'espèces chimiques d'origine anthropique à courtes durée de vie, comme le NO_2 ou le SO_2. Plusieurs instruments ont été développés à l'IASB et testés à bord d'avion ces dernières années. En 2012, le Small Whiskbroom Imager for atmospheric compositioN monitorinG (SWING) a ainsi été construit et testé pour la première fois à partir d'un ULM en Belgique. Cet instrument a été conçu pour un drone ou *Unmanned Aerial Vehicle* (UAV) qui était développé en parallèle dans le cadre d'une collaboration avec l'université de Galati 'Dunarea de Jos' en Roumanie et sa spin-off Reev River Aerospace (RRA).

Le projet présenté ici fusionne les deux activités présentées plus haut. La raison de ce regroupement est qu'un partenaire industriel unique (RRA) nous a offert de régler les aspects UAVs pour les deux activités (développement de plateformes, obtention des permis de vol, et pilotage sur site). Le plan initial était donc d'organiser une campagne unique sur l'Ile de La Réunion, pour les deux différentes activités, qui sont liées par leur sujet général (chimie de l'atmosphère) ainsi que par leur approche technique (mesures à partir de plateformes aéroportées sans pilote).

Objectifs

Les objectifs du projet était divisés en deux catégories, suivant les deux activités :

1) Calibration TCCON de la station de mesure FTIR de l'Ile de La Réunion avec un AirCore attaché à un parachute téléguidé. L'AirCore serait relâché à 30 km d'altitude à partir d'un ballon rempli d'Helium. Le parachute téléguidé, qui serait développé dans le cadre du projet par notre partenaire industriel (RRA) ramènerait l'AirCore dans une zone prédéterminée de 2x2 km^2. La colonne d'air collectée par l'AirCore serait alors analysée par un analyseur PICARRO de l'Institut d'Aéronomie déjà en opération sur l'Ile de la Réunion. Cette expérience révèlerait les distributions verticales du CO_2, CH_4, CO et H_2O au-dessus de la station, nous permettant de calibrer l'instrument FTIR au sol et de devenir une station certifiée TCCON.

2) Démonstration des mesures des émissions de NO_2 et SO_2 avec l'instrument SWING à bord de l'UAV. L'UAV serait piloté par notre partenaire industriel et lancé depuis le port principal de l'Ile de la Réunion, d'où il volerait à une altitude de 3 km au-dessus du panache de gaz d'échappement émis par les navires. Nous pourrions ainsi cartographier à une haute résolution spatiale (200m), les champs de NO_2 et de SO_2, ce qui démontrerait une technique qui pourrait être utilisée à moyen terme pour la surveillance opérationnelle, les émissions de soufre en particulier étant réglementées.

Conclusions

Le projet Pionnier BRAIN-Be a donné des résultats mitigés. Bien qu'aucun des deux objectifs initiaux n'ait été complétement atteint, plusieurs expériences importantes ont été réalisées dans le cadre du projet. Ces expériences nous ont permis de rediriger nos activités dans des directions plus réalistes, tout en maintenant les objectifs scientifiques initiaux.

Nous n'avons pas réalisé de campagnes aéroportées à la Réunion pendant la période du projet. Les recherches préliminaires sur le système d'autorisation des vols sans pilote ont montré que l'obtention des permis aurait été délicate. Il faut remarquer que le cadre législatif en Europe pour les opérations UAV est encore fragmenté, et que différentes lois s'appliquent par exemple en Roumanie ou en France.

Pour l'activité Aircore, deux campagnes de test ont été réalisées à Sodankyla, en Finlande, en Juillet 2014 et en Juin 2015. Deux techniques ont été testées pour ramener l'AirCore : un parachute et une aile volante. Ni l'une ni l'autre n'ont montré de performances satisfaisantes. Comme solution de rechange, nous avons utilisé avec succès un spectromètre calibré, le Bruker EM27/Sun, à la fois à Sodankyla et à l'Ile de La Réunion. Les résultats de ces mesures devraient permettre la reconnaissance officielle de le calibration TCCON à l'Ile de La Réunion en 2017.

Pour l'activité SWING, nous avons décidé de changer de zone cible après avoir évalué le trafic maritime à l'Ile de La Réunion. En effet, ce dernier est apparu trop peu dense pour être certain d'obtenir des données intéressantes dans une campagne de quelques jours. Par conséquent, nous avons étudié la zone de Constanta, en Roumanie. Constanta est un des ports les plus importants de la Mer Noire. Pendant la durée du projet, deux versions de l'instrument SWING ont été utilisés avec succès dans les campagnes de mesures internationales AROMAT (Roumanie et Allemagne), d'abord sur un UAV (Septembre 2014) puis sur un petit avion de type Cessna (Aout 2015 et Avril 2016). Nous avons pu en particulier cartographier la distribution de NO_2 au-dessus de Bucarest et de Berlin, et celle du SO_2 émis par une centrale thermique. Participer à ces campagnes a en outre permis de valider les mesures SWING avec de plus gros instruments. Le vol UAV au-dessus du port de Constanta n'a pas été réalisé à l'heure de finaliser ce rapport. Nous avons par contre effectué en Juillet 2016 un premier vol prometteur au-dessus d'Anvers avec le BN-2 de nos collègues de l'institut Royal des sciences naturelles.

Mots-clés

Drones; Ile de La Réunion; TCCON; AirCore; Calibration ; Profiles de Gaz à effet de serre; Instruments miniature; Cartographie de la pollution

1. INTRODUCTION

It has been the aim of this project to demonstrate new and innovative atmospheric measurement techniques using Unmanned Aerial Vehicles (UAVs), through two parallel demonstration activities that were planned at Reunion Island:

(1) TCCON calibration:

As part of the Total Carbon Column Observing Network (TCCON), which retrieves total columns of atmospheric greenhouse gases with high precision and accuracy, BIRA-IASB operates a Bruker IFS 125HR high-resolution Fourier Transform Infrared (FTIR) spectrometer at Reunion Island. To guarantee the accuracy of TCCON measurements, which is crucial for the exploitation of the data, a calibration to the standards of the World Meteorological Organization (WMO) using in-situ measurements is required. To this end, this project had the intention to develop an innovative lightweight atmospheric sampling system, consisting of an AirCore attached to a homing parafoil system, to be deployed up to 30 km altitude from a balloon. The capability of this system, to sample the vertical profiles of greenhouse gases in the atmosphere up to 30 km, gives it an important advantage over the more conventional aircraft-based calibration systems, which have a maximum altitude of about 13 km.

(2) Test of the newly developed SWING instrument from an UAV: The Small Whiskbroom Imager for atmospheric composition monitorinG (SWING) is a miniaturized payload that has been developed at BIRA-IASB in 2012 (Merlaud, 2013). Preliminary tests from an ultra-light aircraft had already been performed over Belgium. Its capability to operate from a custom built UAV platform had to be demonstrated above the harbour of Reunion Island for the characterization of NO_2 and SO_2 exhausts from ships, as was already done from manned aircraft (Berg, 2012)

2. METHODOLOGY AND RESULTS

2.1 SWING Activity

2.1.1 Investigations on the ship traffic and legislative aspects

We have first investigated the ship traffic in the main harbor of Reunion Island (Le Port), see the two figures below. The data were purchased at Marine Traffic (https://www.marinetraffic.com) and correspond to year 2013. Figure 1 shows the geographical positions of the ships in the Marine Traffic records, and figure 2 presents a histogram of the ship numbers around the harbor in the year 2013. Figure 1 indicates that the optimal take-off/landing site would be north of the harbor, close to the main ship route. Figure 2 shows on the other hand that the ship traffic is sparse in Reunion Island, with a maximum of 7 ships per day and several periods (especially around August- September) where there were no ships at all.

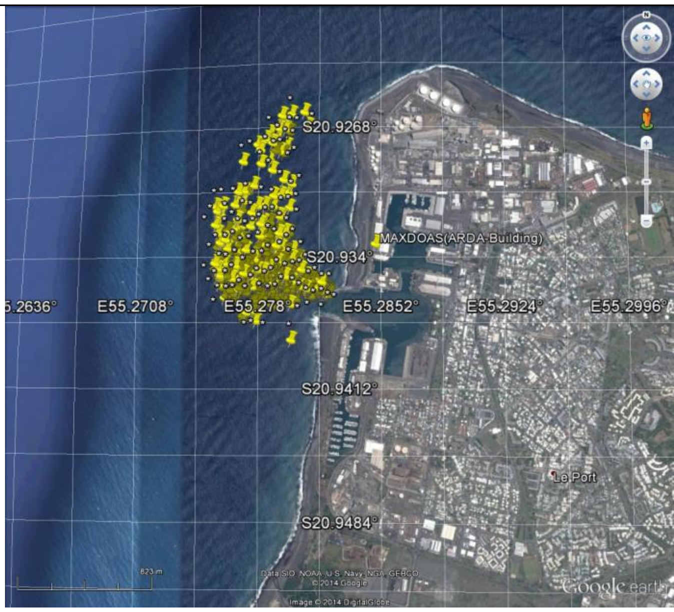


Figure 1. Positions of the boats around the main harbor of Reunion Island (data from Marine Traffic)

Secondly, we have investigated the legislative aspects of flying a UAV platform above Reunion Island. The island is a French territory and therefore French regulations apply. Civilian UAVs commercial operations follow a recent law (published in May 2011) which divide the UAV flight in 4 scenarios. The nominal flight pattern considered so far for SWING (flying at 3 km outside visual range) does not correspond to any of the aforementioned scenarios, whose maximum altitude is 150 m above ground. Therefore, our UAV test flight needed to comply with an even more recent text: 'Démarches pour effectuer des activités particulières en dehors des scénarios' (October 2014)[1]. Note that, at the time of writing this final report, the latest regulations (updated on 20 December 2016) are now available at Noteworthily, a file describing the security of the UAV should have been submitted and the pilot should have some kind of aeronautics license, such as a private pilot license (PPL), or a theoretical gliding license.

[1] At the time of writing this final report, the latest regulations (updated on 20 December 2016) are now available at http://www.developpement-durable.gouv.fr/Demarches-et-formulaires,45926.html

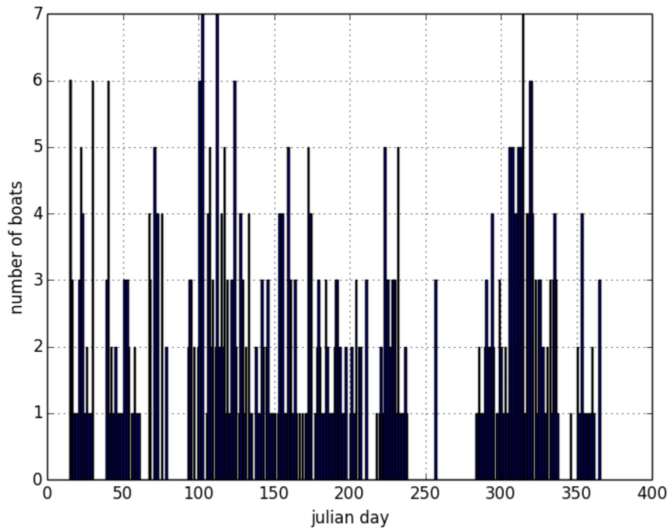


Figure 2. Histogram of the number of Boat around the Reunion harbor (data from Marine Traffic)

Considering the sparse ship traffic in Reunion Island and the difficulty to get the flight approvals (in particular regarding the license of the pilot which is not yet needed in Romania), we have considered difficult to perform the SWING-UAV part of the activity in Reunion Island. Chances were high that the experiment could not be performed in time due to administrative issues, and the sparcity of boats would also imply a longer than expected field campaign to simply ensure a ship presence. Therefore, we have suggested to move this part of the activity in Romania, where the approval problem is already solved by our romanian colleagues. The romanian harbor of Constanta is much more loaded than one of Reunion as can be seen for instance on 24 Nov. 2014 (Figure 3)

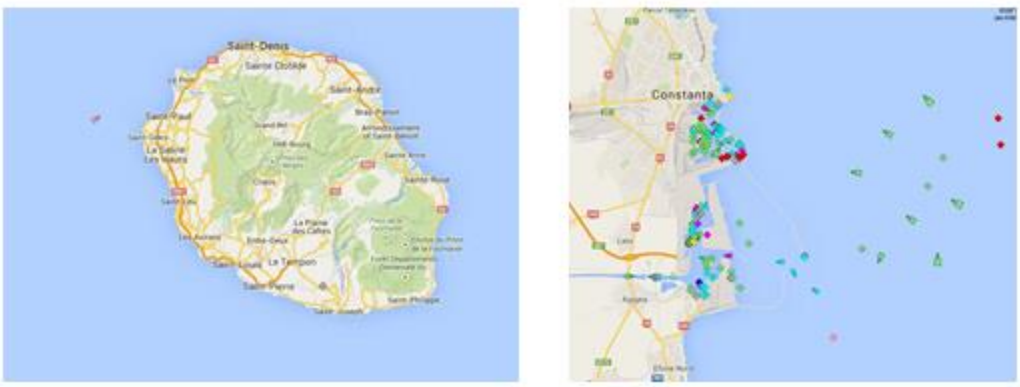


Figure 3. Snapshots of the Ship traffic around Reunion Island and Constanta harbour (24 November 2014)

2.1.2 Participation to the AROMAT Campaign

To test our SWING payload onboard the Reev River Aerospace (RRA) UAV, we have participated in the AROMAT campaign, which was an ESA funded international field campaign coordinated by BIRA. AROMAT took place in Romania in September 2014. The goal of the AROMAT campaign was to test newly developed airborne instruments such as SWING, Uni. Bremen AirMAP (Schönhardt et al., 2015) and the compact NO_2 sonde developed by KNMI (Sluis et al.,2010).

Figure 4 shows the SWING-UAV system before take-off in front of the Turceni power plant (44.66°N, 23.41°E). This power plant burns coal and emits large amounts of NO_x and SO_2 in a rural area. The site is therefore not only particularly interesting for satellite investigation as an isolated source, but also to test UAV-borne instrument due to its location in the countryside.

We performed 4 successful UAV flights with SWING during the AROMAT campaign, on 10 and 11 September 2014. Note that the first test flight on 8 September ended up in a crash due a human mistake. The UAV and the SWING payload could be fixed, but we decided to operate the 4 flights in visual range, meaning that we could sample a smaller area than planned. The maximum altitude we reached was 600 m above ground.

Figure 5 presents a typical fit of the NO_2 spectral signature in a SWING spectrum recorded above Turceni exhaust plume during AROMAT (11 September 2014). The spectral analysis is performed with the DOAS technique (Platt and Stutz, 2008), using the QDOAS software (Danckaert et al., 2014), developed at BIRA. The fit parameters are presented in table I, which includes the interfering absorbers and close-up polynomial. For this DOAS fit, the SNR (understood as the ratio between the slant and its associated error) is 24.

Spectral range	425-490 nm
NO2	Van Daele et al (98)
O4	Hermans
H2O	Harder and Brault (97)
O3	Burrows et al. (99)
Ring	Chance and Spurr (97)
Polynomial order	5

Table I: DOAS settings used for the analysis of the SWING spectra

Figure 4. The UAV at take-off in front of the Turceni power plant

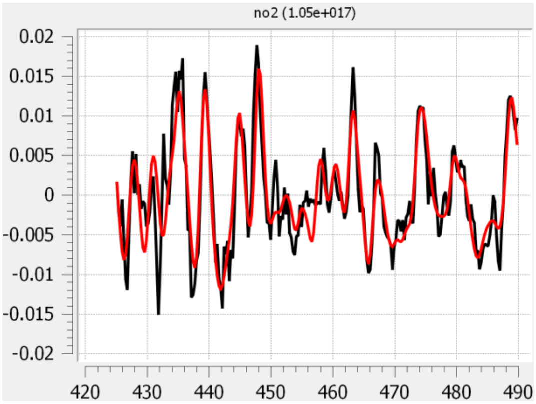


Figure 5. DOAS fit of NO_2 in a SWING spectrum. The measured optical depth (differential and relative to a reference spectrum) appears in black while the red curve is the laboratory NO_2 cross-section.

The output of a DOAS analysis is a Differential Slant Column Density (DSCD), which represents the integrated concentration of the absorber (here NO_2) along the optical path, with respect to the same quantity in the reference spectrum. In our case, the reference spectrum was recorded outside and above the plume through the zenith channel of SWING, the reference spectrum can thus safely be neglected. On the other hand, the optical path needs to be accounted for to derive the vertical column density (VCD), the integrated concentration along the vertical axis, which has a simpler geophysical meaning and can be compared with the measurements performed with other instruments.

We modelled the optical path of the SWING measurements through this work with the DISORT radiative transfer model (Mayer and Kylling, 2005). DISORT was used to calculate so-called Air Mass Factors (AMFs), which represents the enhancement factor between the slant and vertical columns for a given observation. AMFs depend on the geometry (sun position, altitude, line of sight) and on the atmospheric and geophysical parameters (vertical distribution of absorbers and aerosols, ground albedo…). Typical AMF for SWING operated at 500 m AGL are presented in Figure 6.

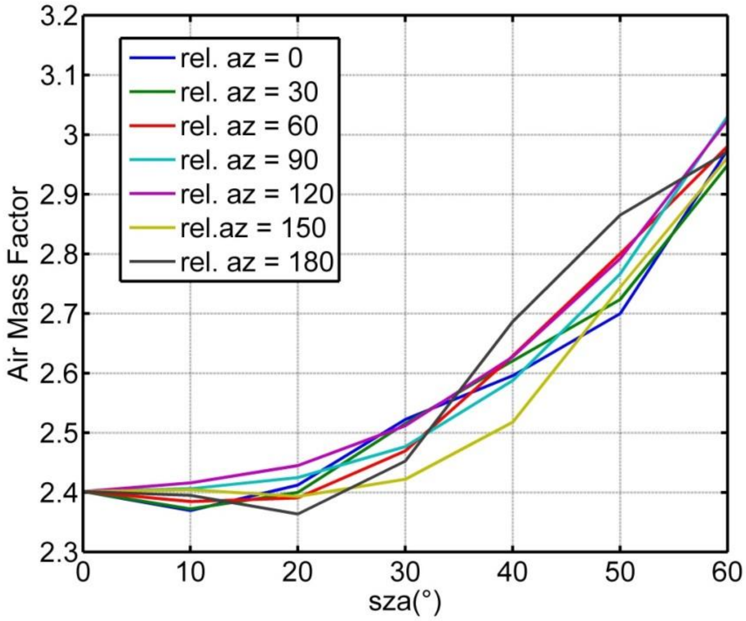


Figure 6. Air Mass Factors as a function of solar zenith angle and relative azimuth for the SWING UAV geometry (flying at 500 m.a.g.l) and the conditions of BLH and aerosol load observed during AROMAT.

Figure 7 presents the SWING measurements of the 1st SWING flight performed on 11 September 2014 (lower panel), together with simultaneous Uni. Bremen AirMAP and Uni. Galati mobile DOAS measurements (upper panel). The three dataset are consistent and indicate a plume pushed westwards by the wind, with maximal NO2 VCDs above 3e16 molec/cm2. Although SWING covered a relatively small area (a circle of ca. 2 km diameter), the measurements were performed at the border of the plume which yield very clear gradients and demonstrate the capability of the technique to investigate NO_2 plumes.

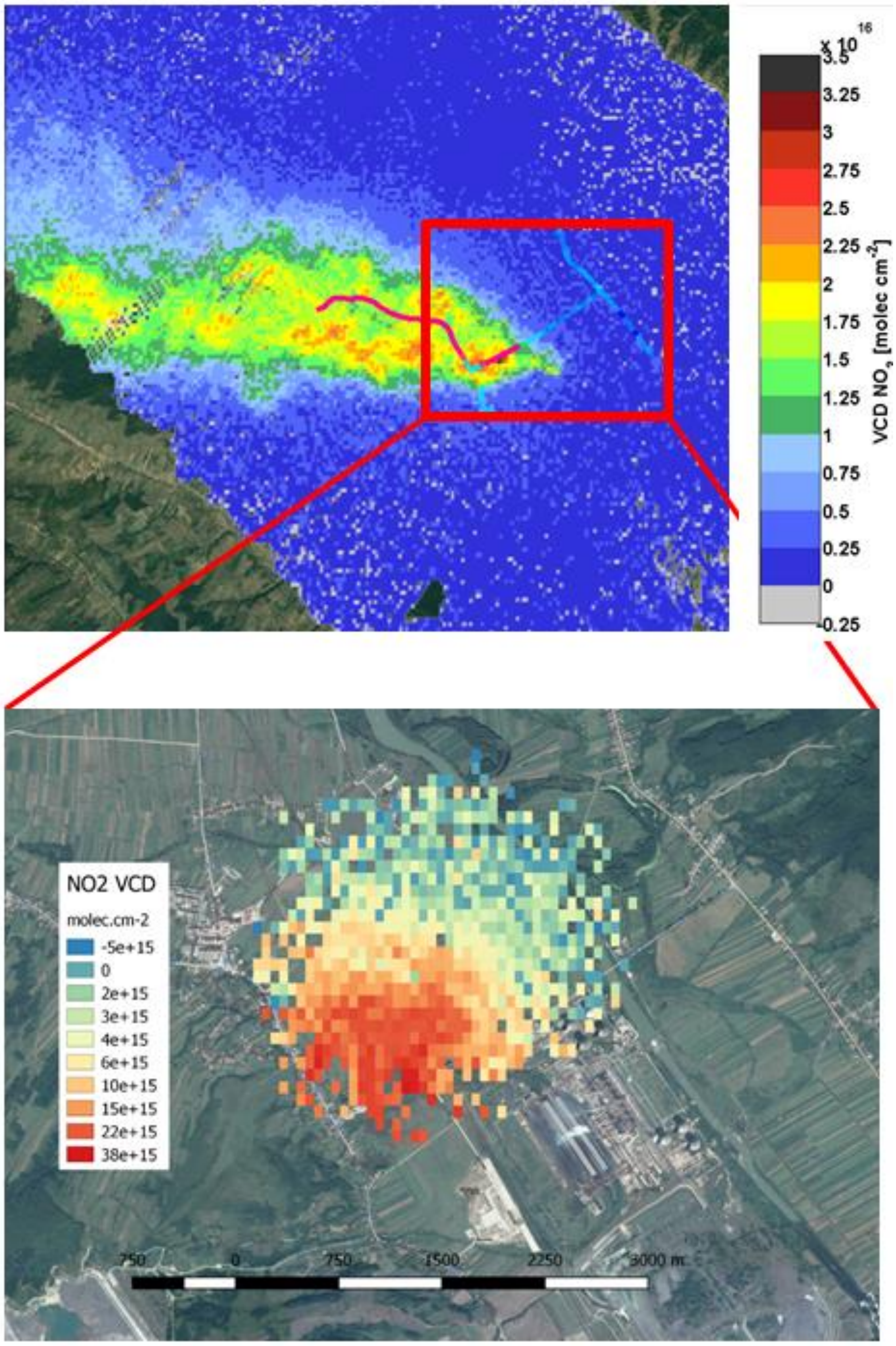


Figure 7. AirMap and Mobile DOAS measurements (upper panel) and simultaneous SWING measurements (below)

2.1.3 Participation to the AROMAT-2 Campaign

The AROMAT-2 campaign was a follow-up of the AROMAT campaign which took place in August 2015, also in Romania and with similar objectives as AROMAT-1, but involving more instruments, both airborne and ground-based. The scope expanded in particular to the measurements of SO_2, which became a target also for the SWING observations. This was made possible with the development of a new version of the SWING instrument, whose main characteristics are summarized in table II.

Spectral range	280-550 nm
Spectral resolution (FWHM)	0.7 nm
Spectrometer	AvaSpec 2048-XL
Optical Fiber	5 cm tube of 800 microns
Instantaneous Field of View	6°
Weight	1.2 kg
Size	33x12x8 cm^3
Power consumption	10 W

Table II: Main characteristics of the SWING instrument (2^{nd} version)

During AROMAT-2 SWING was not operated from the UAV but from the FUB Cessna. It was mounted alongside the AirMAP instrument as can be seen on figure 8. Performing the measurements from this manned aircraft enabled us to cover a much larger area and to improve the intercomparison dataset with the AirMAP instrument, a larger, heavier, and more performant instrument. We performed 4 succesful SWING flights on 28, 30, and 31 August 2015, we show a selection of the dataset hereafter.

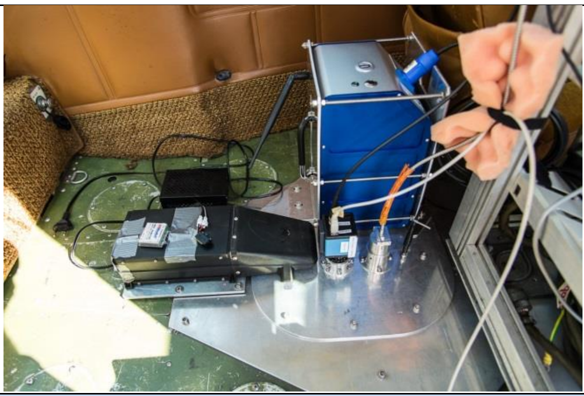


Figure 8. The SWING instrument installed in the Cessna during AROMAT-2, alongside the SO_2 camera, AirMap optical input, and a nadir-only Avantes spectrometer

Figure 9 presents typical DOAS fits of SO_2 (left panel) and NO_2 (right panel) on a spectrum recorded from the Cessna on 28 August 2015 above the Turceni power plant exhaust plume. For this analysis, the SNR (understood as the ratio between the slant column and its error) is 25 for the SO_2 fit and 56 for the NO_2 fit. Note that the SNR has doubled compared to the first version of SWING operated during AROMAT-1 (see previous section) thanks to the better spectrometer and larger optical fiber. This SNR also indicates the typical 1-sigma detection limit for SO_2 and NO_2, respectively 2e^{16} molec.cm^{-2} and 1.8e^{15} molec.cm^{-2}.

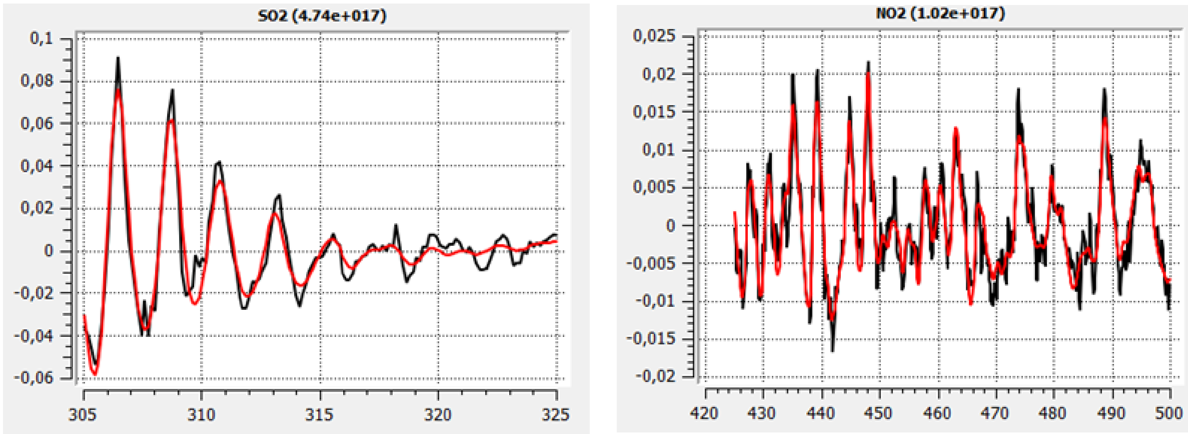


Figure 9. Typical DOAS fits of SO_2 (left panel) and NO_2 (right panel) of SWING spectra from the Cessna flight above the Turceni power plant (9h59 UT, 28 August 2015)

Figure 10 and 11 present the SWING measurements of NO_2 and SO_2, respectively, performed above the Jiu Valley on 28 August 2015. The NO_2 and SO_2 fields exhibit similar spatial patterns with a clear source for both species in the power plant of Turceni, leading to a NO_2 and SO_2 plume going in the North West direction. The largest SO_2 columns are found inside the plume and reach 7e17 molec.cm^{-2} while the maximum NO_2 is around 8e16 molec.cm^{-2}. Interestingly, the maximum for both species is not observed exactly at the same position: the maximum SO2 lies just above the power plant whereas the maximum NO2 is 2.4 km downwind. Although this finding should be taken with care considering the uncertainties, it could be expected from known tropospheric chemistry (NO_x are emitted as NO and are oxidized to NO_2 in a second step).

Three areas with elevated columns on the east of the Turceni plume are also visible on both the NO_2 and SO_2 maps. For both species, the three areas exhibit decreasing columns from North to South. They are probably linked with the power plants downstream of the Jiu River compared to Turceni, namely Isalnita and Craiova II which were not covered by the flight.

Figure 12 presents the intercomparison between SWING and AirMAP for the SO_2 measurements above the Jiu Valley on 28 August 2015. Most of the observed structures in the SO_2 DSCD time series are visible in both dataset. The correlation coefficient is around 0.85, and the slope between the two instruments is between unity and 1.1. SWING time series appear noisier, which is related to the smaller detector and the lack of thermal stabilization of the instrument. Note also that at the beginning of the time series, negative SWING DSCDs are observed which are probably related to instabilities in the UV range of the Avantes spectrometer, an effect which was also observed with the Mobile-DOAS measurements performed from the ground with a similar spectrometer.

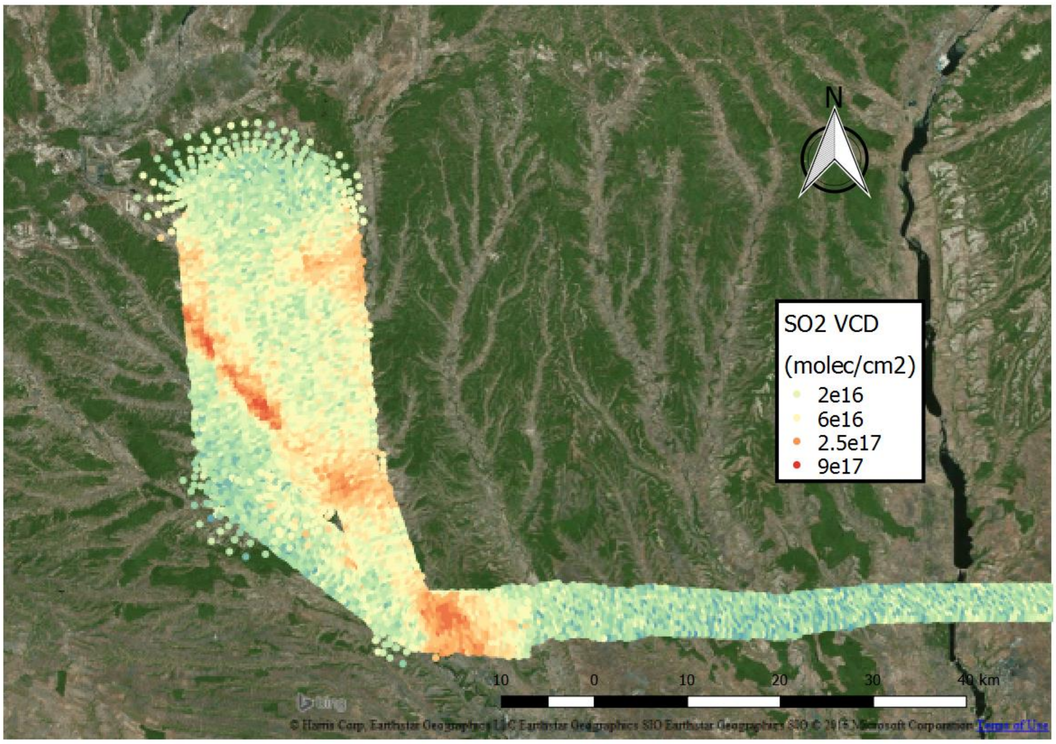


Figure 10. Horizontal distribution of SO_2 as measured by SWING in the Jiu Valley on 28 Aug 2015

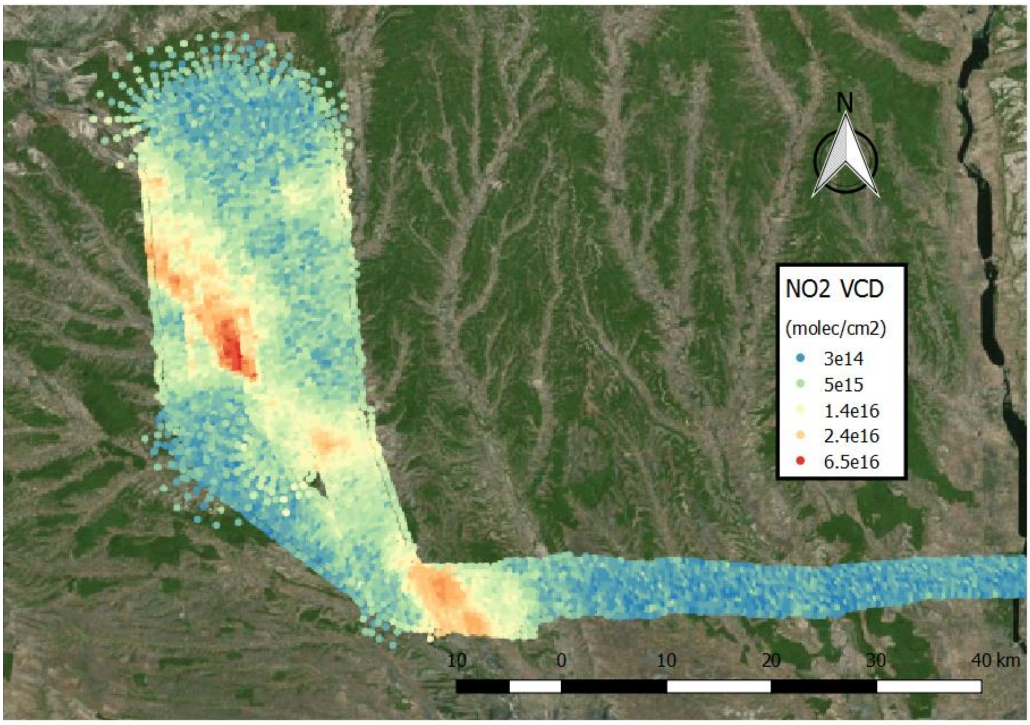


Figure 11. Horizontal distribution of NO_2 VCD as measured by SWING in the Jiu Valley on 28 Aug 2015

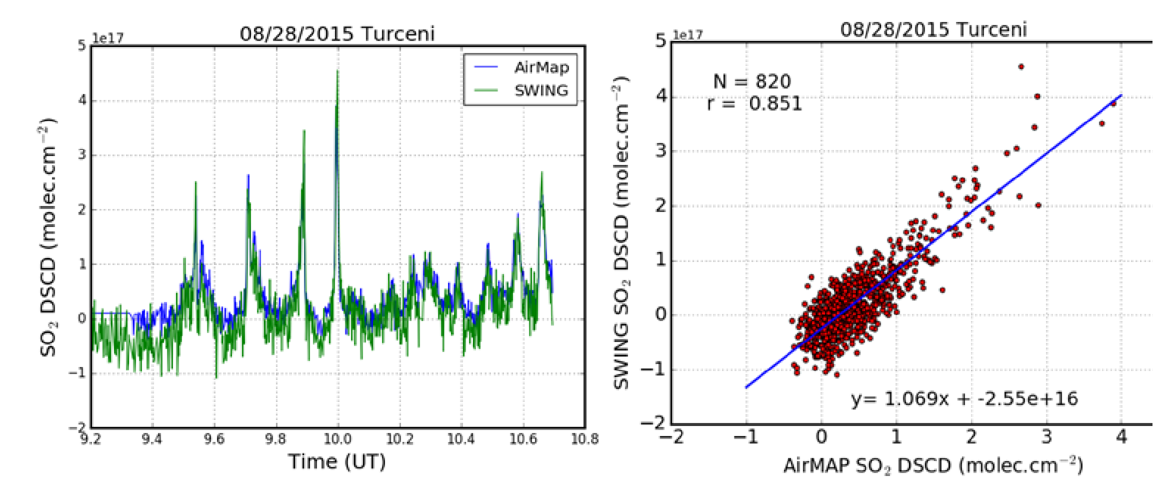


Figure 12 Intercomparison of SWING and AirMAP SO_2 DSCDs above Turceni (28 August 2015)

Figure 13 presents the three overpasses performed on the morning of the Monday flight (31 August 2015). The NO_2 columns are up to 3.3e16 molec.cm^{-2} and show clear spatial gradients. The largest observed NO_2 columns are in the city center, most probably related to traffic emissions of NO_x. Note that the NO_2 columns are increasing and elevated columns seem to move northwards with time during the three overpasses, which can be related to the wind blowing from the south in the second and third overpasses.

Figure 14 presents the SWING NO_2 measurements performed on the afternoon flight of Monday 31 August 2015. The NO_2 columns are lower (2.5e^{16} molec.cm^{-2}) than in the morning, but clear spatial gradients are still clearly visible and show a NO_2 plume blown from the city center to the North West direction. The upwind part of the city appears very clean with background level at or below the detection limit (2e^{15} molec.cm^{-2}).

Figure 15 presents the intercomparison between SWING and AirMAP for NO_2 and for the two flights of Monday 31 August 2015 above Bucharest. The agreement is even better than for SO_2 with similar slopes but correlation coefficients above 0.9. SWING DSCDs are still noisier but no instability can be observed at the beginning of the time series, this pattern seeming to be only present in the UV. Note that the difference between the two flights can be at least partly attributed to the differences in sampled NO_2 fields, which present a lower dynamic range in the afternoon flight.

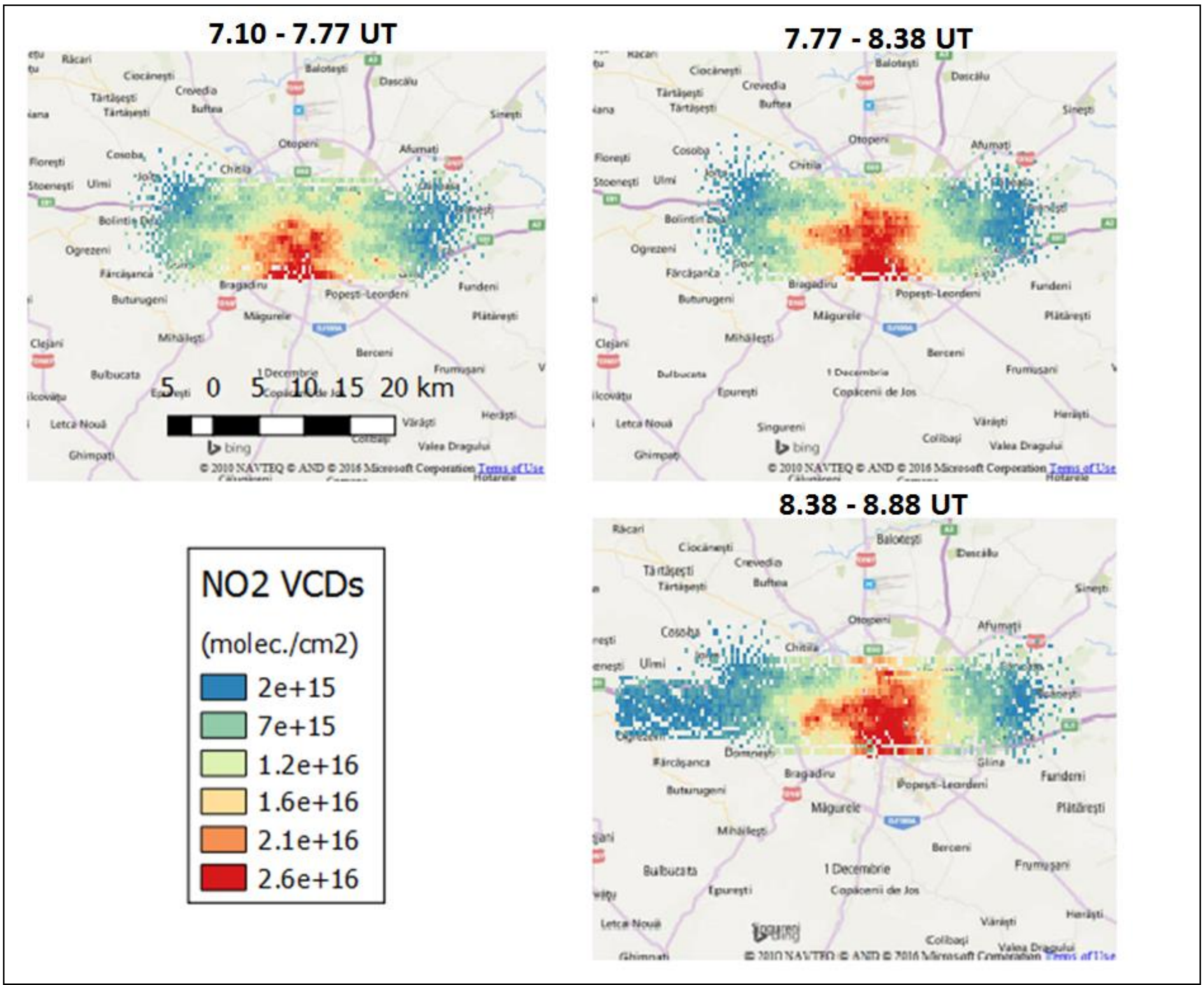


Figure 13 Swing measurements of NO_2 above Bucharest on 31 August 2015 (AM)

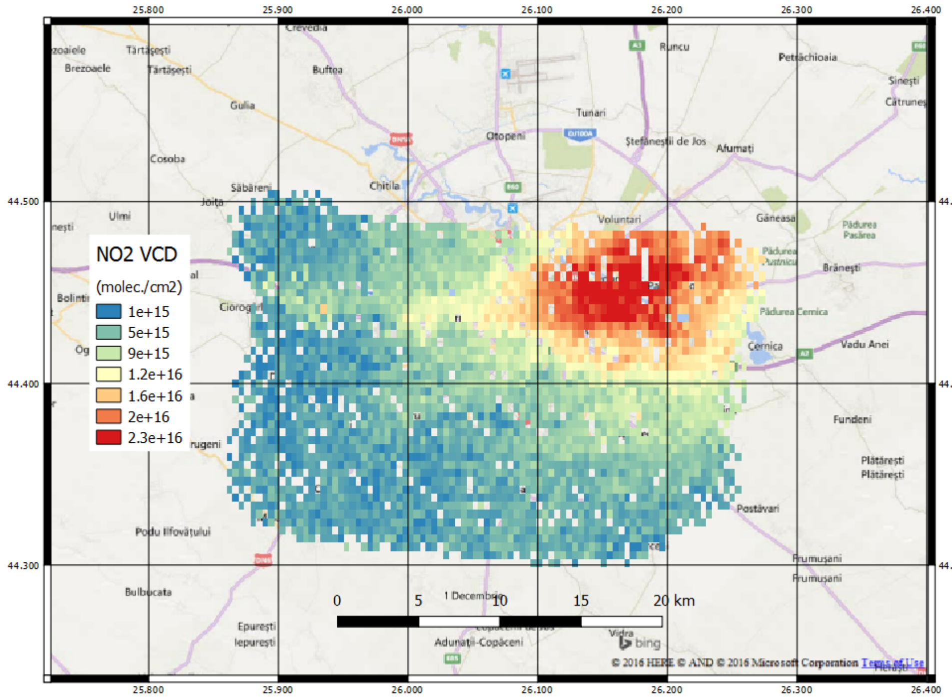


Figure 14 Swing measurements of NO2 above Bucharest on 31 August 2015 (PM flight, first overpass)

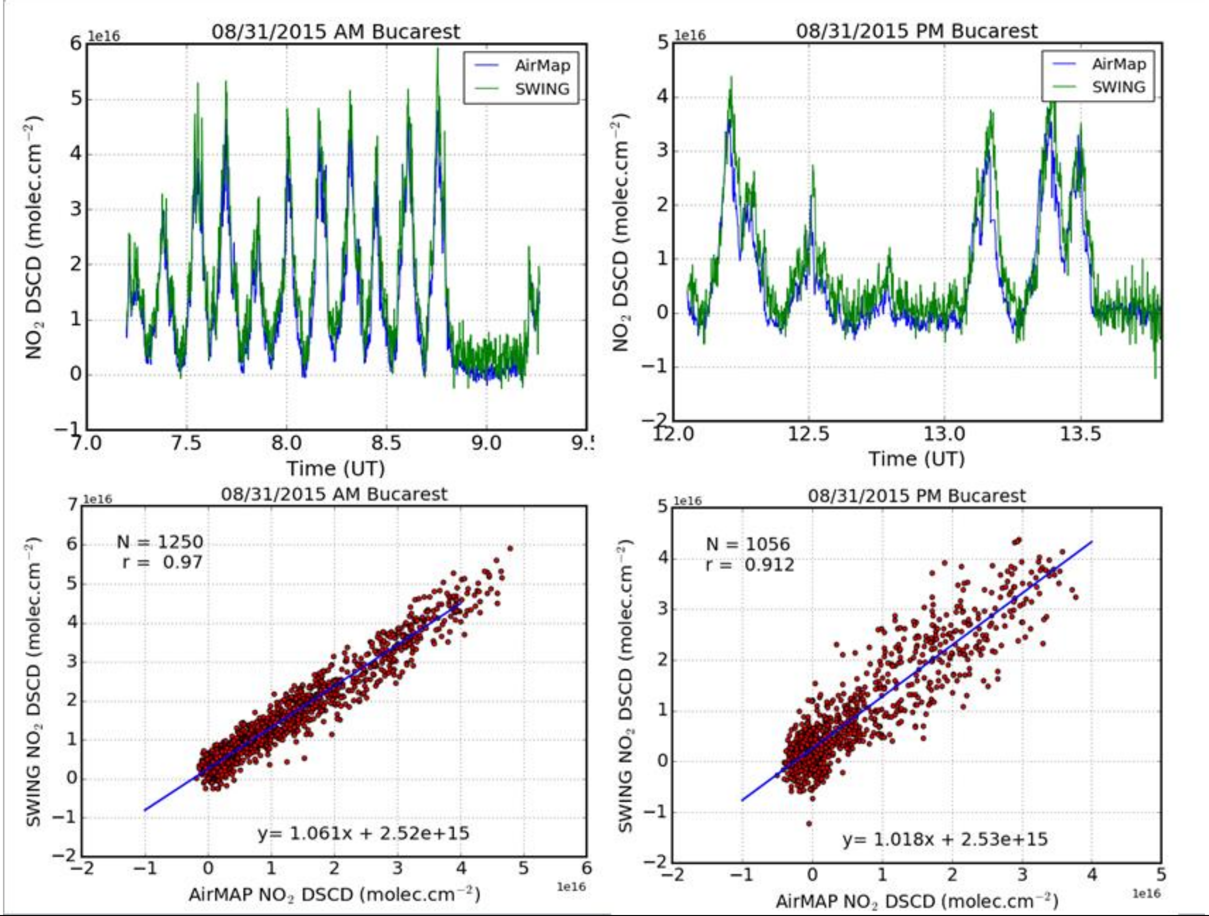


Figure 15 Intercomparison of SWING and AirMAP NO_2 DSCDs for the two Monday flights of AROMAT-2 above Bucharest (31 August 2015)

2.1.4 Participation to the AROMAPEX Campaign

The AROMAPEX campaign took place in Berlin in April 2016. It consisted in operating 4 airborne imagers from two different aircraft. The FUB Cessna was carrying AirMAP, SWING, and SpectroLite (a satellite instrument developed by TNO and TU Delft) and the DLR Do-228 was carrying the APEX instrument (Popp et al., 2012).

The SWING data analysis scheme for the AROMAPEX data is similar to the one presented for AROMAT 1 and 2, but we made use of the APEX albedo product. Note that the afternoon APEX albedos measurements were used for both flights due to a missing flight line in the morning APEX flight. Considering that the ground albedo is amongst the main source of uncertainty in nadir airborne data, the SWING VCDs retrieved from the AROMAPEX data should be more realistic than the ones retrieved from AROMAT-2.

Figure 16 presents the NO_2 VCD distribution measured with SWING during the morning flight of the AROMAPEX campaign. The NO2 spatial distribution is clearly dominated by the exhaust plume of a power plant located in the North West of the city (Reuter West CHP, 52.54°N, 13.24°N). Maximum NO2 VCDs are around 2.6 molec.cm^{-2} close the power plant. Note that as observed during AROMAT-2, this maximum is not located above the plant but somewhat downwind, 1.5 km in this case. The exhaust plume of the power plant is blown towards the east above the northern part of the city. A second plume is visible to the south of the large one, which seems to originate from a location close to the Olympic Stadium (52.51°N, 13.24°E), we have not identified this source.

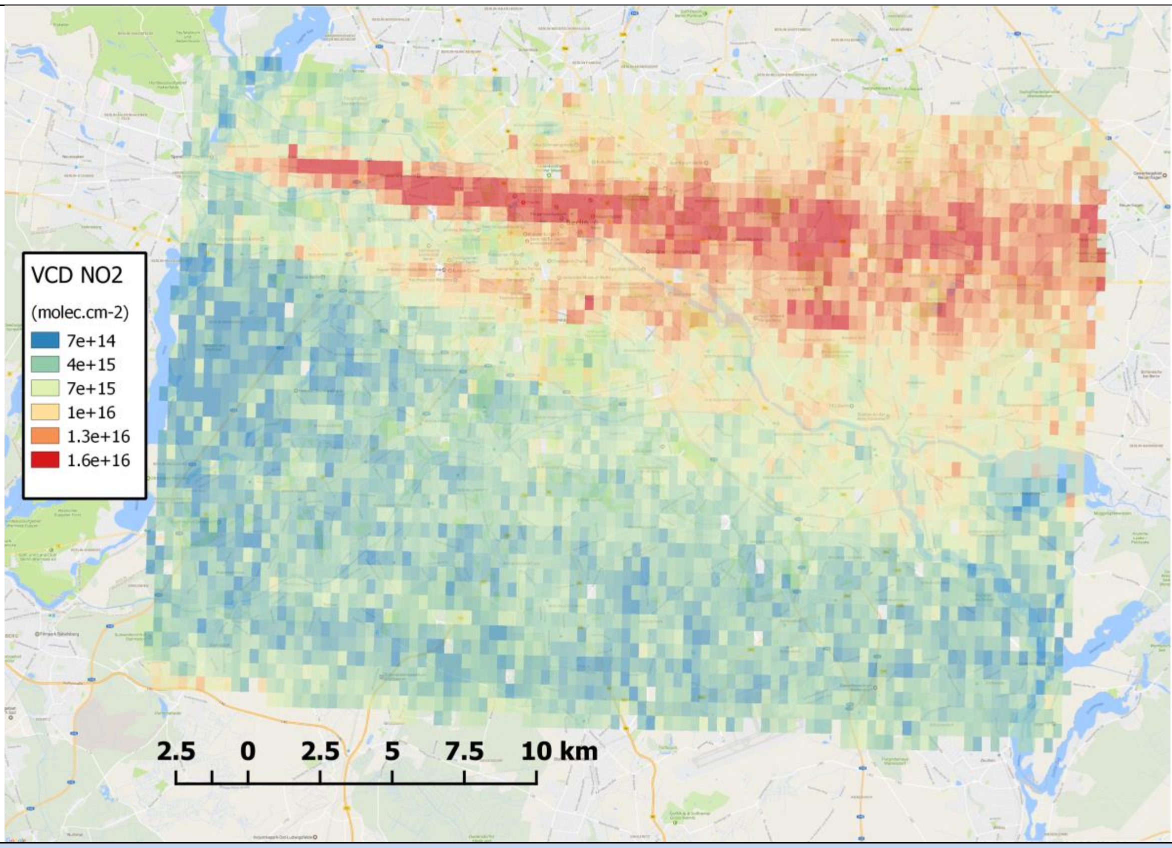


Figure 16 SWING measurements of NO_2 above Berlin (21 April 2016, AM flight)

2.1.5 Test flight with the Mumm BN2 above Antwerp

On 28 July 2016, we performed a test flight above Antwerp Harbor and the Scheldt river from the Mumm BN-2.

Swing could be quickly integrated in the plane and looked through an open nadir port in the back of the plane (see figure 17).

The test flight took place between 14h30 and 15h20 UT in overcast sky conditions (see figure 19). Figure 18 shows the tracks of the Mumm BN-2, with the ship positions: from Antwerp airport it went along the river to above the *Verdronken Land Van Saeftinghe* and back.

Figure 17. The Mumm BN-2 in Antwerp Airport and SWING integration on-board (28 July 2016)

The SWING instrument performed well during the test flight. The SNR was not optimal due to the cloud cover, but we could still clearly see some NO_2 hotspots.

Figure 20 presents the time series of the NO2 DSCDs during the test flight. The three maxima (around UT 14:31:37, 14:57:29 and 15:12:11) respectively correspond to the harbour of Antwerp, north of Terneuzen, and back in Antwerpen. In Terneuze, the reports indicate that we flew above a ship (IDUNA) but it could also be the DOW plant beside.

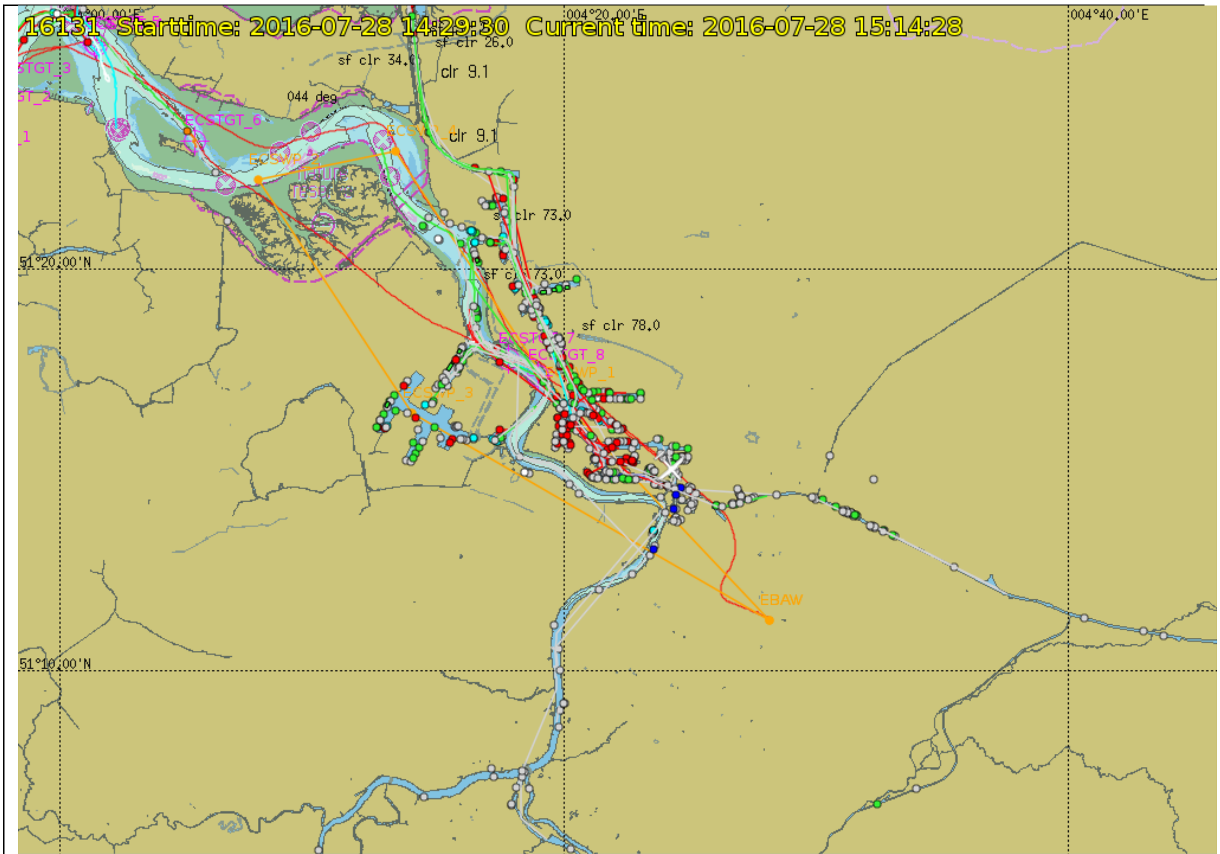


Figure 18. Map of the BN-2 SWING test flight on 28 July 2016

Figure 19. Picture taken from the BN2 on 28 July 2016, showing the overcast conditions.

Overall, the first test of SWING in the Mumm BN-2 was successful, but did not enable us to do a NO_2 map because of the impossibility to access the altitude information recorded in the plane. These parameters (Yaw, Pitch, Roll) are actually recorded in the Mumm BN2 but as they are not used by any of the routine instruments, they are not given as standard outputs. Note that it would have been possible to extract the attitude angles by paying the company in charge of the mission system, but this was not considered useful due to the bad weather conditions encountered during the short test flight above a small number of ships.

We believe that this BN2 experiment was promising and that another test flight should be performed in good weather conditions and recording the attitude angles directly on the SWING PC through an additional interface with the ARINC system. This was not done in the second semester of 2016 because of another campaign involving in-situ systems and thus different flight pattern.

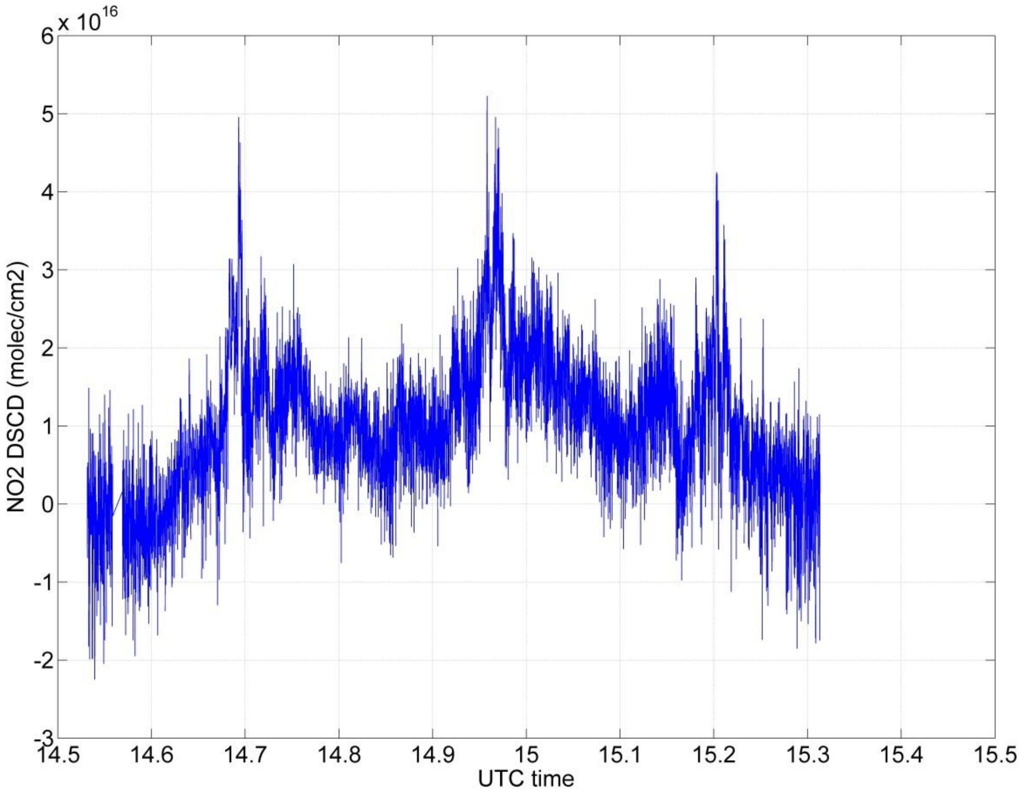


Figure 20. Time series of the NO_2 DSCDs measured with SWING from the BN2 on 28 July 2016

2.1.6 Reconnaissance and Simulations for a UAV flight around Constanta

In parallel with the manned aircraft airborne campaigns described above, we carried on the investigations for a SWING-UAV test flight above ships on the Black Sea, around Constanta harbour.

In April 2015, we did a reconnaissance mission around Constanta and Cape Midia. From Constanta, we could see 16 boats. Our colleagues from Brussels could simultaneously check the real time ship activity on MarineTraffic.com and saw 16 boats, 4 of them moving.

From Cape Midia, there were fewer boats, but still 6 in visual range. These boats were most probably the ones going to/from and waiting around the Petromidia refinery (see figure 21). The port of Midia (the port of the refinery) is a satellite port of the main port of Constanta.

From a logistic point of view, the military base in Capu Midia seems an easy place to take-off. The place is interesting for the boat leaving the port of Midia (7 km away) as well as for the refinery itself which is the largest one in Romania. However, the main ship road (Constanta to Odessa) is a bit far away from the shore (15 to 20 km) in Cape Midia.

Taking off from inside Constanta urban area did not appear realistic. An option might be to take off from the beach south of Constanta, between *Eforie Sud* and *Costineti* (Take off 2, see figure 22). The place is interesting for the ships leaving Constanta harbor (10 km away). Due to the harbor configuration, even the boats coming from Odessa passes nearby (see map). However, we did not see this place physically and on Google Earth it seems a beach and may be crowded in June/July.

Figure 21. Pictures taken in Cape Midia during the reconnaissance mission in April 2015

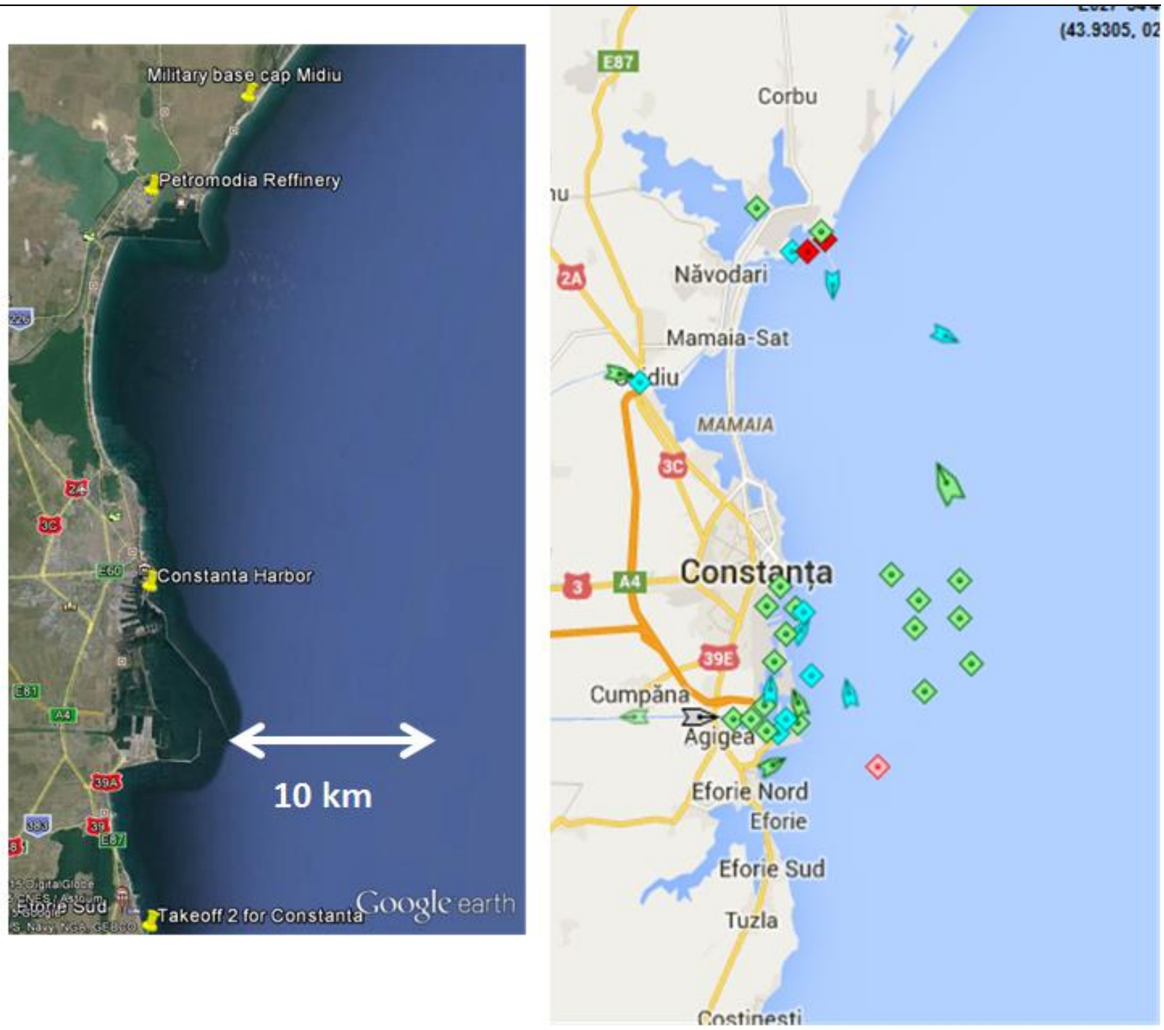
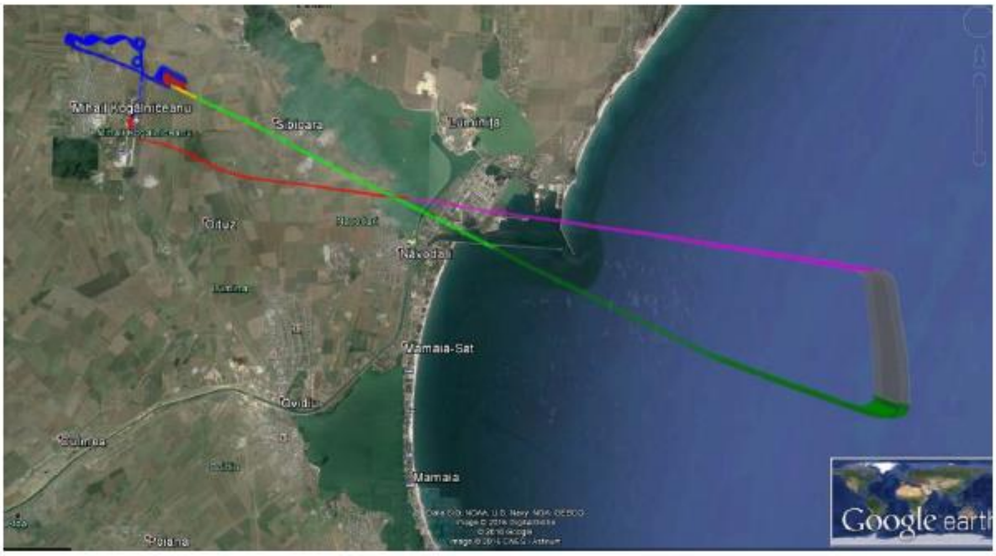


Figure 22. Maps of the Constanta area with the 4 locations mentionned (left), and ship traffic on 8 April 2015 (right)

Following this reconnaissance mission, our colleagues from Reev River Aerospace (manufacturer of the UAV) performed simulations of UAV flights to check the feasibility of a flight at a relatively high altitude (2 km) for ship emission monitoring, taking into account that our new SWING payload was 300 g heavier than the first version.

Figure 23 shows an example of flight simulations performed by our RRA colleagues. This is *hardware in the loop* simulation meaning that the UAV is hooked up to a 6 degrees of freedom simulator and the autopilot flies the entire mission programmed in it.

Actual simulated-flown map:



TRAJECTORY 5:

Altitude as a function of time:

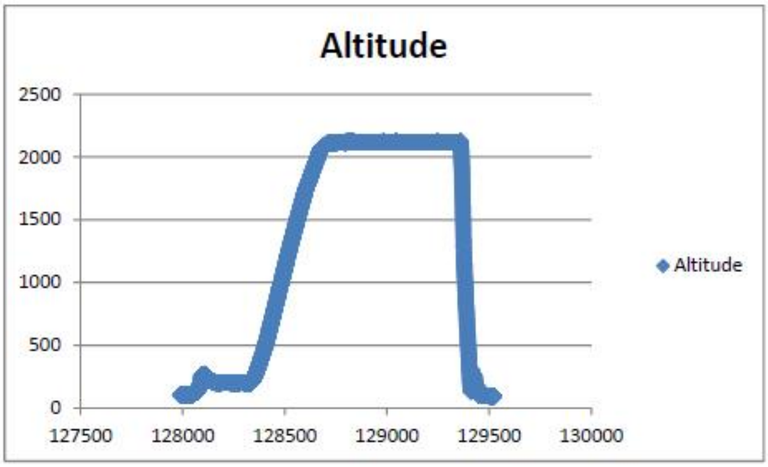


Figure 23. Simulation of a SWING-UAV experiment above Cape Midia

From these simulation exercises, it appeared that flying up to 20 km away from the coast was doable but that the typical mapping pattern in parallel flight lines would be possible only closer to the shore. The main ship lines (Constanta-Odessa) is too far to be mapped taking off from the shore. This reduced the practical utilities of measurements with such a UAV in this area. It also appeared that new batteries would be needed, as well as a stronger and heavier electrical motor, and that the batteries should be moved in front, modifying the central structure. At the time of writing this report, the new batteries had been ordered and we were waiting for the other UAV modifications.

2.2 Aircore Activity

2.2.1 Introduction

To perform the calibration of the TCCON measurements to WMO standards, TCCON requires an in-situ measurement of the vertical profiles of the targeted gases (CO2, CH4, CO) above the TCCON site with a sampler that is itself calibrated to the WMO standards. As TCCON measures total columns of these gases, the higher the altitude range of the in-situ vertical profiles, the more precise the calibration of the total columns will be. Up to now, TCCON data for most sites have been calibrated by a spiralling aircraft in-situ measurement above the site, with a PICARRO instrument onboard. Such a deployment is expensive, especially if it has to be done on a regular basis and not really feasible at remote locations like Ile de La Réunion. The in-situ measurement with an AirCore [Karion et al., 2010] launched at the site with a balloon that brings it up to 30 km altitude – is a very good alternative: it has the advantages of being less expensive, more easy to perform on a regular basis and at the same time providing a vertical profile over a more extended altitude range, but the disadvantages are that one must recover the AirCore payload shortly after its landing which is not always easy, especially not on a small and very mountainous island as Ile de La Réunion. Moreover, the AirCore technique is not yet a fully certified technique: the AirCore preparation, as well as the analysis of its sampled airmass with a PICARRO instrument after its recovery, still require great care and are not yet fully mastered.

Therefore, in this project, we have collaborated with the team of Prof. H. Chen from the Rijksuniversiteit Groningen (RUG, the Netherlands) for the provision and handling of the AirCore, and with the team of F. Mingireanu from the Reev River Aerospace Company of Romania for the development of a recoverable platform to carry the AirCore to 30 km altitude and to bring it back to a pre-defined landing site.

The design and development of the recoverable platform has been done by F. Miringeanu, based on inputs and advices from H. Chen and ourselves (M. De Mazière, F. Desmet, M.K. Sha).

2.2.2 First test campaign at Sodankyla

The initial idea has been to develop a telecommanded parafoil system to carry the AirCore – brought to 30 km altitude by a balloon and descending with remote control to the landing site.

The system has been tested during a measurement campaign at Sodankyla, from July 14 to 19, 2014.

The AirCore that was deployed in Sodankylä had been optimized by H. Chen and his team for the collection of profiles for TCCON calibration (total tube length: 150 m, tropospheric part: 95 m, diameter 4 mm; stratospheric part 53 m, diameter 3.2 mm). The intention is to use this same AirCore tube over Reunion Island.

Figure 24 shows the system upon launch, and Figure 25 shows the gondola that carries the aircore and includes the navigation system.

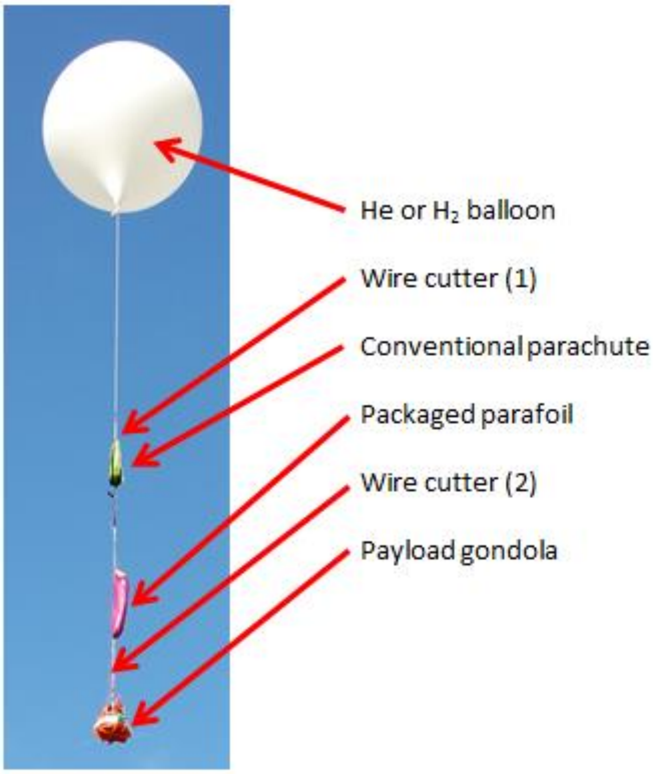


Figure 24. Balloon launching train with the payload gondola during the first test campaign in Sodankyla

Figure 25. Payload gondola resting on a chair just before its launch

None of the test flights during this campaign was completely successful. The main problem that arose was that the unfolding of the parafoil failed and the strings that carried the gondola got twisted. Nevertheless, the campaign flights enabled the testing of subsystems (e.g., autopilot, remote control, aircore performance). A detailed technical report is attached in Annex 1.

2.2.3 Second test campaign at Sodankyla

After the failure of the first test campaign in Sodankyla, F. Miringeanu decided to develop another platform to carry the AirCore, namely a telecommanded flying wing, taken to 30 km altitude by a balloon and then gliding down to the landing site. This concept has been tested during the second campaign that was organised by H. Chen and Tuomas Laurila (Finnish Meteorological Institute, (FMI)) and that was co-funded by an InGoS TNA (Trans-National Access) grant. The campaign included comparisons between several AirCores (from Univ. Bern, RUG, and NOAA) and additional PICARRO in-situ measurements in the lowest layers of the atmosphere from a helicopter. BIRA also installed and operated a Bruker EM27/SUN FTIR spectrometer during the campaign, for testing the performances of this spectrometer compared to the standard Bruker 125HR FTIR spectrometer operated by FMI at Sodankyla.

The campaign took place from 19 to 25 June, 2015.

Two flying wings have been developed for this campaign: a small one (1.4 m wingspan), that was launched and recovered successfully thrice, but without the AirCore payload. The ceiling altitude of the first flight was 700 m, the second flight was 10.38 km with a horizontal distance of 18.7 km, and the third flight was 26.02 km with a horizontal distance of 32.4 km before the balloon was cut-off. A second, larger and heavier one (1.75 m wingspan & 6.95 kg weight), that was designed to carry an AirCore, but that could not be launched due to air traffic restrictions.

Figures 26 to 28 show both flying wings, the aircore package and the EM27/SUN spectrometer.

Figure 26. (left) The large wing in the front, the small wing in the back. The central cylindrical box in the large wing contains the aircore and landing parachute; the nose contains the GPS, all electronics and radiosystem. (right) the small wing with GPS, all electronics and radiosystem in the central position. This wing is for test purposes only; there is no space provided for the payload.

Figure 27 The aircore package before launch, showing the winded tube, the electronics box in the center and the inlet valve at the rear (left). Launch of the small wing (right).

Figure 28. The compact Bruker EM27/SUN installed at Sodankyla, close to the TCCON FTIR spectrometer.

A technical report about the second campaign is attached in Annex 2 and 3.

2.2.4 Summary of results

The initial goal of the project was to design and demonstrate a platform for an AirCore for being released at about 30 km altitude, for sampling an in-situ vertical profile between the release altitude (~30 km) and the ground, and for landing at a pre-determined site. The final objective was to use this platform with AirCore to calibrate our TCCON FTIR spectrometer data at Ile de La Réunion.

Despite the fact that several options to deploy such a platform (parafoil, flying wing) have been designed and tested, none of the options showed appropriate performances.

However, as an alternative means to calibrate the TCCON instrument, we have verified the performance of a calibrated Bruker EM27/SUN spectrometer, both at Sodankyla and at Reunion Island, and these tests have provided conclusive results. The result of the first campaign at Ile de La Réunion has been presented at the annual TCCON meeting in June 2016, a technical report on the preliminary results of this campaign is attached in Annex 3. However, the results of the Sodankyla measurements and the ongoing second campaign at Ile de La Réunion will be published and presented at the next TCCON annual meeting in 2017, and should lead to the official recognition of the calibration of our TCCON experiment at Ile de La Réunion.

Note that the tests at Réunion Island have been performed during two campaigns, one from 21 October to 5 November 2015 and the second one starting from 24 November 2016 and is currently ongoing during which a Bruker EM27/SUN spectrometer lent by KIT has been operated next to our TCCON Bruker IFS 125HR spectrometer. These campaigns have been supported by an ACTRIS TNA grant and by the Belgian support to the participation of BIRA-IASB to the atmospheric component of the ICOS Research Infrastructure (Ministerial Decree FR/35/IC1).

3. DISSEMINATION AND VALORISATION

Regarding the SWING activity, the work has been documented in particular in the ESA documents related to the AROMAT campaigns (Campaign Implementation Plans, Data Acquisition Report, and Final report for AROMAT-1, AROMAT-2, and AROMAPEX). Note that the SWING data will be publically available, alongside all the measurements from the other instruments on the ESA campaigns database, from March 2017.

The work with SWING and the AROMAT/AROMAPEX campaigns has been presented in several international conferences and workshop:

- Merlaud, A., Tack, F., Constantin, D.-E., Fayt, C., Maes, J., Mingireanu, F., Van Roozendael, M. (2014). Small Whiskbroom Imager for atmospheric compositioN monitorinG (SWING) from an Unmanned Aerial Vehicle (UAV): status and perspectives, Poster presentation at the European Geoscience Union General Assembly, 2014
- Merlaud, A., Tack, F., Constantin, D., Fayt, C., Maes, J., Mingireanu, F., Van Roozendael, M. (2015). Small Whiskbroom Imager for atmospheric compositioN monitorinG (SWING) from an Unmanned Aerial Vehicle (UAV): Results from the 2014 AROMAT campaign. Poster presentation at the European Geoscience Union General Assembly, 2015
- Merlaud A., Tack F., Constantin D., Fayt C., Maes J., Mingireanu F., Mocanu I., Meier A., Richter A., Georgescu. L., Van Roozendael M. , Small Whiskbroom Imager for atmospheric composition monitoring (SWING) from an Unmanned Aerial Vehicle (UAV): Results from the 2014 AROMAT campaign, oral presentation at the 7th DOAS workshop
- Merlaud, A., Tack, F., Van Roozendael, M., Iordache, D., Meuleman, K., Meier A., Richter A., Schonardt A., Burrows, J. T. Rhutz, C.Lindemann, Vlemmix, T., Ge, X., de Goeij, B., van der Wal, Ardelean M., Boscornea A., Schuettemeyer D. and the AROMAPEX team, Oral presentation at the 5TH Workshop on Atmospheric Composition Validation and Evolution, Frascati, October 2016, *Intercomparison of Airborne Imaging DOAS Systems for Mapping of Tropospheric NO2 (AROMAPEX Campaign, Berlin, April 2016)*

Regarding the AirCOre activities:

- Desmet, F., B. Langerock, C. Vigouroux, N. Kumps, C. Hermans, M. De Mazière, J.-M. Metzger, J.-P. Cammas, The Fourier Transform InfraRed (FTIR) measurements at La Réunion - Maido & Results of the ACTRIS TNA missions, oral presentation by M. De Mazière at the ACTRIS 4th General Assembly, Clermont-Ferrand, June 10-13, 2014.
- Desmet, Filip, Christian Hermans, Nicolas Kumps, Francis Scolas, Corinne Vigouroux, Bavo Langerock, Martine De Mazière, Jean-Marc Metzger, Jean-Pierre Cammas, Reunion Island site report, oral presentation by F. Desmet at the NDACC IRWG Annual meeting, Bad Sulza, Germany, May 12-15, 2014.

- Desmet, Filip, Christian Hermans, Martine De Mazière, Huilin Chen, Bert Kers, Marcel de Vries, Rigel Kivi, Pauli Heikinnen, Juha Hatakka, Tuomas Laurila, Florin Mingireanu, Aurel Chirila: Greenhouse Gas Measurements at La Réunion in the frame of TCCON and ICOS (oral presentation), ICOS Science Conference, Brussels, Belgium, September 24 2014.
- De Mazière, Martine, Filip Desmet, Christian Hermans, Jean-Marc Metzger, Jean-Pierre Cammas: The Belgian Institute for Space Aeronomy and ICOS (oral presentation), ICOS Belgium Study Day, Antwerp, Belgium, April 22 2015.
- Chen, H., R. Kivi, B. Kers, P. Heikkinen, J. Hatakka, T. Laurila, T. Newberger, J. Higgs, P. Tans, Martine De Mazière, Mahesh Kumar Sha: AirCore, aircraft, and FTS measurement campaigns at Sodankylä, oral presentation by H. Chen at the INGOS Meeting and Science Conference 2015, Utrecht, 21 – 24 Sep 2015.
- Sha, Mahesh Kumar, Martine De Mazière, Christian Hermans, Michel Ramonet, Jean-Marc Metzger, Jean-Pierre Cammas: Ile de la Réunion (21° S, 55° E) – ICOS site, An unique atmospheric observatory in the Indian Ocean, oral presentation at the Second ICOS Belgium Consortium Study Day, Gembloux, Belgium, 4 May 2016.
- Sha, Mahesh Kumar, Martine De Mazière, Jean-Marc Metzger, Jean-Pierre Cammas, Matthias Frey, Matthäus Kiel, Frank Hase: The use of the portable EM27/SUN FTIR spectrometer as a travel standard for the TCCON, oral presentation by M. K. Sha at the annual joint NDACC-IRWG & TCCON meeting 2016, Jeju, South Korea, May 30 – June 3, 2016.
- Sha, Mahesh Kumar, Bavo Langerock, Corinne Vigouroux, Christian Hermans, Nicolas Kumps, Francis Scolas, Minqiang Zhou, Martine De Mazière, Jean-Marc Metzger, Valentin Duflot, Jean-Pierre Cammas: Ile de La Réunion Site Report, oral presentation by M. K. Sha at the annual joint NDACC-IRWG & TCCON meeting 2016, Jeju, South Korea, May 30 – June 3, 2016.

4. PERSPECTIVES

Regarding the SWING activity, we are currently developing at BIRA-IASB an improved version of the SWING instrument that will be installed in a plane from our colleagues of INCAS, in the framework of an ESA project (RAMOS). The first airborne tests are scheduled in September 2017. We are evaluating the AROMAT database which offers unique possibility in term of evaluating instrumental performance, in particular due to the airborne intercomparison and the ground-based measurements. We also consider performing another test flight above the North Sea in better weather conditions with the Mumm BN-2 in 2017.

Regarding the AirCore activity, we have continued to pursue the development of a suitable platform for the AirCore payload: we have solicited various funding sources, (ESA, EU-Eureka, Brussels region, …) – however without success up to now. At present, we are preparing a proposal in response to the EU call for a Research and Innovation Action, H2020-SC5-2016-2017, Topic: Novel in-situ observation systems (SC5-18-2017) with Dutch (RUG), Swiss, and Belgian partners, and possibly the Université de La Réunion as French partner.

5. PUBLICATIONS

5.1 SWING Activity

Non peer reviewed

Air Quality under new scrutiny, article on the AROMAT campaign published on the European Space Agency website , 2014

http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Campaigns/Air_quality_under_new_scrutiny

Mapping air quality from an Unmanned Aerial Vehicle, A. Merlaud and M. Van Roozendael, book chapter in 50 years of research at the Belgian Institute for Space Aeronomy, 2014

Inter-comparison of airborne atmospheric imagers during the AROMAPEX campaign, M. Ardelean, A. Merlaud, article on the AROMAPEX campaign published on the European Facility for Airborne Research (Eufar) website, 2016

http://www.eufar.net/weblog/2016/06/15/inter-comparison-airborne-atmospheric-imagers-during-aromapex-campaign/

5.2 TCCON calibration Activity

Non peer reviewed

ACTRIS-2 TNA Activity Report: Calibration of FTIR instruments at MAIDO-OPAR laboratories using portable EM27/SUN spectrometer, FTIR-Cal-LaReunion, Sep 2016 – Mahesh Kumar Sha (1), Martine De Mazière (1), Christian Hermans (1), Jean-Marc Metzger (2), Jean-Pierre Cammas (2,3), Matthias Frey (4), Matthäus Kiel (4), Frank Hase (4); Organization(s): (1) Royal Belgian Institute for Space Aeronomy (IASB-BIRA), Brussels, Belgium. (2) Unité Mixte de Service (UMS 3365), Observatoire des Sciences de l'Uniers à La Réunion, Université de la Réunion, Saint-Denis de la Réunion, France. (3) Laboratoire de l'Atmosphère et des Cyclones (LACy), Université de la Réunion, UMR CNRS-Météo-France 8105, Saint-Denis de la Réunion, France. (4) Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research (IMK-ASF), Karlsruhe, Germany, doi: 10.18758/71021027

6. ACKNOWLEDGEMENTS

This project was achieved in collaboration with two institutional partners, namely the University of Groningen, which built the AirCore, and Reev River Aerospace, which built the airborne platforms. We acknowledge our colleagues there and especially Huilin Chen (Uni. Groningen) and Florin Mingireanu (Reev River Aerospace).

Regarding the SWING activity, we also would like to warmly thank our colleague Jeroen Maes, from the engineering department, who has done an amazing job in putting all the hardware we needed in a compact and lightweight instrument. We also thank all of our AROMAT colleagues who have committed themselves to the success of the campaigns in Romania and in particular Michel Van Roozendael and Frederik Tack (BIRA-IASB), Daniel Constantin (Uni. Galati) and Dirk Schuettemeyer (ESA). We are also very grateful to Thomas Ruhtz (FU Berlin) and Andreas Meier (Uni. Bremen) thanks to whom we could operate SWING from the Cessna during AROMAT-2 and AROMAPEX. The AROMAT campaigns were funded by ESA under the contract 400011351. AROMAPEX was also partly supported by EUFAR. Ward Van Roy's support for the SWING integration in the Mumm's BN2 was very efficient and greatly appreciated.

Regarding the AirCore activity, the authors would like to acknowledge the contribution of the BIRA-IASB mechanical and electronic team in the project. We also thank Rigel Kivi (FMI), Jean-Marc Metzger (Université de La Réunion) for their help during the execution of the campaigns at Sodankyla and Ile de La Reunion and for their support regarding air traffic regulations.

7. REFERENCES

Berg, N., Mellqvist, J., Jalkanen, J.-P., & Balzani, J. (2012). Ship emissions of SO2 and NO2 DOAS measurements from airborne platforms. *Atmospheric Measurement Techniques*, *5*(5), 1085–1098. http://doi.org/10.5194/amt-5-1085-2012

Constantin, D. E., Merlaud, A., Van Roozendael, M., Voiculescu, M., Fayt, C., Hendrick, F., … Georgescu, L. (2013). Measurements of tropospheric NO2 in Romania using a zenith-sky mobile DOAS system and comparisons with satellite observations. *Sensors (Basel, Switzerland)*, *13*(3), 3922–3940. http://doi.org/10.3390/s130303922

Frey, M., Hase, F., Blumenstock, T., Groß, J., Kiel, M., Mengistu Tsidu, G., Schäfer, K., Sha, M. K., and Orphal, J.: Calibration and instrumental line shape characterization of a set of portable FTIR spectrometers for detecting greenhouse gas emissions, Atmos. Meas. Tech., 8, 3047-3057, doi:10.5194/amt-8-3047-2015, 2015.

Hase, F., Frey, M., Blumenstock, T., Groß, J., Kiel, M., Kohlhepp, R., Mengistu Tsidu, G., Schäfer, K., Sha, M. K., and Orphal, J.: Application of portable FTIR spectrometers for detecting greenhouse gas emissions of the major city Berlin, Atmos. Meas. Tech., 8, 3059-3068, doi:10.5194/amt-8-3059-2015, 2015.

Karion, A., Sweeney, C., Tans, P., and Newberger, T.: AirCore: An Innovative Atmospheric Sampling System, J. Atmos. Ocean. Tech., 27, 1839-1853, 10.1175/2010jtecha1448.1, 2010.

Mayer, B., & Kylling, A. (2005). Technical note: The libRadtran software package for radiative transfer calculations - description and examples of use. *Atmos. Chem. Phys.*, *5*(7), 1855–1877.

Merlaud, a., Van Roozendael, M., Theys, N., Fayt, C., Hermans, C., Quennehen, B., … De Mazière, M. (2011). Airborne DOAS measurements in Arctic: Vertical distributions of aerosol extinction coefficient and NO2 concentration. *Atmospheric Chemistry and Physics*, *11*(17), 9219–9236. http://doi.org/10.5194/acp-11-9219-2011

Merlaud, a., Van Roozendael, M., van Gent, J., Fayt, C., Maes, J., Toledo-Fuentes, X., … De Mazière, M. (2012). DOAS measurements of NO_2 from an ultralight aircraft during the Earth Challenge expedition. *Atmospheric Measurement Techniques*, *5*(8), 2057–2068. http://doi.org/10.5194/amt-5-2057-2012

Merlaud, A. (2013). *Development and use of compact instruments for tropospheric investigations based on optical spectroscopy from mobile platforms*. Presses univ. de Louvain.

Messerschmidt, J., Geibel, M. C., Blumenstock, T., Chen, H., Deutscher, N. M., Engel, A., … Xueref-Remy, I. (2011). Calibration of TCCON column-averaged CO2: the first aircraft campaign over European TCCON sites. *Atmospheric Chemistry and Physics*, *11*(21), 10765–10777. http://doi.org/10.5194/acp-11-10765-2011

Platt, U., & Stutz, J. (2008). *Differential Optical Absorption Spectroscopy: Principles and Applications* (1st ed.). Springer.

Popp, C., Brunner, D., Damm, A., Van Roozendael, M., Fayt, C., & Buchmann, B. (2012). High-resolution NO 2 remote sensing from the Airborne Prism EXperiment (APEX) imaging spectrometer. *Atmospheric Measurement Techniques*, *5*(9), 2211–2225. http://doi.org/10.5194/amt-5-2211-2012

Schönhardt, A., Altube, P., Gerilowski, K., Krautwurst, S., Hartmann, J., Meier, A. C., … Burrows, J. P. (2015). A wide field-of-view imaging DOAS instrument for two-dimensional trace gas mapping from aircraft. *Atmospheric Measurement Techniques*, *8*(12), 5113–5131. http://doi.org/10.5194/amt-8-5113-2015

Sluis, W. W., Allaart, M. A. F., Piters, A. J. M., & Gast, L. F. L. (2010). The development of a nitrogen dioxide sonde. *Atmospheric Measurement Techniques*, *3*, 1753–1762. http://doi.org/10.5194/amt-3-1753-2010

Wunch, D., Toon, G. C., Blavier, J.-F. L., Washenfelder, R. A., Notholt, J., Connor, B. J., … Wennberg, P. O. (2011). The Total Carbon Column Observing Network. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *369*(1943), 2087–2112. http://doi.org/10.1098/rsta.2010.0240

Wunch, D., Toon, G. C., Wennberg, P. O., Wofsy, S. C., Stephens, B. B., Fischer, M. L., … Zondlo, M. A. (2010). Calibration of the Total Carbon Column Observing Network using aircraft profile data. *Atmospheric Measurement Techniques*, *3*(5), 1351–1362. http://doi.org/10.5194/amt-3-1351-2010

ANNEXES

1. Technical report of the first test campaign to perform aircore flights onboard a telecommanded parafoil system at Sodankyla.
   Document title: "BIRA_report_Sodankyla_2014July.pdf".
2. Technical report of the second campaign to perform aircore flights onboard a telecommanded flying wing system at Sodankyla.
   Document title: "ingos_report.pdf".
3. Technical report of the Transnational Access (TNA) campaign to perform EM27/SUN measurements and testing of a telecommanded flying wing system at Sodankyla. Document title: "Report_InGos_TNT_campaign_SHA.pdf".
4. Technical report on the first EM27/SUN measurement campaign at Ile de La Réunion. Document title: "ACTRIS-2 TNA Activity Report_MAIDO_FTIR-Cal-LaReunion.pdf"