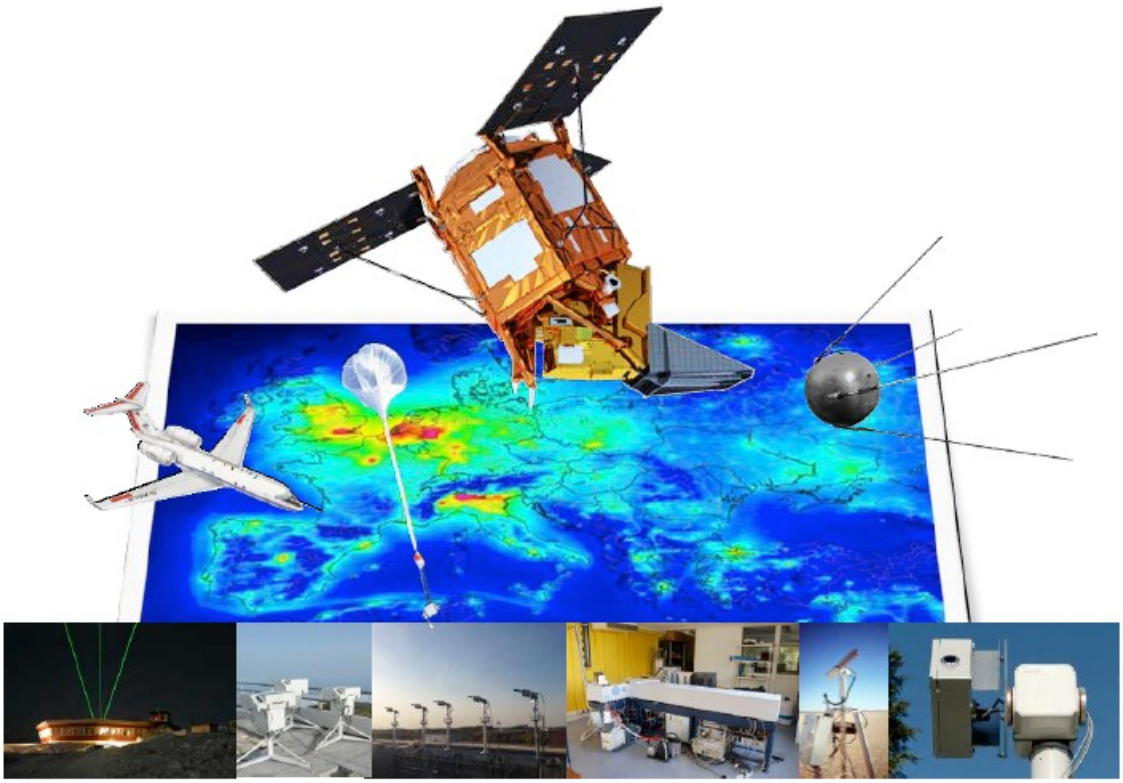
Sentinel-5 Precursor Campaign Implementation Plan



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1 Introduction

1.1 Scope of this document

This document describes the work to be executed and the deliverables required for the definition of a general concept and implementation of the campaign(s) for the calibration and validation of the Sentinel-5 Precursor operational products. All steps required for the implementation of the Sentinel-5 Precursor validation campaign(s) will be identified. This includes the establishment of the campaign objectives, tasks and deliverables, the identification of ground-based and air-borne instrumentation, supporting modeling activities and satellite observations, target sites and time periods, coordination with other (inter)national campaigns, as well as an initial cost estimate and implementation options. The main deliverable of the project will be the Campaign Implementation Plan that will be used by the European Space Agency to implement the validation campaign(s) as well as to foster international collaboration.

1.2 Abbreviations and acronyms

ACAM	Airborne Compact Atmospheric Mapper
AD	Applicable Document
AFOV	Angular field of view
AGL	Above Ground Level
AirMAP	Airborne imaging DOAS instrument for Measurements of Atmospheric Pollution
ALH	Aerosol Layer Height
AO	Announcements of opportunity
AOD	Aerosol Optical Depth
APEX	Airborne Prism EXperiment
AROMAT	Airborne ROmanian Measurements of Aerosols and Trace gases
ATBD	Algorithm Theoretical Baseline Document
ATC	Air Traffic Control
BIRA-IASB	Royal Belgian Institute for Space Aeronomy
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAMS	Copernicus Atmospheric Modeling Services
CAPS	Cavity Attenuated Phase Shift
CCD	Convective-Cloud-Differential method
CESAR	Cabauw Experimental Site for Atmospheric Research
CF	Cloud Fraction
CIP	Campaign Implementation Plan
CINDI	Cabauw Intercomparison Campaign of Nitrogen Dioxide

COCCON	COllaborative Carbon Column Observing Network
CSA	Cloud Slicing Algorithm
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DR	Digital Reference
EASA	European Aviation Safety Agency
ECMWF	European Centre for Medium-Range Weather Forecasts
E-PRTR	European Pollutant Release and Transfer Register
ESA	European Space Agency
EURAD	EURopean Air pollution Dispersion
EVDC	ESA Validation Data Centre
FP	Final Presentation
FRM	Fiducial Reference Measurement
FRM4DOAS	Fiducial Reference Measurements for ground-Based DOAS Air-Quality Observations
FTIR	Fourier Transform InfraRed
FUB	Freie Universität Berlin
FRM4GHG	Fiducial Reference Measurements for Ground-Based Infrared Greenhouse Gas Observations
FZJ	Jülich Research Center
GAW	Global Atmosphere Watch
ICOS	Integrated Carbon Observing System
IFOV	Instantaneous field of view
INCAS	National Institute for Aerospace Research Elie Carafoli
INGV	National Institute of Geophysics and Volcanology
INOE 2000	National Institute for Research and Development in Optoelectronics
IUP-UB	Institute of Environmental Physics
JRC	Joint Research Centre
KIT	Karlsruhe Institute of Technology
KNMI	Royal Netherlands Meteorological Institute
KOM	Kick-Off Meeting
LULC	Land Use Land Cover
MAX-DOAS	Multi-Axis Differential Optical Absorption Spectroscopy
MPC	Mission performance center
MPIC	Max-Planck Institute for Chemistry Mainz
MTR	Mid-Term Review
NDACC	Network for the Detection of Atmospheric Composition Change
NRW	North Rhine Westphalia
OMI	Ozone Monitoring Instrument
PM	Progress Meeting
RAMOS	Technical Assistance For A Romanian Atmospheric Observation System
RD	Reference Document
ROM	Rough Order of Magnitude
SVIP	Scientific Validation Implementation Plan
S-5p	Sentinel-5 Precursor

S5PVT	Sentinel-5 Precursor Validation Team
SHADOZ	Southern Hemisphere ADditional OZonesondes
SNPP	Suomi National Polar-orbiting Partnership
SNR	Signal-To-Noise Ratio
SoW	Statement of Work
SSA	Single Scattering Albedo
SWING	Small Whiskbroom Imager for atmospheric Composition monitoring
TCCON	Total Carbon Column Observing Network
TPM	Third Party Mission
UGAL	"Dunărea de Jos" University of Galați
VDAF	Validation Data Analysis Facility
VOC	Volatile Organic Compounds
WMO	World Meteorological Organisation
WOUDC	World Ozone and Ultraviolet Radiation Data Centre

1.3 Applicable documents

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[DR 2] RAMOS campaign, http://environment.inoe.ro/category/81/ramos
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[DR 5] Fiducial Reference Measurements for Ground-Based Infrared Greenhouse Gas Observations (FRM$_4$GHG), http://frm4ghg.aeronomie.be
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[DR 14] EVDC S-5p overpass tool, https://evdc.esa.int/orbit/

[DR 15] BRITTEN-NORMAN BN-2 Islander, www.skybrary.aero/index.php/BN2P

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[DR 17] European Environment Agency: The European Pollutant Release and Transfer Register (E-PRTR), Member States reporting under Article 7 of Regulation (EC) No 166/2006, http://www.eea.europa.eu/ds_resolveuid/710e9a407c0e4fecb376ee87ec9515c

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[DR 24] Accepted S5PVT projects, https://earth.esa.int/web/guest/pi-community/search-results-and-projects/mission?IFRAME_SRC=/pi/esa%3FitemsPerPage%3D10%26sideExpandedNavigationBoxId%3DprojectSearch%26displayMode%3Dcenter%26cmd%3Dinstrument%26showAll%3Dfalse%26topSelectedNavigationNodeId%3DSEARCH%26downloadAsCsv%3Dfalse%26targetIFramePage%3D%252Fweb%252Fguest%252Fpi-community%252Fsearch-results-and-projects%252Fmission%26ts%3D1481203473767%26colorTheme%3D03%26startFrom%3D0%26sideNavigationType%3DSEARCH%26instrumentid%3D1260

2 Background and Motivation

The Sentinel-5 Precursor (S-5p) mission with the TROPOMI payload was launched on 13 October 2017. S-5p is the first mission of the Copernicus Programme dedicated to perform atmospheric measurements with high spatio-temporal resolution, relating to air quality, climate, ozone and UV radiation. S-5p will continue the European time series of low polar orbiting satellites measuring the global atmospheric composition using spectrometers in nadir configuration that has started with the GOME instrument on ERS-2 in 1995 and was continued by SCIAMACHY on ENVISAT, GOME-2 on the EUMETSAT MetOp platforms and the Dutch/Finnish OMI instrument hosted on the NASA AURA mission. The S-5p mission is also a preparatory programme covering product and applications definition for Sentinel-5 to be operated on MetOp-SG platforms.

The new sensor technology and retrieval approaches, as well as the much finer spatial resolution introduces many new opportunities and challenges, requiring to carefully assess the quality and validity of the generated data products by comparison with independent measurements and analyses. Independent validation provides credibility to the overall mission and allows users to assess the end-to-end mission performance and data product quality. In addition, it can be a critical source of information for the ESA S-5p Mission Manager and the Data Quality Manager to identify and decide where and how to improve the overall data production chain, ranging from the satellite to the data distribution system.

Routine validation activities are performed in the frame of the S-5p Mission Performance Center (MPC). The MPC is responsible for the assessment of the operational product content quality, and the provision of validation support to the evolution of the Level 2 data processing. The routine validation by the MPC is, however, restricted to data products that can be addressed by a limited number of Fiducial Reference Measurements (FRM) that can be operationally delivered to the Validation Data Analysis Facility (VDAF). In addition, there is a strong need for validation activities conducted in research mode as part of the S5PVT (S-5p Validation Team) and for field campaigns, bringing together various teams and instruments, that can provide a more in-depth, complete insight into the S-5p instrument performance and the fitness for purpose of its data products. As field campaigns are usually confined in space and time due to their high cost and logistical needs, campaigns need a solid planning, taking into account the validation objectives and requirements, while considering all limiting factors.

A number of campaigns were recently organised in support of the preparation of the S-5p validation activities, such as the 2014-2015 AROMAT [DR 1] and 2017-2018 RAMOS [DR 2] campaigns in Romania, AROMAPEX in 2016 in Berlin [DR 3], CINDI-2 in 2016 in Cabauw [DR 4], and the FRM$_4$GHG campaign in 2017 in Sodankyla (that is extended to

2018) [DR 5]. The experience gained and lessons learned as well as the established consortiums constitute valuable assets in the frame of the proposed activities.

3 Objectives

This document aims at establishing a general Campaign Implementation Plan (CIP) that will be used by the European Space Agency to prepare and implement a set of validation campaign activities as well as to foster international collaboration. The CIP is a key document in the preparation, implementation, execution and analysis of each validation campaign. To define the validation campaign(s), the CIP addresses the following topics:

- Review and consolidation of validation campaign requirements for all operational S-5p products, assessing whether or not they can be efficiently addressed in the frame of a validation campaign.
- Definition of a general campaign concept for the full S-5p lifetime by addressing the identified campaign requirements, describing potential instruments, target areas and time windows. The synergistic use of observations will be emphasized, e.g. simultaneous observations of SO_2 and NO_2 tropospheric columns by an airborne DOAS imaging system. For each product, responsibilities will be assigned to experts in the calibration/validation of satellite atmospheric remote sensing products.
- Description of a concrete implementation plan for the first campaign deployment(s) foreseen in 2019. All scientific, technical and logistical aspects shall be specified in preparation of the concrete implementation of the campaign(s). This includes identification and justification of:
    - the instrumentation: The possible instrumentation required for a full validation ranges from the UV to the infrared, involves passive and active remote sensing techniques, as well as in-situ analysers. The instruments can be operated from the ground (ground-based stations or mobile platforms, such as cars or bikes) or from airborne platforms, such as balloons, UAVs or aircraft. For the airborne component, type of flights will be identified, e.g. mapping and transect flights to address the S-5p intra- and inter-pixel variability as well as profiling flights to address the vertical distribution.
    - campaign sites, ideally suited for synergetic validation of tropospheric reactive trace gases, greenhouse gases, aerosols and clouds, which can have a high variability in time and space, both horizontally and vertically.
    - time windows, taking into account seasonality of the products and favorable weather conditions.

- planned (inter)national campaigns, that can be linked to the S-5p validation campaign(s). Their synergy and complementarity will be reviewed and options for collaborations will be explored.

- Secondary objectives will be reviewed such as the potential for validation of scientific S-5p products not generated operationally, and the possible usage of campaign measurements to address specific science topics.

4 Validation Campaign Requirements

In order to define the priorities for campaign activities, the requirements for validation that have been formulated as part of the mission preparation must be properly reviewed. In particular the requirements listed in the S-5p ATBDs [DR 6], and the Cal/Val and Science Validation Implementation Plans [DR 7], [DR 8] are reviewed as to whether they can be addressed through campaign activities.

For each operational data product (see list in Table 4.1) and based on knowledge of validation activities planned as part of (a) the operational MPC VDAF, and (b) the various S5PVT AO projects, we identify the key requirements not covered by routine/operational activities and that can be addressed most efficiently by validation campaign deployment(s).

Table 4.1: List of S-5p operational data products and their target accuracies

Parameter	Data Product	Vertical Resolution	Accuracy	Precision
Ozone	Ozone Profile	6 km	10-30%	10%
	Total Ozone	total column	3.5-5%	1.6-2.5%
	Tropospheric Ozone	trop column	25%	10%
NO_2	Stratospheric NO_2	strat column	<10%	0.5×10^{15} mol/cm^2
	Tropospheric NO_2	trop column	25-50%	0.7×10^{15} mol/cm^2
SO_2	SO_2 enhanced	total column	30%	0.15-0.3 (0.06-0.12) DU
	Total SO_2	total column	30-50%	1-3 (0.4-1.2) DU
Formaldehyde	Total HCHO	total column	40-80%	1.2×10^{16} mol/cm^2
CO	Total CO	total column	15%	<10%
Methane	Total CH_4	total column	1.5%	1%
Cloud	Cloud Fraction	total column	<20%	0.05
	Albedo (Optical Thickness)	total column	<20%	0.05 (10)
	Cloud Height (Pressure)	total column	<20%	<0.5 km (<30hPa)
Aerosol	Aerosol Layer Height	total column	<100hPa	<50hPa
	Aerosol Type	total column	~1 AAI	<0.1 AAI
S5P-SNPP Cloud	VIIRS Cloud Classification	N/A	TBD	TBD
	Mean VIIRS M7 Radiance (865 nm)	N/A	TBD	TBD
	Mean VIIRS M9 Radiance (1.378 µm)	N/A	TBD	TBD
	Mean VIIRS M11 Radiance (2.25 µm)	N/A	TBD	TBD
Surface UV	Surface UV Radiance	N/A	TBD	TBD

Specific validation requirements have been identified by the S-5p level-2 developers for their respective products. This includes validation of parameters related to the:

- algorithm and processing itself, e.g., input data, intermediate products, algorithm assumptions;
- spatial validation requirements, e.g., global, over land, tropics, urban;
- temporal validation requirements, e.g., long time series, seasonal cycle;
- special validation requirements, e.g., artic vortex, natural emission regimes.

The requirements listed below (also compiled in [DR 7]) have been extracted from [DR 9] and the ATBDs for the different products [DR 6]. Where relevant for each data product, additional specific campaign requirements are identified.

4.1 Ozone Profile (O_3Pr)

4.1.1 Accuracy and Precision

[VAL-O3Pr-01] Accuracy: 10-30%

[VAL-O3Pr-02] Precision: 10%

4.1.2 Algorithm Parameter

[VAL-O3Pr-03] Validation of vertical O_3 profile

[VAL-O3Pr-04] Effective cloud fraction (CF) in UV

4.1.3 Spatial Validation Requirements

[VAL-O3Pr-05] Global validation

[VAL-O3Pr-06] Measurement representativeness 50 x 50 km^2

[VAL-O3Pr-07] Vertical resolution higher than 6 km

4.1.4 Temporal Validation Requirements

[VAL-O3Pr-08] Covering all seasons

4.1.5 Special Validation Requirements

[VAL-O3Pr-09] Stratospheric intrusions conditions

[VAL-O3Pr-10] Biomass burning conditions

[VAL-O3Pr-11] Ozone hole conditions

4.1.6 Specific Campaign Validation Requirements

None

It is not foreseen that specific campaigns will be needed to support ozone profile validation for specific algorithm features. However, results of campaigns that measure ozone profiles are certainly interesting for validation purposes. Most useful for ozone profile validation are measurements made with balloon borne ozone sondes at different locations on the Earth. This can be usefully complemented by stratospheric lidar and microwave measurements which provide extended coverage at higher altitudes. In summary, there are no specific campaign validation requirements for this product, but any relevant measurement of the ozone vertical distribution being performed in a campaign should be made available to the S-5p validation teams.

4.2 Total Ozone Column (O_3TC)

4.2.1 Accuracy and Precision

[VAL-O3TC-01] Accuracy: 3.5-5%

[VAL-O3TC-02] Precision: 1.6-2.5%

4.2.2 Algorithm Parameter

[VAL-O3TC-03] Validation of vertical O_3 profile

4.2.3 Spatial Validation Requirements

[VAL-O3TC-04] Global scale validation

[VAL-O3TC-05] Measurement representativeness 10 x 10 km^2

4.2.4 Temporal Validation Requirements

[VAL-O3TC-06] Long time series

[VAL-O3TC-07] Covering all seasons

4.2.5 Special Validation Requirements

None

4.2.6 Specific Campaign Validation Requirements

None

Like for ozone profiles, the main emphasis for total ozone validation is on quality assessment at the global scale and over long time periods. Relevant validation exercises should establish whether total ozone data quality meets the requirements of most demanding geophysical research applications like long term trend monitoring on the global scale, polar process studies, and research on ozone-climate interactions. To this aim, most useful comparisons are performed using correlative observations acquired by ground-based reference instruments contributing to WMO's Global Atmosphere Watch (GAW), namely, Brewer and Dobson ultraviolet spectrophotometers (WOUDC) and DOAS UV-visible spectrometers (NDACC). As a result, there are no specific campaign validation requirements for this product, but relevant total ozone measurements being performed in a campaign should be made available to the S-5p validation teams for possible integration in more global exercises.

4.3 Tropospheric Ozone (O_3Tr)

4.3.1 Accuracy and Precision

[VAL-O3Tr-01] Accuracy: 25%

[VAL-O3Tr-02] Precision: 10%

4.3.2 Algorithm Parameter

[VAL-O3Tr-03] Validation of vertical O_3 profile

[VAL-O3Tr-04] Validation of stratospheric O_3 assumption

4.3.3 Spatial Validation Requirements

[VAL-O3Tr-05] Validation in the Tropics

[VAL-O3Tr-06] Global validation

[VAL-O3Tr-07] Measurement representativeness 50 x 50 km^2

4.3.4 Temporal Validation Requirements

[VAL-O3Tr-08] Covering all seasons

4.3.5 Special Validation Requirements

None

4.3.6 Specific Campaign Validation Requirements

None

The S-5p tropospheric ozone products are derived using two different approaches: the Convective-Cloud-Differential method (CCD), and the Cloud Slicing Algorithm (CSA). Since both methods are based on an analysis of the impact of convective clouds on ozone, their range of applicability is restricted to tropical and equatorial regions. The validation strategy for tropical tropospheric ozone products essentially relies on established ozone sonde facilities, in particular the SHADOZ-network which has lot of suitable stations measuring ozone profiles up to two times a month. For adequate validation, measurements over long periods of time are necessary to gather statistically significant results. As a result, there are no specific campaign validation requirements for the tropical tropospheric ozone products.

4.4 Nitrogen Dioxide Total and Tropospheric Column (NO_2)

4.4.1 Accuracy and Precision

4.4.1.1 Stratospheric Column

[VAL-NO2-01] Accuracy: <10%

[VAL-NO2-02] Precision: 0.5×10^{15} mol/cm^2

4.4.1.2 Tropospheric Column

[VAL-NO2-03] Accuracy: 25-50%

[VAL-NO2-04] Precision: 0.7×10^{15} mol/cm^2

4.4.2 Algorithm Parameter

[VAL-NO2-05] Validation of vertical NO_2 profile in the PBL (for tropospheric NO_2)

[VAL-NO2-06] Validation of vertical NO_2 stratosphere

[VAL-NO2-07] Validation of a-priori NOx emissions

4.4.3 Spatial Validation Requirements

[VAL-NO2-08] Representativeness for zonal bands for stratospheric NO_2

[VAL-NO2-09] Validation in polluted conditions (anthropogenic)

[VAL-NO2-10] Validation in presence of natural emissions, e.g., biomass burning, microbial soil activity and lightning

[VAL-NO2-11] Validation in clean conditions

[VAL-NO2-12] Validation under partly cloudy conditions

4.4.4 Temporal Validation Requirements

[VAL-NO2-13] Validation information covering the diurnal cycle

4.4.5 Special Validation Requirements

[VAL-NO2-14] Near Arctic Vortex (break-up conditions, i.e., late winter/early spring)

[VAL-NO2-15] Validation in areas with horizontal gradients on the order of the satellite pixel

[VAL-NO2-16] Validation collocated with aerosol profile information

4.4.6 Specific Campaign Validation Requirements

The most important validation need for NO_2 is for tropospheric NO_2 under polluted and clean conditions. Under polluted NO_2 conditions, column and profile information in the lower troposphere are essential for validation. The validation of tropospheric NO_2 under polluted conditions (e.g. urban areas) is particularly challenging due to the issue of representativeness of the point-size ground-based and in-situ measurements in comparison to the finite-sized satellite ground pixels. Although the improved spatial resolution of S-5p in comparison to previous sensors will reduce this representativeness issue, it will remain a major source of difficulty for the interpretation of validation results. Indeed the natural scale of NO_2 plumes emitted and transported by winds in polluted areas is still an order of magnitude smaller than the scale of S-5p pixels (3.5 x 7 km^2). One possible way to overcome this difficulty is to accumulate a large number of correlative observations at static ground-based reference sites and analyse them in a statistical way, taking into account ancillary information available at the sites. This approach will be developed as part of long-term validation activities making use of suitable DOAS-type Fiducial Reference Measurements developed in projects such as Pandonia and FRM4DOAS in support of the S-5p Mission Performance Center (MPC), and within the various S5PVT projects. Another approach is to deploy airborne and surface mobile systems to accurately map the small scale variability of the tropospheric NO_2 plumes and thereby provide a more direct validation of the satellite observation. Such an approach can only be achieved through dedicated field campaigns where suitable instrumentation is deployed over highly relevant areas. For adequate end-to-end validation, not only tropospheric NO_2 columns should be measured, but simultaneous observations of a number of key ancillary parameters should be performed, in particular (1) the vertical distribution of the NO_2 concentration, (2) the aerosol content and profile, (3) the surface albedo. Field campaigns should also be scheduled to allow for optimal overlap in time with S-5p and enough of satellite pixels should be covered to allow for statistically significant validation results.

[VAL-NO2-17] Validation using ground-based mobile DOAS systems

[VAL-NO2-18] Validation using airborne NO_2 imaging DOAS systems

[VAL-NO2-19] Validation of NO_2 vertical distributions and/or other ancillary retrieval parameters (e.g. surface albedo, aerosol profile, clouds)

4.5 Total and enhanced Sulphur Dioxide Total Column (SO_2)

4.5.1 Accuracy and Precision

4.5.1.1 Enhanced Total Column

[VAL-SO2-01] Accuracy: 30%

[VAL-SO2-02] Precision: 0.15-0.3 (0.06-0.12) DU

4.5.1.2 Total Column

[VAL-SO2-03] Accuracy: 30-50%

[VAL-SO2-04] Precision: 1-3 (0.4-1.2) DU

4.5.2 Algorithm Parameter

[VAL-SO2-05] Validation of vertical tropospheric SO_2 profile

4.5.3 Spatial Validation Requirements

[VAL-SO2-06] Global covering degassing and eruptive volcanoes

[VAL-SO2-07] Regions for which the SO_2 concentrations exceeds the observational threshold or Regions with significant SO_2 pollution

4.5.4 Temporal Validation Requirements

[VAL-SO2-08] Long-term validation

4.5.5 Special Validation Requirements

[VAL-SO2-09] Validation in volcanic plume environment, in particular plume height

[VAL-SO2-10] Validation of aerosol loading with optical properties in the UV

[VAL-SO2-11] Validation in areas with horizontal SO_2 gradients (of the order of a pixel size)

4.5.6 Specific Campaign Validation Requirements

For the case of SO_2, one must consider the different cases of anthropogenic SO_2 emissions (pollution) and volcanic emissions. The measurement (and validation) of anthropogenic SO_2 is generally a difficult task because of the low column amount and reduced measurement sensitivity of the satellite close to the surface. Volcanic SO_2 detection from space is facilitated by the typically larger SO_2 columns, however the retrieved SO_2 columns are strongly dependent on the plume height which is variable and often unknown. For strong eruptions, volcanic plumes are transported over long-distances in a rather unpredictable way, so that validation planning is very difficult.

Volcanic SO_2 case

Dedicated aircraft campaign flights can in principle measure volcanic SO_2 clouds, but these rely on the occurrence of volcanic events. Aircraft trajectory can however be planned with relative ease to cross known degassing volcanoes or sustained eruptive plumes. Ground-based mobile observations can also be usefully deployed. However, comparison with moving ground instruments can be complicated by the fast displacement of the volcanic cloud with respect to the ground spectrometer and possible heterogeneity on small scales. Such campaign activities therefore require careful planning and high flexibility with respect to operations.

[VAL-SO2-12] Validation of volcanic plumes using mobile systems

[VAL-SO2-13] Validation of volcanic plumes using imaging sensors

Anthropogenic SO_2 case

Comparisons of individual satellite SO_2 measurements and MAX-DOAS data is notoriously difficult, due to satellite data scatter and cloud cover. Although the situation for S-5p is expected to be better due to improved spatial resolution, spatial and temporal averaging will be needed. Ideally MAX-DOAS instruments should operate in parallel with airborne instruments that provide complementary information on the 3-D distribution of atmospheric SO_2. Like for NO_2, SO_2 validation airborne campaigns should be designed to allow for ancillary observations of SO_2 vertical profiles, aerosol content and surface albedo.

[VAL-SO2-14] Validation using ground-based mobile DOAS systems

[VAL-SO2-15] Validation using airborne SO_2 imaging DOAS systems

4.6 Formaldehyde Total Column (HCHO)

4.6.1 Accuracy and Precision

[VAL-HCHO-01] Accuracy: 40-80%

[VAL-HCHO-02] Precision: 1.2×10^{16} mol/cm^2

4.6.2 Algorithm Parameter

[VAL-HCHO-03] Validation of the vertical profile of HCHO, in particular first three kilometers

4.6.3 Spatial Validation Requirements

[VAL-HCHO-04] Validation in the tropics

[VAL-HCHO-05] Validation in temperate forests (April-September)

[VAL-HCHO-06] Validation in boreal forests

[VAL-HCHO-07] Validation in sub-urban environment

[VAL-HCHO-08] Validation in urban areas

[VAL-HCHO-09] Global validation

4.6.4 Temporal Validation Requirements

[VAL-HCHO-10] Validation of the seasonal cycle.

[VAL-HCHO-11] Validation of the diurnal cycle.

[VAL-HCHO-12] Long-term validation

4.6.5 Special Validation Requirements

None specified

4.6.6 Specific Campaign Validation Requirements

As for other tropospheric data products, the validation of HCHO column measurements from S-5p is difficult and challenging. The effect of a priori vertical profiles, aerosols, clouds, albedo changes, and spatial gradients must be taken into account. Like for NO_2 and SO_2, HCHO validation requires not only information on the total tropospheric HCHO column, but also information on its vertical distribution is needed, especially in the lowest three kilometers where the bulk of formaldehyde generally resides. In this altitude range, the a-priori vertical profile shapes have the largest systematic impact on the satellite column errors due to the strong decrease of the satellite UV measurement sensitivity near the surface. Although

ground-based remote-sensing MAXDOAS and FTIR instruments, complemented by in-situ systems, are best suited for the long-term routine validation of column measurements, this type of instrument can only validate column and surface HCHO concentrations and provide very limited information of the HCHO vertical distribution. Therefore, additional information on the vertical profile, which can be acquired through airborne campaign deployment, is required to make the link with the satellite retrieved column. Campaigns should preferably target regions of strong VOC emissions, from natural causes (e.g. vegetation under hot conditions) or from anthropogenic causes (e.g. urban traffic). To maximize the HCHO signal, hot summer conditions should be favoured for deployment.

[VAL-HCHO-13] Validation using ground-based mobile DOAS systems

[VAL-HCHO-14] Validation using airborne HCHO imaging DOAS systems

[VAL-HCHO-15] Validation of HCHO vertical distributions and/or other ancillary retrieval parameters (e.g. surface albedo, aerosol profile, clouds)

4.7 Carbon Monoxide Total Column (CO)

4.7.1 Accuracy and Precision

[VAL-CO-02] Accuracy: 15%

[VAL-CO-03] Precision: <10%

4.7.2 Algorithm Parameter

[VAL-CO-04] Validation of the vertical CO profile

[VAL-CO-05] Validation of the vertical water vapour profile

[VAL-CO-06] Validation of CH_4

4.7.3 Spatial Validation Requirements

[VAL-CO-07] Global over land

[VAL-CO-08] Polluted conditions

[VAL-CO-09] Background conditions

4.7.4 Temporal Validation Requirements

[VAL-CO-10] All seasons

4.7.5 Special Validation Requirements

[VAL-CO-11] Humid atmospheric conditions

[VAL-CO-12] Dry atmospheric conditions

[VAL-CO-13] High albedo conditions

[VAL-CO-14] Low albedo conditions

4.7.6 Specific Campaign Validation Requirements

The main source of validation for CO consists of independent ground-based FTIR measurements at TCCON sites, complemented by AirCore balloon measurements of the CO vertical profile which, together with the column averaging kernel of the retrieval, allow testing the relevance of the vertical retrieval sensitivity. Although the bulk of validation for CO relies on long-term monitoring at TCCON sites, requirements for complementary campaign activities have been identified:

[VAL-CO-15] Observation of localized sources to deduce detection limit for small scale variations. This could be obtained through deployment of a suitable airborne CO spectrometer system.

[VAL-CO-16] Detection of possible spurious variations as a function of the observed line-of-sight, e.g. through deployment of (trans)portable FTIR ground-based systems.

[VAL-CO-17] Detection of possible problems under worse than ideal meteorological conditions (e.g. partially cloudy scenes or scenes affected by thin clouds).

4.8 Methane Total Column (CH_4)

4.8.1 Accuracy and Precision

[VAL-CH4-01] Accuracy: 1.5%

[VAL-CH4-02] Precision: 1%

4.8.2 Algorithm Parameter

[VAL-CH4-03] Validation of the vertical CH_4 profile

[VAL-CH4-04] Validation of vertical water vapour profile

[VAL-CH4-05] Validation of cirrus cloud detection, in particular in the tropics

[VAL-CH4-06] Validation of fluorescence correction

4.8.3 Spatial Validation Requirements

[VAL-CH4-07] Global over land

4.8.4 Temporal Validation Requirements

[VAL-CH4-08] All seasons

4.8.5 Special Validation Requirements

[VAL-CH4-09] High albedo conditions

[VAL-CH4-10] Low albedo conditions

4.8.6 Specific Campaign Validation Requirements

For S-5p retrievals of XCH_4, the TCCON network will be the prime source of validation data. TCCON XCH_4 measurements have been calibrated and validated against the WMO-standard of in-situ measurements using dedicated aircraft campaigns resulting in an accuracy assessment of 0.4% (2σ value). However, an important limitation of the TCCON network for validation of satellite retrievals of greenhouse gas concentrations is the limited albedo range that is covered by the TCCON stations, as well as their locations are mainly covering background concentrations. Therefore, there is a strong need for validation stations that cover higher surface albedos. This is very important as these scenes pose a strong challenge for the XCH_4 retrieval algorithm because of the large sensitivity to aerosols. Also TCCON stations at the challenging very low albedo conditions are lacking to some degree. In addition, regions with elevated CH_4 concentrations near source regions need to be covered to validate CH_4 gradients which contain the information on local sources. An interesting development in this respect is the development of somewhat cheaper low-resolution spectrometers complementary to the TCCON high spectral resolution FTIRs. Such systems, which might be deployed in campaigns would be very useful for S-5p XCH_4 validation provided that their accuracy is high enough.

In addition, in situ measurements of the full vertical CH_4 profile would be extremely useful as they allow the S-5p column averaging kernel to be applied and hence the retrieved XCH_4 from S-5p can be compared without the smoothing component in the comparison uncertainty budget. TCCON delivers the column integrated values (XCH_4) which can be also be used for intercomparison with S-5p column integrated values (XCH_4) however this leads to a remaining smoothing uncertainty component in the comparison. Vertical profiles can be obtained by aircraft, which could be deployed in campaigns, however they do not sample the full total column. In this respect, a very interesting new development is provided by the

recently-developed balloon-borne AirCore system. A clear advantage of AirCore is the lower cost in comparison to airborne deployment and the fact that it can in principle sample the profile across the entire column.

Like for CO, specific requirements for campaign activities have been identified as follows:

[VAL-CH4-11] Observation near strong source areas to deduce detection limit for small scale variations. This could be obtained through deployment of an airborne CH_4 imaging system.

[VAL-CH4-12] Detection of possible spurious variations as a function of the observed line-of-sight, e.g. through deployment of (trans)portable FTIR systems.

[VAL-CH4-13] Detection of possible problems under worse than ideal meteorological conditions (e.g. scenes affected by thin clouds) or difficult surface conditions.

4.9 Clouds

4.9.1 Accuracy and Precision

4.9.1.1 **Cloud Fraction (CF)**

[VAL-Cloud-01] Accuracy: <20%

[VAL-Cloud-02] Precision: 0.05

4.9.1.2 **Albedo (Optical Thickness)**

[VAL-Cloud-03] Accuracy: <20%

[VAL-Cloud-04] Precision: 0.05 (10)

4.9.1.3 **Cloud Height (Pressure)**

[VAL-Cloud-05] Accuracy: <20%

[VAL-Cloud-06] Precision: <0.5 km (<30 hPa)

4.9.2 Algorithm Parameter

[VAL-Cloud-07] Validation of Cloud Fraction

[VAL-Cloud-08] Validation of Cloud-Top-Height (-Pressure)

[VAL-Cloud-09] Validation of COT and Albedo

[VAL-Cloud-10] Horizontal inhomogeneity in cloud fields/3D cloud effects

4.9.3 Spatial Validation Requirements

[VAL-Cloud-11] Validation on global scale, in particular over ocean

[VAL-Cloud-12] Validation over snow/ice

4.9.4 Temporal Validation Requirements

[VAL-Cloud-13] Covering all seasons

4.9.5 Special Validation Requirements

[VAL-Cloud-14] All cloud types

4.9.6 Specific Campaign Validation Requirements

A ground validation campaign for the S-5p cloud algorithms is difficult to envisage. Validation against ground-based cloud observations is necessarily confined to continental areas where there is a dense cover of surface synoptic observations. There is also a strict requirement on close time coincidences in this kind of validation. Polar orbiting and geostationary satellite measurement comparisons offer a more fruitful field for comparisons. Instruments with high spatial resolution are important here. Space-borne lidar measurements from the CALIPSO instrument (aerosol profiles) and Radar measurements from CLOUDSAT (cloud profiles) have also proved very useful for the validation of cloud products from previous sensors. Although general in scope, the following requirements are especially applicable to campaigns targeting cloud information:

[VAL-Cloud-15] Cloud observations should provide vertical profiles of cloud macroscopical and cloud microscopical properties, i.e. vertical cloud masks and vertical cloud target classification masks.

[VAL-Cloud-16] Cloud observations should provide information about the spatial distribution and coverage of clouds.

[VAL-Cloud-17] Cloud observations should be representative of cloud fields during S5P overpasses and time intervals prior to and after the time of satellite sensing.

4.10 S5P-SNPP Cloud product

4.10.1 Algorithm Parameter

[VAL-NCloud-01] Cloud Fraction

[VAL-NCloud-02] Cloud Albedo

[VAL-NCloud-03] Vertical extinction profile

4.10.2 Spatial Validation Requirements

[VAL-NCloud-04] Global validation

4.10.3 Temporal Validation Requirements

[VAL-NCloud-05] Covering all seasons

4.10.4 Special Validation Requirements

[VAL-NCloud-06] All cloud types

4.10.5 Specific Campaign Validation Requirements

None

4.11 Aerosol Layer Height (ALH)

4.11.1 Accuracy and Precision

[VAL-ALH-02] Accuracy: <100 hPa

[VAL-ALH-03] Precision: <50 hPa

4.11.2 Algorithm Parameter

[VAL-ALH-04] Validation of aerosol parameter profiles (e.g., SSA, phase function, extinction, backscatter)

[VAL-ALH-05] Validation of AOD

[VAL-ALH-06] Validation of chlorophyll fluorescence assumption

4.11.3 Spatial Validation Requirements

[VAL-ALH-07] Validation of all climatological regions (“global”)

[VAL-ALH-08] Measurement representativeness of a pixel size (7 x 7 km2)

4.11.4 Temporal Validation Requirements

None specified

4.11.5 Special Validation Requirements

None specified

4.11.6 Specific Campaign Validation Requirements

For the ALH product, collocated measurements over selected ground-based lidar sites should be the main source of validation data. Comparisons with a number of other passive satellite retrievals can also be carried out. Ground-based lidar measurements provide backscatter profiles and in some cases extinction profiles. These profiles can unambiguously indicate the presence of aerosol and cloud layers. Although lidar measurements have a very good vertical resolution, their horizontal coverage is limited. To construct a validation set with statistical significance, lidar measurements from a variety of lidar networks and platforms need to be collected and collocated with S-5p observations. Next, profiles from different types of lidar instruments have to be interpreted in terms of the ALH profile parameter (e.g. height of the assumed single aerosol layer) in a consistent way. This step requires knowledge of instrument sensitivities of both the lidar instrument as well as the S-5p spectrometer. It is recommended that future research addresses the question of how to compare lidar profiles with S-5p aerosol profile parameters. Since availability and collocation of lidar measurements may be too sparse, dedicated validation campaigns can help to further substantiate the validation data set. The following requirements should be kept in mind when planning campaign activities addressing the ALH product:

[VAL-ALH-09] Vertical profiles of aerosol distributions.

[VAL-ALH-10] Vertical profiles of aerosol optical properties, including backscatter, extinction and wavelength dependence.

[VAL-ALH-11] Vertical profiles and columnar observations of aerosols should be simultaneously available from independent observations.

4.12 Aerosol Index

4.12.1 Accuracy and Precision

[VAL-AAI-01] Accuracy: ~ 1 AAI

[VAL-AAI-02] Precision: < 0.1 AAI

4.12.2 Algorithm Parameter

[VAL-AAI-03] Validation of aerosol parameter profiles (e.g., SSA, asymmetry, extinction)

[VAL-AAI-04] Validation of AOD and ALH

[VAL-AAI-05] Validation of Ozone Profiles

4.12.3 Spatial Validation Requirements

[VAL-AAI-06] Validation of all climatological regions ("global").

[VAL-AAI-07] Measurement representativeness of a pixel size (7 x 7 km^2)

4.12.4 Temporal Validation Requirements

None specified

4.12.5 Special Validation Requirements

None specified

4.12.6 Specific Campaign Validation Requirements

Validation of the UVAI cannot be carried out in a traditional way because it is not a physical quantity and depends upon too many different parameters. However, tests to evaluate the performance of AI can be carried out in several ways. One is to intercompare S-5p UVAI to similar data sets from other satellite sensors such as OMI, GOME-2, and OMPS. OMI and OMPS are ideal for comparison since they both have afternoon overpass times. Airborne spectrometers covering the UV spectral range are a good alternative as long as they measure at sufficiently high altitude. One example is the NASA Airborne Compact Atmospheric Mapper (ACAM) which measures in the spectral range from 310 nm to 520 nm and is optimized for tropospheric pollutants and water vapour but could also be used to calculate UVAI. Flights using this instrument could be used for validation of UVAI ALH if timed to be adequately close to the expected S-5p overpass time.

[VAL-AAI-07] Validation of UVAI using airborne nadir hyperspectral sensors covering the relevant spectral range

5 Inventories of measurement infrastructures, model tools, target areas, related field campaigns, campaign participants

As a first preparatory step, the team has compiled a non-exhaustive inventory of the existing and most relevant (ground-based and airborne) measurement infrastructures currently available for potential contribution to the S-5p campaign activities. This list also includes supporting model tools, potential target areas for campaign deployment, related nationally funded field campaigns and a preliminary list of campaign participants. Note that detailed descriptions for the measurement infrastructures listed in Table 5.1 are provided in Annex A.

As required in the SoW, this inventory addresses:

- availability of ground-based instrumentation at static locations
- availability of ground-based instrumentation for mobile operation
- availability of ground-based mobile or movable platforms (and associated teams)
- availability of airborne platforms
- availability of airborne instrumentation for remote-sensing and in-situ measurements
- availability of on-ground support for ground-based and airborne operation (including on-ground logistics, fuel, possible balloon launching sites, flight clearance procedures, etc.)
- meteorological forecast and weather statistics at envisaged deployment sites
- identification of surface conditions (e.g. albedo and terrain height variability, level of urbanization, etc.)
- plans for nationally funded campaign activities and identification of possible synergies

Table 5.1: Inventory of the most relevant (ground-based and airborne) measurement infrastructures.

Instrument	Owner organisation	Contact person	Measured variables	Platform	Platform operator	Periods of non-availability in 2019	CIP core team lead
Airborne RS							
AirMAP	IUP-UB	Andreas Richter	NO_2 or SO_2, HCHO column, surface reflectance	Cessna 207T aircraft	FUB	None so far	IUP-UB
SWING+	BIRA/ESA/INCAS	Alexis Merlaud, Angelo Voicu	NO_2, SO_2 column	BN-2A 27 aircraft	INCAS	RAMOS campaign	BIRA
APEX	VITO	Bart Bomans, Frederik Tack	NO_2 column, surface reflectance	Cessna Grand Caravan (HB-TEN)	SFS	None so far	BIRA
Spectrolite	TNO	Tim Vlemmix	NO_2, SO_2 and HCHO column	Cessna 207T aircraft	FUB	None so far	KNMI
ULM-DOAS	UGAL	Daniel Constantin	NO_2 column		UGAL	None so far	BIRA
MAMAP	IUP-UB	Heinrich Bovensmann	Background normalized XCH_4 and XCO_2	Cessna 207T aircraft	FUB	None so far	IUP-UB
GHOST	Uni. Leicester	Hartmut Boesch	CO, CH_4	DO-228	BAS (tbc)	None so far	IUP-UB
FUBISS-ASA2	FUB	Thomas Ruhtz	Extinction profile	Cessna 207T aircraft	FUB	None so far	IUP-UB
Airborne in-situ							
TD-LIF	UNICH	Piero Di Carlo	NO_2 VMR profile	ATr-42, BaAe-145, Partenavia P68B D-GERY	EUFAR	None so far	BIRA
AS32M CAPS	ESA/INCAS	Andreea Calcan, Magdalena Ardelean	NO_2 VMR profile	BN-2A 27 aircraft	INCAS	RAMOS campaign	BIRA
IT-CIMS	DLR-IPA	Anke Roiger	SO_2 VMR profiles	DLR FALCON	DLR	Methane-To-Go campaign	IUP-UB

ISAF HCHO analyzer	NASA/JPL	Tom Hannisco, Jim Gleason	HCHO VMR profile	BN-2A 27 aircraft	INCAS	Integration in BN-2 TBC	BIRA
PICARRO G2107	INCAS	Andreea Calcan	HCHO VMR profile	BN-2A 27 aircraft	INCAS	RAMOS campaign	BIRA
BBLIFF	UNICH	Piero Di Carlo	HCHO VMR profile	ATr-42, BaAe-145, Partenavia P68B D-GERY	EUFAR	Under development; Not available for 2019 campaign; Probably available from 2020 onwards	BIRA
PICARRO G2401-mc	INCAS	Andreea Calcan	CO, CO_2, CH_4, H_2O VMR profile	BN-2A 27 aircraft	INCAS	RAMOS campaign	BIRA
PICARRO G2401-mc	LSCE	Michel Ramonet	CH_4, CO, CO_2 VMR profile	Piper Arrow (up to 3 km)	Private	None so far	BIRA
Los Gatos Research UGGA multi.gas CRDS	IUP-UB	Heinrich Bovensmann	CH_4, CO, CO_2 VMR profile	Cessna 207T aircraft	FUB	None so far	IUP-UB
Dual Quantum Cascade Laser System (Aerodyne)	DLR-IPA	Anke Roiger	CH_4, CO, CO_2, C_2H_6 VMR profile	DLR FALCON	DLR	Methane-To-Go campaign	IUP-UB
TSI Aerosol particle sizer 3321	INOE	Livio Belegante	Aerosol size distribution	BN-2A 27 aircraft	INCAS	RAMOS campaign	BIRA
TSI Nephelometer 3563	INCAS	Andreea Calcan	(back)Scattering and angstrom coefficients	BN-2A 27 aircraft	INCAS	RAMOS campaign	BIRA
Ground-based RS							
Tropospheric Ozone lidar	NASA	Barry Lefer	O_3 VMR profile	Static	NASA	Availability during campaign at Cabauw	KNMI
5 to 10 Pandora 2S	NASA	Bob Swap, Barry Lefer	NO_2, O_3 column	Static	TBD	Availability during campaign in Ruhr area	IUP-UB
Pandora 2S	ESA - ESRIN	Alexandru	NO_2, O_3 column	Static	INOE	None so far	BIRA

		Dandocsi					
4-azimuth scanning DOAS	MPIC Mainz	Thomas Wagner	NO_2, SO_2, HCHO column	static	MPIC	None so far	IUP-UB
IMPACT imaging DOAS	IUP-UB	Andreas Richter	NO_2 column	Static	IUP-UB	None so far	IUP-UB
MAX-DOAS	IUP-UB	Andreas Richter	NO_2, SO_2, HCHO column	Static	IUP-UB	None so far	IUP-UB
ENVIMES MAX-DOAS	IUP-Heidelberg	Jan-Lukas Tirpitz	NO_2 SO_2, HCHO and aerosol vertical profiles	Static	IUP-Heidelberg	None so far	BIRA
PMAX – Polarisation Sensitive MAX-DOAS Instrument	IUP-Heidelberg	Jan-Lukas Tirpitz	NO_2, HCHO VMR profiles; aerosol extinction profiles + microphysical properties	Static	IUP-Heidelberg	Instrument under development	BIRA
Mobile-DOAS	BIRA	Alexis Merlaud	NO_2, SO_2 column	Car mobile-DOAS	BIRA	None so far	BIRA
Mobile-DOAS	MPIC Mainz	Thomas Wagner	NO_2, SO_2, HCHO column	Car mobile-DOAS	MPIC	None so far	IUP-UB
Mobile-DOAS	UGAL	Daniel Constantin	NO_2, SO_2 column	Car mobile-DOAS	UGAL	None so far	BIRA
Mobile-DOAS	BOKU/IUP-UB	Stefan Schreier	NO_2, SO_2, HCHO column	Car mobile-DOAS	BOKU/IUP-UB	None so far	IUP-UB
Bike-DOAS	BIRA	Frederik Tack	NO_2, SO_2 column	Bike	BIRA	None so far	BIRA
SO_2 camera	BIRA	Hugues Brenot	SO_2 column	Static	BIRA	None so far	BIRA
COCCON (Collaborative Carbon Column Observing Network) - Bruker EM27/SUN portable FTIR spectrometer network	different investigators inside and outside EU (contact: KIT)	Frank Hase	H_2O, CO, CH_4 column	Static	different investigators inside and outside EU (contact: KIT)	None so far	KIT
Bruker Vertex70	IUP-UB & BIRA	Justus Notholt & Martine De Maziere	CO, CH_4, H_2O, HCHO (TBC)	Static	IUP-UB & BIRA	None so far	BIRA

Sun-lunar photometer CIMEL	INOE	Livio Belegante	Aerosol	Static	INOE	RAMOS campaign	BIRA
Multiwavelength Raman lidar	INOE	Livio Belegante	Aerosol	Static	INOE	RAMOS campaign	BIRA
Fixed stations at Cabauw supersite (e.g. Max-DOAS, Ceilometer, CIMEL, etc.)	KNMI	Arnoud Apituley				None so far	KNMI
Fixed stations at Magurele supersite (e.g. Max-DOAS, Ceilometer, CIMEL, etc.)	INOE	Doina Nicolae				RAMOS campaign	BIRA
Ground-based in-situ							
AS32M CAPS	BIRA	Alexis Merlaud	NO_2 surface concentration	Static	BIRA	None so far	BIRA
Mobile lab	INOE	Livio Belegante	Gas analyzers, UV depolarisation lidar, weather station	van	INOE	RAMOS campaign	BIRA
Los Gatos Research UGGA multi.gas CRDS	IUP-UB	Heinrich Bovensmann	CH_4, CO, CO_2 VMR profile	car/van	IUP-UB	None so far	IUP-UB
NO_2-sonde	KNMI	Piet Stammes	NO_2 VMR profile	Weather balloon or drone	KNMI	None so far	KNMI
AirCore	UGroningen	Huilin Chen	CH_4, CO, CO_2	Meteorological balloon	UGroningen	None so far	BIRA
AirCore	LSCE	Michel Ramonet, Cyril Crevoisier	CH_4, CO, CO_2	Launch from Trainou tall tower	LSCE	None so far	BIRA

Table 5.2: Inventory of supporting model tools.

Supporting model tools	Institute	Contact person	Modeled variables	Horizontal resolution	Vertical resolution	Time resolution	NRT/forecast capability
CAMS C-IFS	ECMWF	Richard Engelen	>55 species	40 km	60 levels covering full atmosphere	3 hours	Yes
CAMS European Air Quality (Ensemble Model)	ECMWF	Richard Engelen	All key pollutants, aerosol, pollen, etc.	10 km	10 to 20 levels in 0-5 km altitude range	1 hour	Yes
WRF-CHEM 3.9	BIRA	Jenny Stavrakou	Meteorological, chemical and aerosol variables.	Variable, from 25, 15, 3 km down to 1 km	Variable, in general in between 30 - 90 levels	Time step: depending on configuration and resolution, CFL criterion	Yes
IMAGES/MAGRITTE	BIRA	Jenny Stavrakou	Chemical species (171 compounds, more than 40 VOCs)	Variable, from 2x2.5 degrees, 1x1 degrees to 0.5x0.5 degrees	40 vertical levels from the surface to lower stratosphere	Time step : variable (from 1 day to 20 minutes)	No
TM5; CAMS-Regional CIFS; LOTOS-EUROS	KNMI	Henk Eskes	Chemical species (O_3, NO_2, PM, etc), met fields	TM5: 1 x 1 deg; 0.1 x 0.1 deg ; LOTOS-EUROS: 7 x 7 km	TM5: variable, more near-surface 173 layers	TM5: hourly or per 30 minutes; LOTOS-EUROS: hourly	N/A
MCARTIM 3 (3-D inversion) from MAX-DOAS measurements	MPIC Mainz	Thomas Wagner	3-D-Gradients of NO_2, SO_2, and HCHO	2 – 5 km	200 – 500 m	30 min	No
GeosChem	Univ. Wollongong	J. Fisher	CH_4, CO, CO_2	0.25 degrees	1 km	hourly	No

Table 5.3: Inventory of potential target areas for campaign deployment.

Target areas for campaign deployment	Local organisation	Contact person	Latitude (°N)	Longitude (°E)	Comments/ possible deployment strategy
Deployment of airborne and ground-based component for trace gases					
Romania, Bucharest	INOE	Doina Nicolae	44.4	26.1	Mapping of urban area; Experience gained during AROMAT campaigns; Focus on NO_2
Romania, Jiu Valley	INOE	Doina Nicolae	44.7	23.3	Mapping of exhaust plumes over major power plants in the Jiu Valley; Experience gained during AROMAT campaigns; Focus on NO_2, HCHO, SO_2
Belgium, Antwerp	BIRA	Frederik Tack	51.1	4.5	Mapping of urban area and industrial sites in the harbor of Antwerp; Experience gained during BUMBA campaigns; Focus on NO_2
The Netherlands, Cabauw + Rotterdam area	KNMI	Arnoud Apituley	52.0	4.9	Mapping of urban area and background; CESAR supersite; Flight regulations to be assessed; Established experience for flying drones at Cabauw site from ground to ~200m
(Northern) Germany	IUP-UB	Andreas Richter	52.5	13.4	Mapping of urban agglomerations in northern Germany; Possible sites: Berlin (experience gained from >4 flights and AROMAPEX campaign), Hamburg (no experience, two ground based DOAS stations & Aeronet station available); mapping of Ruhr industrial area; Transect flight from South to North Germany
Northern Italy	TBD	TBD	45.0	10.5	Potential target area for VOC (HCHO, CO) and NO_2 validation
Deployment of ground-based component for trace gases					
Shipping cruises in the North Sea	TBD	TBD	50 - 55	-8 - 7	Deployment of ground-based instruments on cruise/ferry ships; Potential for NO_2 and SO_2 validation from shipping and pollution outflow sources
Shipping cruises in Mediterranean area	TBD	TBD	35 - 43	-5 - 20	Deployment of ground-based instruments near Etna and on cruise/ferry ships; Potential target area for NO_2, HCHO and volcanic SO_2 validation
Vienna, Austria	Boku	Stefan Schreier	48.2	16.4	Two stationary MAX-DOAS, German co-funding for mobile DOAS measurements and Donau tower horizontal DOAS, localized high NO_2 and HCHO, mapping of city and surroundings as measurement strategy
Deployment of airborne and ground-based component for GHG					
Poland, Upper Silesian Basin	IUP-UB	Heinrich Bovensmann	50.2	18.9	"Light" campaign version based on experience gained during COMET in 20017/2018. Interesting mix of NO_2, CO and CH_4 emitters, but focus on

					CH_4
Suriname	Meteorological service Suriname (MDS)	Huilin Chen	3.9	-56.0	Plan of tropical campaign to sample with AirCores gaining measurements of CH_4, CO and CO_2
The Netherlands, De bilt + Cabauw	KNMI	Huilin Chen	52.1	5.2	Plan of mid-latitude field campaign to sample with AirCores gaining measurements of CH_4, CO and CO_2
Deployment of ground-based component for GHG: EM27/SUN (COCCON)					
Central Europe	KIT & COCCON partners	Frank Hase	Central Europe	Central Europe	Extension of COCCON activities planned across Europe for improving the capability of detecting spurious across-track variations in S-5p data products; Complement announced activities in Western and Eastern Europe with additional EM27/SUN observations in Central Europe
USA, Alaska (high Arctic)	UAF, LANL, KIT	William Simpson	64.9	-147.8	CH_4 gradients; Use of two spectrometers for gradient observations has been demonstrated successfully at UAF before.
Germany, Hamburg	TUM & COCCON partners	Jia Chen	53.5	10.0	CH_4 city emissions; Deployment of several spectrometers around the Hamburg area, preferred period July - September
Mexico, Mexico City	UNAM, LSCE	Michel Grutter	19.4	-99.1	CH_4 and CO emissions; UNAM has successfully operated small FTIR spectrometers in that area before
Spain, Madrid	AEMET	Omaira Garcia	40.4	-3.7	AEMET will perform a campaign for observing Madrid in autumn 2018, so experience with local conditions can be assumed afterwards
Namibia, Gobabeb site (high-albedo site)	KIT, Gobabeb Research and Training Site	Frank Hase	-23.6	15.0	For a duration of two years, a spectrometer has been successfully operated at the site previously
Romania, Margurele site + campaign observations	INOE	Dragos Ene	44.4	26.0	Campaign observations of mud volcanoes, landfills, refineries; INOE operates an ESA-owned EM27/SUN spectrometer in Romania since spring 2017
Spain, Almeria	AEMET	Omaira Garcia	37.1	-2.4	High ground albedo region (desert); Plataforma Solar de Almería (PSA, 37ºN, 2ºW), located in the Tabernas desert with high ground albedo (desert)
LAMTO (Ivory Coast) and AM5 (Morocco) surface measurement sites	LSCE	Michel Ramonet	6.2 (Lamto) 31.1 (Morocco)	5.2 (Lamto) -7.6 (Morocco)	June – August: in Morocco this correspond to the period of dust coming from Africa. Nov - Feb: In Lamto for the observation of the biomass burning plumes

NZ's Arrival Heights laboratory on Ross Island, Antarctica	NIWA, KIT	Dave Pollard	-77.8	166.7	Austral summer period 2019 (January-April and October-December)
Uganda, Jinja	U. Leicester, TUM	Hartmut Boesch	0.4	33.2	Observe CH_4 and CO in tropical wetlands (and fire);One spectrometer available, planned to be deployed for duration of 12 months
Poland, Upper Silesian Coal Basin	IUP-Heidelberg, KIT, TUM, DLR	André Butz	50.0	18.7	Mobile EM27/SUN will be deployed in network configuration with 4 stationary COCCON spectrometers (KIT, TUM, INOE); Mobile deployments have successfully been performed during three field campaign and led to peer-reviewed publications (Klappenbach et al., 2015; Butz et al., 2017)
Poland, Upper Silesian Basin	AGH	Jaroslav Necki	50.2	18.9	Experience gained during COMET in 20017/2018. Interesting mix of NO_2, CO and CH_4 emitters. Contact to be established via IUP-UB

Table 5.4: Non-exhaustive list of related nationally funded field campaigns.

Related field campaigns	Leading agency/ institute	Contact person	Target area	Campaign objectives/topics	Measured variables
New York City area (2018)	NASA	Jay Al-Saadi	US, New York city area	Urban emissions	NO_2, HCHO column, aerosol layer height and optical depth
FireChem (2019)	NASA	Jay Al-Saadi	The whole of US	Forest fires emissions	O_3 tropospheric column and VMR profile, NO_2, HCHO, CO, CH_4 column
AJAX (2018-2020)	NASA	Jay Al-Saadi	US, San Francisco bay area	VMR profiles	O_3, NO_2, HCHO, CH_4, H_2O VMR profiles
Innsbruck campaign (2019 ground based – 2020 airborne)	UNICH	Piero Di Carlo	Innsbruck	Testing new compact airborne instrument, based on laser induced fluorescence technique	HCHO and NO_2 VMR profiles
RAMOS (May 2019) – focus on trace gases	INOE, INCAS, UGAL, BIRA	Dragos Ene	Romania, Bucharest, Jiu Valley and Constanta	Testing scientific infrastructure for mobile atmospheric observation, including ground-based and airborne mapping and profiling flights	Airborne: NO_2 and SO_2 column, NO_2, O_3, HCHO VMR profiles, in situ H_2O, HCHO and NO_2 Ground-based: NO_2, O_3, SO_2, H_2CO column
RAMOS (July 2019) – focus on greenhouse gases	INOE, INCAS, UGAL, BIRA	Dragos Ene	Poland, Rzecin	Testing scientific infrastructure for mobile atmospheric observation, including ground-based and airborne mapping and profiling flights	Airborne: CO_2, CO, CH_4, H_2O VMR profiles Ground-based: O_2, CO_2, CH_4, H_2O, CO column
COMET HALO (2018)	DLR, IUP-UB	Andreas Fix, Heinrich Bovensmann	Upper Silesian Basin, Poland	Combined active and passive remotes sensing of CH_4, estimate CH_4 emissions from USB	CH_4, CO_2 columns and VMR profiles
MAGIC-COMET (2018)	LMD, LSCE, GSMA, LOA,	Cyril Crevoisier	Trainou, Aire-sur-l'Adour, France and	Understanding of vertical exchange of GHG along	CH_4 and CO total columns

	LERMA		Upper Silesian Basin, Poland	the atmospheric column, in connection with atmospheric transport, sources and sinks of the gases at the surface and in the atmosphere	
Methane-To-Go (Nov. 2019)	DLR-IPA	Anke Roiger	Persian Gulf	Emissions from oil and gas operations	CH_4, CO, CO_2, C_2H_6, N_2O, H_2O, SO_2, NO VMR profiles
RINGO campaigns (2019)	UGroningen	Huilin Chen	Trainou, France	Development of vertical profile measurements using AirCore and TCCON	CH_4, CO and CO_2 VMR profiles
AEOLUS	KNMI	Ad Stoffelen	Cabauw, The Netherlands	Validation of Aeolus wind, aerosol and cloud profiles of backscatter, extinction and lidar-ratio using CESAR observations during close proximity overpasses. Assessment of representativeness of Aeolus wind, aerosol and cloud products using time series of CESAR observations.	Campaign planning status unknown at this moment, but initial interest in combining with TROPOMI campaign at Cabauw

Table 5.5: Preliminary list of campaign participants.

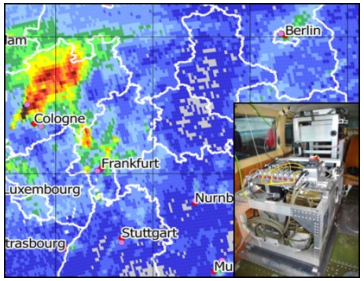
Participants	Institute	E-mail address	Comments
Michel Van Roozendael	BIRA	michel.vanroozendael@aeronomie.be	
Frederik Tack	BIRA	frederik.tack@aeronomie.be	
Alexis Merlaud	BIRA	alexis.merlaud@aeronomie.be	
Martine De Mazière	BIRA	martine.demaziere@aeronomie.be	
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Thorsten Fehr	ESA	thorsten.fehr@esa.int	
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Jay Al-Saadi	NASA	j.a.al-saadi@nasa.gov	
Bart Bomans	VITO	bart.bomans@vito.be	

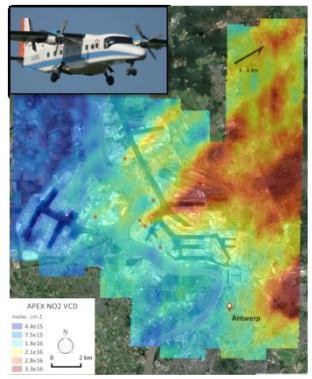
Daniel Iordache	VITO	marian-daniel.iordache@vito.be	
Thomas Wagner	MPIC	thomas.wagner@mpic.de	
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Udo Friess	IUP-UH	udo.friess@iup.uni-heidelberg.de	
Lucas Tirpitz	IUP-UH	tirpitz@stud.uni-heidelberg.de	

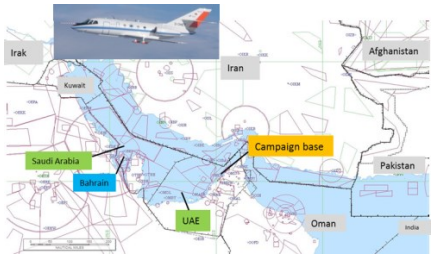
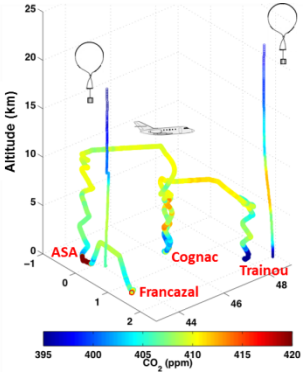
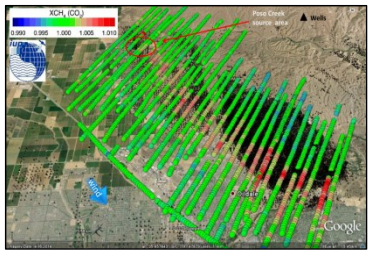
6 Validation campaign concepts addressing all operational products covering the S-5p lifetime

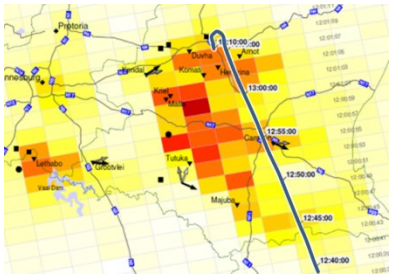
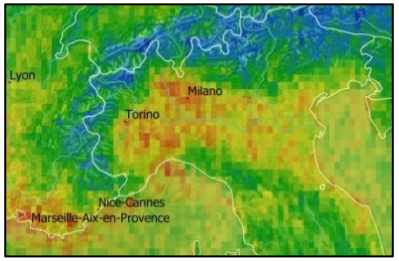
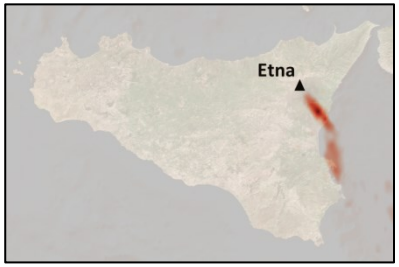
Based on the requirement analysis presented in section 4, and the inventory of available infrastructures presented in section 5, we have identified a series of campaign strategies addressing key priorities for campaign deployment. The proposed choices are listed in Table 6.1, where they are also traced back to the relevant validation campaign requirements. Further descriptions are given in the following sub-sections. In each case, we also provide a synthetic SWOT analysis.

Table 6.1: Overview of S-5p validation campaign concepts covering the full S-5p lifetime

ID	Campaign concepts	S-5p products	Validation requirements addressed	Campaign teams	Campaign instruments	
1	Airborne deployment for the validation of NO_2, SO_2 and HCHO tropospheric columns in high emission regions in Romania	NO_2 HCHO SO_2	3-4, 9, 15-19 1-2, 7,-8, 13-15 3-4, 7, 11, 14-15	BIRA, INOE 2000, INCAS, UGAL	SWING+, AS32M CAPS, PICARRO G2401-mc, TSI Aerosol particle sizer 3321, TSI Nephelometer 3563, ISAF HCHO analyzer, Pandora 2S, UV depolarization lidar, Sun-lunar photometer CIMEL, Mobile lab, Mobile-DOAS	
2	Airborne deployment for the validation of tropospheric NO_2 point sources and plumes in the German Ruhr area	NO_2 HCHO SO_2	3-4, 9, 15-19 1-2, 7-8, 13-14 3-4, 7, 11	IUP-UB, FUB	AirMAP, nadir Avantes DOAS, FUBISS-ASA2, ground-based Pandora (TBC), mobile car-DOAS	

3	COCCON ground-based FTIR deployment for the validation of CH_4 and CO columns	CH_4 CO	1-2, 8-10, 12-13 2-3, 6, 10, 16-17	KIT & COCCON team	EM27/Sun FTIR spectrometer	
4	CO, CH_4, NO_2, HCHO, cloud and ALH validation at the CESAR super-site [partly funded by national contribution]	NO_2 HCHO CH_4 CO S5P cloud ALH	3-5, 9, 12, 16, 19 1-2, 7, 11, 15 1-3, 4, 11, 13 2-4, 6, 8, 15, 17 15-17 9-11	KNMI, RIVM, TNO BIRA, IUP-UB, Univ of Groningen,	Pandora, MAXDOAS, ACTRIS/Cloudnet, ACTRIS/EARLINET, NO_2 lidar, NO_2 sonde, UV-depolarisation lidar Bruker Vertex 70, AirCore (drone borne and standard),	
5	APEX NO_2 deployment above major Belgian cities [partly funded by national contribution]	NO_2	3-4, 9, 15-19	BIRA, VITO	APEX, Mobile-DOAS, MAX-DOAS	

6	Methane-To-Go campaign in Persian/Arabian Gulf [partly funded by national contribution]	CH_4 CO SO_2	3 4 5, 7	DLR-IPA, DLR-IMF, DLR-FX	Dual Quantum Cascade Laser System (QCLs) Aerodyne, PICARRO, IT-CIMS	
7	MAGIC: a multi-instruments campaign for greenhouse gases and validation of space missions	CH_4 CO	1-3 2-4, 6, 8-9	LMD, CNES, SAFIRE, GSMA, LOA, LSCE, LERMA	Picarro/Falcon20, AirCore, Amulse, CHRIS	
8	Airborne deployment for the validation of CH_4 (and CO) gradients in Upper Silesian Basin (Poland)	CH_4 CO	1-3, 11 2-4, 15	IUP-UB, MPI BGC, DLR IPA, IUP-HD, Univ. Leicester, KIT, AGH, Univ. Groningen	MAMAP CH_4 airborne spectrometer, GHOST CO airborne spectrometer (TBC), ground based mobile FTIR (EM27 etc.), ground based mobile in-situ, airborne in-situ, wind lidars	

9	Airborne deployment for the validation of NO_2, SO_2 and HCHO spatial distribution using transect flights	NO_2 HCHO SO_2	3-4, 9, 15-19 1-2, 7-8, 13-14 3-4, 7, 11	TBD	MAX-DOAS, mobile-DOAS, airborne imaging and in-situ sensors	
10	Airborne deployment for the validation of NO_2, HCHO and CO columns in the Italian Po-valley area	NO_2 HCHO CO	3-4, 9, 15-19 1-2, 7,-8, 13-15 2-4, 6, 15, 17	TBD	MAX-DOAS, mobile-DOAS, airborne imaging and in-situ sensors, EM27/SUN, sunphotometer, aerosol lidar, in-situ pollution monitoring stations	
11	Airborne deployment for the validation of SO_2 plumes emitted by the Etna volcano, Sicily	SO_2	1-2, 9, 12-13	TBD	Airborne imaging DOAS and in-situ sensors, ground-based UV, VIS and TIR cameras, scanning DOAS and lidar	

6.1 Airborne deployment for the validation of NO_2, SO_2 and HCHO tropospheric columns in high emission regions in Romania

Bucharest (44°25'57" N, 26°06'14" E) is the capital and largest city in Romania with a population close to two million. It is a significant source of NO_2, mainly due to traffic emissions but also related to several power plants, located within the Bucharest ring road. During summer time, the area is characterized by hot sunny conditions which favor the release of VOCs from natural (vegetation) and anthropogenic sources in the city. Located at approximately 200 km west of the city, the large power plants of the Gorj county (Turceni and Rovinari) are also strong emitters of pollutants. During the precursor AROMAT campaigns in 2014 and 2015, large plumes of NO_2 and SO_2 have been detected with NO_2 columns reaching up to 1e17 mol/cm^2 and SO_2 columns up to 4e18 mol/cm^2. Although all the NO_2 sources can be clearly resolved in the TROPOMI NO_2 data, it is at the moment uncertain whether SO_2 columns can still be detected, since emissions in the Jiu Valley have sharply decreased after the recent installation of desulfurization units. Based on OMI experience, it is anticipated that HCHO columns will be detected by TROPOMI.

The proposed campaign concept aims at taking full benefit of the experience acquired during two successive AROMAT campaigns held in September 2014 (Merlaud et al., 2018) and August 2015 and the AROMAPEX campaign in 2016 (Tack et al., 2018). The infrastructure developed during the RAMOS project (2017-2019) would also be used. To test the infrastructure, there will be a dedicated RAMOS campaign over Bucharest and the Jiu Valley in May 2019. Campaign activities will be well-synchronized with S-5p overpasses.

Based on all expertise, both airborne and complementary ground-based static and mobile observations would be deployed. The strategy would consist in operating airborne mapping and vertical sounding flights, on multiple days, with the aim to capture a statistically significant sample of the target tropospheric pollutants while concurrent observations performed with various measurements systems from the ground would provide the necessary ancillary information (e.g. on aerosol distribution).

In a first phase of the campaign, we propose to focus on the Bucharest area. The airborne deployment will be based on the INCAS BN-2A 27 scientific aircraft, which is equipped to perform both mapping and profiling flights and includes various in-situ and remote-sensing instruments (See Table 7.2). At the ground, continuous measurements will be routinely performed at the INOE/RADO observatory in Magurele with a suite of relevant instruments (PANDORA, aerosol lidar, in-situ samplers, sun photometer). This can be further complemented by the INOE mobile laboratory and the mobile-DOAS systems from UGAL.

In a second phase of the campaign, the focus would move to the large power plants of the Gorj county (Turceni and Rovinari). Although there are four major active power plants (from North to South: Rovinari, Turceni, Isalnita, and Craiova II), we propose to concentrate on the Turceni power station (44°40'7.74" N, 23°24'24.00" E), which is the largest producer of electricity in Romania and one of the largest thermal power plants in Europe. Using the INCAS BN-2 aircraft, mapping flights addressing NO_2 and SO_2 could be performed according to a flight strategy already optimized during the AROMAT campaigns. In-situ sounding flights are clearly more challenging due to the small spatial extent of the power plant exhaust plumes, and therefore the feasibility of performing such flight would have to be investigated possibly with the help of real-time ground-based measurements. At the ground, we would deploy the INOE mobile laboratory consisting of an aerosol lidar, and trace gases monitors. Additionally, one static MAX-DOAS and two mobile DOAS systems operated by UGAL could be deployed to provide reference measurements, including Aerosol Optical Depth (AOD).

Table 6.2: Romanian campaign concept summary and SWOT analysis.

Addressed S-5p products	NO_2, HCHO and SO_2 tropospheric columns; NO_2 and HCHO VMR profiles; aerosol layer height
Campaign teams	BIRA, INOE 2000, INCAS, UGAL
Campaign instruments	SWING+, AS32M CAPS, PICARRO G2401-mc, TSI Aerosol particle sizer 3321, TSI Nephelometer 3563, ISAF HCHO analyzer, Pandora 2S, UV depolarization lidar, Sun-lunar photometer CIMEL, Mobile lab, Mobile-DOAS
Strengths / Opportunities	• Significant sources of air pollutants and elevated levels, observed from space • Sound expertise, built during the AROMAT-1 and -2 campaigns: high maturity level and reduces preparation efforts and costs • Benefit from the ground-based and airborne infrastructure, developed during the RAMOS project and the RAMOS campaign activities taking place in May, 2019
Weaknesses / Threats	• Instrument integration in INCAS BN-2 aircraft and EASA certification is still ongoing at time of writing (July, 2018) • Flight autonomy is 6 hours without instruments but limited to 2 hours when all instruments switched on • Flight altitude is limited to 3 km • Uncertain if anthropogenic SO_2 can still be observed in the Jiu Valley due to desulfurization

6.2 Airborne deployment for the validation of tropospheric NO_2 point sources and plumes in the German Ruhr area

North Rhine Westphalia (NRW) is the most populous federal state of Germany, with a population of approximately 18 million. Large parts of NRW are characterized by contiguous urban agglomerations with many industrial sites, such as the Ruhr area in the north western part of NRW. The southern part of NRW accommodates some of the largest coal fired power plants in Germany, located south west of Cologne. This makes the NRW area a suitable site for the characterization of industrial, as well as urban NO_2 plumes, which are readily discernible in daily NO_2 S5-p overpass data.

The S-5p NO_2 product shall be validated by airborne imaging DOAS measurements of the AirMAP instrument, aiming at gapless measurements above the envisaged target sites. The spectra acquired by AirMAP will be used to retrieve the NO_2 VCD below the aircraft, as well as the surface reflectance of the covered ground scenes in the spectral interval of the NO_2 DOAS analysis. Installed on the FUB Cessna, the AirMAP measurements shall be complemented by vertical soundings of the AOD by the FUBISS-ASA2 airborne sun photometer, installed on the same aircraft, from which aerosol extinction coefficient profiles can be derived. The information about the vertical aerosol distribution will assist in improving the accuracy of both AirMAP products (NO_2 VCD and surface reflectance) using the derived aerosol profile as input for radiative transfer simulations. An additional nadir viewing Avantes spectrometer will provide sub-aircraft columns of NO_2, HCHO, and SO_2, albeit without mapping capabilities. These data can be used to evaluate spatial gradients in SO_2 and HCHO and if conditions are sufficiently homogeneous, also for validation of the corresponding S5-p products.

The airborne imaging DOAS measurements shall be supported by ground-based instrumentation consisting of (mobile) (MAX)-DOAS instruments deployed during the campaign. Furthermore, the representativeness of the airborne sun photometer measurements can be investigated by performing mobile AOD measurements with a handheld sun photometer. In addition to instrumentation specifically deployed, the campaign should also take advantage of existing infrastructure for measurements of atmospheric parameters that can help in the validation and interpretation of the campaign data sets. This includes for example the dense in-situ air quality network in NRW, as well as the AERONET station installed at the Jülich Research Center (FZJ) or the regional chemistry model, EURAD, developed and operated at the University of Cologne. Temporary installation of additional Pandora sites in the area is currently under investigation.

We propose to focus on two target sites, with at least two flights per location to be able to judge the representativeness of the measurements at a specific site.

A well-suited area for rather isolated industrial emissions is the area between Aachen, Düsseldorf and Cologne, where three large coal fired power plant are located.

a) Power plant Weisweiler at about 50.8N, 6.3E and

b) Power plant Niederaußem at about 51.0N 6.67E and

c) Power plant Neurath at about 51.0N 6.60E

Possible sites for urban NO_2 plumes are manifold in the NRW area. Here the choice of a good target site depends mainly on the wind conditions during the flight. In order to capture strong horizontal gradients, and also to acquire a background spectrum for the AirMAP DOAS analysis, rather clean areas should be covered in addition to pollution hot spots. We thus propose to decide the exact location based on the expected wind direction. For winds coming from west or north, the area around Duisburg (51.5°N, 6.8°E) appears to be a good candidate with a mixture of urban and industrial emissions. For winds coming from south / southwest, the measurements should concentrate on the area around Cologne to cover rather clean parts upwind of the city.

An advantage of the proposed location is the vicinity to nationally funded campaign activities organized by IUP-UB (Germany) and KNMI (The Netherlands), which may reduce cost by avoiding additional costs from transfer flights.

Table 6.3: German campaign concept summary and SWOT analysis.

Addressed S-5p products	NO_2, HCHO and SO_2 tropospheric columns
Campaign teams	IUP-UB, FUB, Pandora and mobile DOAS teams (TBC)
Campaign instruments	AirMAP, nadir Avantes-DOAS, FUBISS-ASA2, Mobile-DOAS
Strengths / Opportunities	• Significant pollution sources and elevated levels, observed from space • Sound expertise, built during the AROMAT-1 and -2 and other campaigns: high maturity level and reduced preparation and costs • Unique combination of power plant and city sources, large signals, excellent surface in-situ network • Investigation of surface reflectance
Weaknesses / Threats	• No NO_2 vertical profiles beyond what is provided by ground-based Pandora / MAX-DOAS • Magnitude of SO_2 and HCHO columns may be too low for quantitative detection by S5-p • Validation measurements are best performed under cloud-free or partially cloud-free conditions which are not guaranteed • The maximum flight altitude of the FUB Cessna limits the vertical extent of the tropospheric columns determined

6.3 COCCON ground-based FTIR deployment for the validation of CH_4 and CO columns

The COCCON (COllaborative Carbon Column Observing Network) is comprised of portable low-resolution EM27/SUN FTIR spectrometers. These spectrometers record solar absorption spectra in the near infrared spectral region. From these observations, column averaged trace gas abundances of water vapour, carbon dioxide, methane, and carbon monoxide can be deduced. The spectrometers within COCCON have been quality-checked and calibrated with respect to TCCON before going into operation at a central facility hosted by KIT, Germany. All spectrometers have identical design, and a very low scatter of instrument-specific residual characteristics. A review demonstrating the consistency between individual spectrometers and the long-term stability of the EM27/SUN spectrometer has recently been submitted to AMT (Frey et al., 2018).

A common preprocessing tool for the recorded interferograms is already available (deliverable in the framework of the ESA project COCCON-PROCEEDS), which allows immediate generation of spectra including quality selection by the operator. The subsequent trace gas analysis will either be done by the operator using standardized code provided by KIT, or ideally performed at a centralized data retrieval facility. In this case the operator simply will submit the spectra resulting from the preprocessing together with required auxiliary information to the central facility. Whether the central facility will already be operational in 2019 for the COCCON campaign data depends on the further progress achieved in this respect before end of 2018. Independent from the chosen approach – preliminary distributed analysis with common code or the desired centralized processing scheme – the data processing chain will be identical for all spectrometers, to ensure strict conformity of results not only with respect to hardware, but also with respect to processing algorithms.

Due to the fact that COCCON delivers column-averaged abundances of methane and carbon monoxide with consistent data quality at selectable sites, it becomes a highly promising component for the validation of these S-5p data products.

(A) The data set will offer a wide latitudinal coverage for checking variations of S-5p data performance (scatter and bias) on a global scale.

(B) The data set will cover high- and low albedo sites for checking possible variations of S-5p data with respect to ground characteristics.

(C) The data set will contain observations of localized sources (large cities, ventilation shafts of Silesian coal mines, Australian bush fires, etc.), which will allow to deduce S-5p's detection limit for small-scale variations in the distribution of carbon monoxide and methane.

(D) The COCCON data collected across Europe for the purposes A - C will in addition be exploitable for detecting possible spurious variation of S-5p as function of the nadir angle of the satellite observation (systematic across-track dependency).

(E) As the COCCON spectrometers due to the short integration time and moderate spectral resolution can still be operated successfully under partly cloudy / hazy / cirrus conditions, the data set will also be exploitable for detecting problems of the S-5p data products under less-than ideal meteorological conditions.

The COCCON activities span a large observation area and a major fraction of 2019, which will allow for merging the largest number of potentially valuable contributions into a comprehensive validation data set. Also, the temporal equalization of various campaign activities during 2019 will corroborate the permanent long-term observations of TCCON (which are not part of the dedicated S-5p campaign) in the detection of drifts and seasonal variations of the satellite data.

Table 6.4: COCCON campaign concept summary and SWOT analysis.

Addressed S-5p products	CH_4 and CO total columns
Campaign teams	KIT, Germany Univ. Heidelberg, Germany TUM, Germany AEMET, Spain Univ. of Alaska Fairbanks, USA LANL, USA Univ. of Leicester, UK Univ. of Wollongong, Australia LSCE, France CNES, France NIWA, New Zealand INOE, Rumania UNAM, Mexico
Campaign instruments	Network of portable, centrally calibrated EM27/SUN FTIR spectrometers.
Strengths / Opportunities	• Uses centrally calibrated technically identical FTIR spectrometers and common data processing scheme, low infrastructure requirements • Distributed campaign, covers a wide range of geophysical parameters, allows synergistic combination of resulting data pool for testing S-5p data in various respects (latitude, season, humidity, ground albedo, cloud cover, signals on different geometric scales, etc.) • Low vulnerability due to degree of spatial and temporal distribution and involvement of many teams with FTIR experience
Weaknesses / Threats	• The extent of several suggested activities depend on availability of national co-funding (low risk) • Few suggested components require temporal shipment of spectrometers to non-EU destinations, delays or rejection by customs possible (very low risks)

6.4 CO, CH_4, NO_2, HCHO, cloud and ALH validation at the CESAR super-site [partly funded by national contribution]

The Cabauw Experimental Site for Atmospheric Research (CESAR) is located in the western part of The Netherlands (51.971° N, 4.927° E) in a polder 0.7 m below average sea-level, about 25 km south-west of Utrecht. The site has a long history of performing atmospheric measurements since its establishment in 1972. It has been used for monitoring long-term tendencies in atmospheric changes and for the study of atmospheric and land surface processes for climate modeling and validation of space-borne observations. The Cabauw site is equipped with a tall tower (213 m AGL) and several in-situ and remote sensing measurement facilities, which makes it a supersite for atmospheric research [DR 10].The site is well equipped and ample experience exists for hosting large-scale campaigns (e.g. CINDI-2 in 2016, PEGASOS campaign in 2012). This makes it well suited to reach the campaign goals, which will be developed along two lines of activities addressing respectively: 1) the validation of CO and CH_4 columns, and 2) the impact of clouds on the accuracy of NO_2 and HCHO columns and ALH measurements.

CO and CH_4 column validation

The proposed campaign concept addresses the simultaneous measurements of CH_4 and CO columns and vertical profiles. Column measurements will be performed using an automated low-resolution Bruker Vertex70 FTIR spectrometer equipped with a home-built solar tracker system and demonstrated as part of the ESA FRM4GHG project. The Vertex70 records solar absorption spectra in the near infrared (NIR) and mid infrared (MIR) spectral regions from which dry air trace gas concentrations of CH_4, CO and other gases can be retrieved. FTIR measurements will be complemented by in-situ measurements of CH_4 and CO performed at four layers (20 m, 60 m, 120 m and 200 m) on the Cabauw tower. These measurements form an important part of the ICOS research infrastructure [DR 11]. In addition, several AirCore launches will be performed to capture the vertical profile (from the surface up to 30 km) of the respective target gases (CO_2, CH_4 and CO). Since the lower-most part of the AirCore profile typically has a larger uncertainty, this part of the profile will be further sampled using drone-based AirCore measurements which can provide accurate measurements in the lowermost layers of the atmosphere.

The possibility to perform such an extensive combination of measurements is unique to the CESAR site and will provide significant added-value for the validation of the targeted S-5p products of total CH_4 and CO columns. Intensive measurements are planned to be conducted between May and August 2019. During this period, AirCore launches (drone + standard) will be performed on several days during the morning hours (weather-permitting) to capture the profile shape variability of the target species.

NO_2 and HCHO column, ALH and cloud effect validation

The unprecedented high-resolution observations of S-5p at 3.5 x 7 km^2 result in cloud effects that have been of less importance to previous missions due to lower resolution. These cloud effects include 3D cloud effects under broken cloud conditions, effects of multi-layered clouds and shadowing effects of convective clouds on the land surface.

Campaign goals:

- Study effects of complex cloud conditions on S-5p trace gas retrievals, in particular NO_2
- Study effects of aerosol conditions on S-5p trace gas retrievals, in particular NO_2
- Study effects of vertical NO_2 distribution in the troposphere under complex cloud conditions on S-5p trace gas retrievals, in particular NO_2

Study angular dependence in nadir measurements and their impact on NO_2 retrievals under complex cloud conditions.

Table 6.5: CESAR campaign concept summary and SWOT analysis.

Addressed S-5p products	CH_4 and CO total columns, NO_2, HCHO, ALH, S-5p Clouds
Campaign teams	KNMI (responsible for access to Cabauw infrastructure and for campaign support), RIVM, TNO, BIRA, IUP-UB, Univ of Groningen
Campaign instruments	Bruker Vertex70, AirCore (drone-borne), AirCore (standard), Pandora, MAX-DOAS, ACTRIS/Cloudnet, ACTRIS/EARLINET, NO_2 lidar, NO_2 sonde, UV-depolarisation lidar
Strengths / Opportunities	• Background site under the influence of several major sources of air pollutants • Large number of instruments in-place to perform the correlative observations. Unique capabilities are available for NO_2 profiling (sonde and DIAL). • Large suite of ancillary observations, in particular for clouds and aerosols, including in-situ, column integrated and profiling instruments • Demonstrated experience of hosting large-scale campaigns (e.g. PEGASOS, CINDI-2); availability of ICOS standard in-situ measurements of CH_4 and CO • Links with various other campaign concepts are possible.
Weaknesses / Threats	• Remote sensing measurements using the direct solar absorption technique in the infrared spectral region can only be performed under clear or partly cloudy conditions such that the solar disk is clearly visible and we have sufficient signal level (low risk) • AirCore launches can only be performed under good meteorological conditions and flight permission has to be obtained for the standard AirCore launch (low risk)

6.5 APEX NO_2 deployment above major Belgian cities [partly funded by national contribution]

This campaign deployment focuses on urban and industrial emissions of tropospheric reactive gases of some of the largest and most heavily polluted Belgian cities, such as Brussels (50°51'02" N, 04°20'56" E, 1.2 million inhabitants) and Antwerp (51°15'37" N, 04°24'10" E, 0.5 million inhabitants). Flights are also foreseen over the port of Antwerp, one of the biggest (petro)chemical clusters in Europe. The horizontal distribution of the trace gas field will be mapped based on hyperspectral Airborne Prism EXperiment (APEX) observations. APEX was also one of the airborne hyperspectral imagers, operated during the AROMAPEX campaign over Berlin (Tack et al., 2018), alongside AirMAP, SWING and Spectrolite Breadboard Instrument. As the APEX instrument does not cover the UV band, the focus will be on the spatial distribution of tropospheric NO_2 solely. During previous flights with APEX over Brussels and Antwerp in the framework of the BUMBA project (Tack et al., 2017), clear NO_2 hotspots and strong horizontal gradients could be detected, related to traffic and industry. The city plumes can also be resolved in recent S-5p daily orbits. The flights will be carefully planned and optimized to coincide with the S-5p overpasses in order to fully cover multiple S-5p pixels (in the order of 10-30) with a short temporal offset, facilitating validation of the S-5p tropospheric NO_2 product. In addition to the airborne component there will be ancillary ground-based component consisting of MAX-DOAS and mobile-DOAS instruments.

Table 6.6: APEX campaign concept summary and SWOT analysis.

Addressed S-5p products	NO_2 tropospheric columns
Campaign teams	BIRA, VITO
Campaign instruments	APEX, MAX-DOAS, Mobile-DOAS
Strengths / Opportunities	• Significant sources of air pollutants and elevated levels, observed from space • Recurrent APEX activities in Belgium (each year multiple campaigns, but mostly for LULC applications) • Sound expertise, built during the BUMBA and AROMAPEX campaigns: high maturity level and reduces preparation efforts and costs
Weaknesses / Threats	• Airborne campaign costs would be covered by national BELSPO funding. However there is no formal agreement on this so far. • APEX lifetime: No major instrument repair is foreseen in case of severe failure. An APEX successor (able to monitor air pollutants) is currently not operational.

6.6 Methane-To-Go campaign in Persian/Arabian Gulf [partly funded by national contribution]

The proposed campaign focuses on emissions from the off- and on-shore natural gas and oil operations in the Persian/Arabian Gulf region (~24-27°N, ~50-56°E), a wealthy region which contains about 50% of the world´s oil reserves. The flaring, venting and combustion processes produce large amounts of CH_4, a greenhouse gas that is about 25 times more potent than CO_2 and in focus of current mitigation strategies trying to reduce global warming. However, there is a huge lack of detailed CH_4 measurements in the Gulf region and the contribution from this region to the global CH_4 mass balance is presently unknown.

Furthermore, recently a first global satellite-derived SO_2 emission inventory was established based on measurements with the Ozone Monitoring Instrument (OMI) on the NASA Aura satellite, showing a number of SO_2 hot spots in the Persian/Arabian Gulf region (Fioletov et al., 2016; Krotkov et al., 2016; McLinden et al., 2016). The Middle East region was also highlighted as the region with the most missing SO_2 sources compared to reported sources in the global emission inventories. The petroleum industry operations are mainly responsible for these emissions. In addition, the southern part of the Gulf region is known to be a region with a high density of ship traffic, emitting large but not yet quantified amounts of SO_2, besides the traffic emissions from big cities along the coast, as Dubai (~3 million inhabitants) and Abu Dhabi (~1 million inhabitants) in the United Arab Emirates (UAE). In addition to SO_2 and CH_4, high amounts of other trace gases as CO and NO, and also aerosols are emitted from the different sources mentioned above.

We suggest the performance of airborne in-situ measurements with the German Deutsches Zentrum für Luft- und Raumfahrt (DLR) Falcon-20 during two weeks in October/November 2019 to probe the isolated, outstanding emission plumes from the different CH_4, CO, NO (and SO_2) sources in the southern part of the Gulf region as mentioned above (aircraft base in Bahrain or in Abu Dhabi, UAE).

The proposed campaign concept, covered by funding from EDF/UNEP and DLR-IPA, includes ~3 survey flights in the southern part of the Gulf region between Bahrain and UAE (maximum flight duration 3.5 hours), as well as ~7 single plume study flights focusing on the emissions from single oil and natural gas installations in the Gulf region. Depending on the funding from ESA, we suggest to conduct additional flights/flight hours to provide validation data for TROPOMI CH_4, CO (and optional SO_2) products.

Together with the DLR flight department (DLR-FX) the DLR-IPA has gathered extensive experience in conducting airborne field experiments worldwide in the past years (e.g. Huntrieser et al., 2016), also with the focus on off-shore pollution sources (oil/gas facilities,

ships), see Roiger et al. (2014, 2015). Successful stop-overs with DLR aircraft have already been performed in Bahrain and Abu Dhabi (Klausner, 2016), however no DLR field campaign has previously been based in this region. An airborne field campaign is connected to high costs, however, the proposed campaign (except the TROPOMI validation flights) is already funded by EDF/UNEP and DLR-IPA.

Table 6.7: Methane-To-Go campaign concept summary and SWOT analysis.

Addressed S-5p products	CH_4, CO (and SO_2) VMR profiles and tropospheric columns
Campaign teams	DLR-IPA, DLR-IMF, DLR-FX
Campaign instruments	Dual Quantum Cascade Laser System (QCLs) Aerodyne, PICARRO, IT-CIMS
Strengths / Opportunities	• Significant sources of air pollutants and elevated levels, hot spots observed from space • Validation in a non-European area • Operation region is generally cloud-free and covered with several hot spots • Falcon-20 research aircraft can follow satellite orbit and covers an altitude range up to 12 km • High precision in-situ instrumentation (in-flight calibration) • Extensive experience in conducting airborne field experiments worldwide, also with the focus on off-shore pollution sources (oil/gas facilities, ships)
Weaknesses / Threats	• High costs for an airborne field campaign, however mainly covered by already funded projects from EDF/UNEP and DLR-IPA (low risk) • Partly unstable political situation in the target area; will be continuously evaluated in the preparation phase (low risk) • Flight permission for the Persian/Arabian Gulf has to be obtained, however the DLR flight department (DLR-FX) is experienced and scientific contacts are already established (low to medium risk) • Instrument certification for Falcon-20 not yet completed (certification of SO_2 measurement system not yet funded), but instruments have been installed on DLR aircraft before (medium risk)

6.7 Monitoring of atmospheric composition and greenhouse gases through multi-instruments campaigns (MAGIC) [partly funded by national contribution]

Carbon dioxide (CO_2) and methane (CH_4) are the two main greenhouse gases (GHG) emitted by human activities. To better understand their concentration and vertical distribution in several key regions and to prepare future space missions dedicated to GHG, the MAGIC initiative has been put in place [DR 12].

Gathering scientists from 5 CNRS laboratories (LMD, LSCE, GSMA, LOA, LERMA), CNES, Ecole polytechnique, Météo-France and the Universities Versailles-Saint-Quentin-en-Yvelines, Lille and Reims (40 scientists all together), the campaigns have two main goals:

- to better understand the vertical exchange of GHG along the atmospheric column, in connection with atmospheric transport, sources and sinks of the gases at the surface and in the atmosphere
- to prepare future French space missions for the monitoring of greenhouse gases, that were announced at COP21 in Paris: Merlin (French-German methane measurement mission), MicroCarb (French mission for measuring carbon dioxide) and IASI-NG (European mission for the measurement of atmospheric composition and climate)

To address these objectives, various instruments are deployed simultaneously on various platforms: aircraft, balloons, ground. They perform simultaneous observations of GHG concentrations: direct in-situ observations at the surface or along the vertical, total and partial weighted columns.

The MAGIC campaigns rely on SAFIRE Falcon20 (Météo-France/CNRS/CNES) which makes in-situ measurements of gas concentrations, temperature/humidity/wind and particles between 0 and 11 km altitude. In particular, the Falcon20 is equipped with a G2401-m Picarro analyser (CO_2/CH_4/CO/H_2O). The Falcon20 allows flying under any satellite tracks and making 0-11 km profiles at specific locations, such as ICOS/TCCON sites.

The aircraft observations are complemented by balloon-borne instruments making 0-30 km profiles: the AirCore atmospheric sampler developed at LMD and flown regularly at Aire-sur-l'Adour and Trainou; the Amulse light laser-diode spectrometer developed at GSMA. Combining aircraft and balloon profiles allows covering most of the atmosphere to which GHG space missions are sensitive and fully validate total columns derived from space.

Finally, measurements of total columns are made by portable FTS from the ground: EM27/SUN operated by CNES, LERMA and LSCE, as well as CHRIS FTS developed for LOA by Bruker. These FTS are typically located at the launching and landing points of the balloons, as well as at the aircraft profiling point.

The two first MAGIC campaigns have been organized in January and May 2018, the latter in the framework of the CoMet (Carbon dioxide and Methane) campaign lead by DLR. In particular, on May 24, a coordinated flight between SAFIRE/Falcon20 and DLR/HALO has been performed to compare the column of CH4 measured by the lidar CHARM-F on board of HALO to the column computed from simultaneous Falcon20 and AirCore profiles. All together, two research aircrafts, 19 launches of meteorological balloons, four ICOS instrumented sites and a dozen instruments for measuring the concentration of gases have been deployed for the 3-days May campaign.

The two next MAGIC campaigns are already planned: between June and September 2019 in France (Trainou and Aire-sur-l'Adour) and in 2020 at high latitudes, to benefit from the CNES annual balloon campaign in Kiruna.

Table 6.8 : MAGIC campaign concept summary and SWOT analysis.

Addressed S-5p products	CH_4 and CO total columns
Campaign teams	LMD, CNES, SAFIRE, GSMA, LOA, LSCE, LERMA
Campaign instruments	Picarro/Falcon20, AirCore, Amulse, CHRIS
Strengths / Opportunities	• Following satellite orbit with Falcon20 research aircraft • Colocation of in-situ and remote-sensing techniques at two supersites (Trainou and Aire-sur-l'Adour) • Excellent facility at both sites and past experience of large-scale campaigns with simultaneous measurements with aircraft/ballons/ground-based FTS: availability of ICOS standard in-situ measurements of CH_4 and CO; experience on site with regular AirCore launches; high maturity level reducing preparation efforts and costs
Weaknesses / Threats	• Remote sensing measurements using the direct solar absorption technique in the infrared spectral region can only be performed under clear or partly cloudy conditions (low risk) • Flight permission has to be obtained for AirCore launches at Trainou (very low risk)

6.8 Airborne deployment for the validation of CH_4 (and CO) gradients in Upper Silesian Basin (Poland)

One new application area of S-5p CH_4 data will be the quantification of strongly emitting areas of oil, gas and coal production globally, covering emissions in the order of magnitude of 500kt CH_4/year and more. It is therefore important to validate S-5p CH_4 data not only under background conditions but also in areas of spatially heterogeneous atmospheric CH_4 distributions.

Due to the venting of CH_4 from local coal mining activities, the Upper Silesian Basin (USB) around Katowice (Poland) is the largest anthropogenic European CH_4 source region (approx. 500kT CH_4/year in an area < 50 km^2, emitted via coal mine ventilation shafts). The USB falls into the unique category of the large CH_4 emitters like oil/gas/coal production areas worldwide and is easily accessible for airborne and ground-based measurements as successfully demonstrated during the COMET 1.0 campaign in May/June 2018.

During COMET 1.0, ground-based (EM27) and airborne (MAMAP, CHARM-F) remote sensing of XCH_4 in the USB demonstrated that enhanced concentrations (1-3% relative to the background) are frequently occurring in that area on scales of several km. This is also confirmed by airborne in-situ data.

The proposed campaign concept addresses simultaneous measurements to determine the spatial distribution of and spatial gradient in CH_4 (and CO) at and below the spatial resolution of S-5p in the USB. The concept is based on the experienced gained during COMET 1.0 in May/June 2018. It aims at deploying airborne spectrometers for CH_4 (MAMAP/2D) and potentially for CO (GHOST) in combination with several ground-based FTIRs (EM27, Bruker Vertex70), some of which are mounted on mobile platforms (vans) to characterise spatial variability. To characterise small scale CH_4 vertical and horizontal variability and to verify the remote sensing data with in-situ data, the remote sensing measurements need to be complemented by ground-based mobile (car, drone AirCore) and airborne in-situ measurements of CH_4, CO and other relevant tracers. To allow later data interpretation also wind lidars need to be deployed. A campaign duration of 4-6 weeks in the time frame of late spring to early autumn 2020 is the preferred option.

The combination of these measurements is ideal for the validation of gradients in S-5p products of total CH_4 (and CO) columns relevant to determine emissions form such source areas. The data set will also allow investigating the impact of XCH_4 variations on scales below the S-5p spatial resolution on S-5p data quality.

Table 6.9: Polish campaign concept summary and SWOT analysis.

Addressed S-5p products	CH_4 and CO columns
Campaign teams	IUP-UB, MPI BGC, DLR IPA, IUP-HD, Uni. Leicester, KIT, AGH, Uni. Groningen, more TBC
Campaign instruments	MAMAP CH_4 airborne spectrometer, GHOST CO (TBC), ground-based mobile FTIR (EM27 etc.), ground-based mobile in-situ, airborne in-situ, wind lidars
Strengths / Opportunities	• Validation of S-5p data in an area where it can support verification of CH_4 (and CO) emissions • USB is the European CH_4 emission hotspot • Significant sources of elevated levels of CH_4 and CO • Very positive past experience of hosting basin wide airborne campaigns at Katowice airport • Link to ICOS standard in-situ measurements via air-sampler MPI BGC • experience and contacts (AGH) on site from past COMET campaign; • sound expertise of partners from COMET campaign • Benefit from the colocation of in-situ and remote sensing techniques • Data will allow investigation of impact of spatial heterogeneity in XCH_4 fields on S-5p XCH_4
Weaknesses / Threats	• Airborne and ground-based remote sensing measurements using the solar absorption technique in the short wave infrared spectral region can only be performed under clear-sky conditions (low risk – depending on season) • Onset of convective clouds at noon may reduce number of cloud-free colocations with S-5p (low risk – depending on season) • Availability of wind information – to be mitigated by deploying wind lidars.

6.9 Airborne deployment for the validation of NO_2, SO_2 and HCHO tropospheric columns using transect flights

In contrast to mapping flights, consisting of many adjacent flight lines, over a certain industrial or urban hotspot, as proposed in concept 1 and 2, this campaign concept focuses on a transect flight, consisting of one near-straight South-North oriented flight line, following closely the nadir track of the S-5p satellite. Instead of mapping a complete city or industrial area and its plumes, a transect flight can target many different hotspots and background areas, however, just a part of its emissions are captured.

Based on previous research, e.g. the AROMAPEX campaign over Berlin, a NO_2 field equal in size to approximately 30 S-5p/TROPOMI pixels (7 x 3.5 km^2 per pixel) could be covered in ~2.5 hours in case of a typical mapping flight with e.g. the AirMAP or APEX hyperspectral imager. During mapping flights, adjacent flight lines are acquired which are slightly overlapping in order to avoid data gaps. The flight lines are typically flown from south to north, and from north to south and due to large roll angles, spectra acquired during turns of the aircraft in between flight lines are usually excluded from intercomparison studies. Transect flights have the added-value that more S-5p/TROPOMI pixels can be covered assuming the same flight time, and subsequently more pixels can be intercompared for validation purposes. Taking into account a ground speed of 60 m s-1 (the speed of the FUB Cessna 207T D-EAFU, operated during AROMAT and AROMAPEX) and the same flight time of 2.5 hours, approximately 77 S-5p/TROPOMI pixels could be covered during a transect flight, instead of 30 in case of a mapping flight. Depending on the hyperspectral imaging instrument, pixels from (nearly) one or more satellite tracks could be covered. Pushbroom imagers typically have a fixed angular field of view, i.e. 51.7° in case of AirMAP. This results in a swath width of 3 km at a typical flight altitude of 3 km above sea level with the FUB Cessna 207T D-EAFU. The angular field of view of the SWING whiskbroom imager is tunable but restricted to 110°. This would allow to cover multiple satellite tracks but with the consequence of a larger effective pixel size for the airborne data and/or undersampling of the S-5p/TROPOMI pixel.

Similar to mapping flights, the flight time should be well synchronized with the overpass of the S-5p satellite. Additionally, the flight pattern should follow closely one of the satellite near-nadir tracks, requiring a careful planning and input from the overpass tools.

Obtaining flight approvals is always a possible limiting factor. Its complexity would be reduced in case country borders do not need to be crossed. France or Germany are potential countries with a long latitudinal distance or north-south extent as well as many hotspots that can be observed in S-5p data. A preliminary flight plan for example could be to fly from Stuttgart to Bremen, eventually making a small detour to cover as well ground-based stations

(e.g. MAX-DOAS) being set-up at MPIC in Mainz, IUP-UH in Heidelberg, IUP-UB in Bremen, etc. This would be approximately a flight of 500 km or 2.5 hours.

Transect flight patterns were performed before by members of the current S-5p-CIP consortium over Germany and the Netherlands and also to Ny-Alesund, Italy and Nairobi in the context of SCIAMACHY validation, mainly for stratospheric NO_2 (Fix et al., 2005; Wang et al., 2005). Similar flights were also performed over the Highveld in South Africa with the iDOAS imaging instrument (Heue et al., 2008) in order to study the intra-pixel variability in OMI and SCIAMACHY tropospheric NO_2 columns (Broccardo et al., 2018).

Table 6.10: Transect campaign concept summary and SWOT analysis.

Addressed S-5p products	NO_2, HCHO and SO_2 tropospheric columns
Campaign teams	Ground-based and airborne operation teams TBD
Campaign instruments	MAX-DOAS, mobile-DOAS, airborne imaging and in-situ sensors
Strengths / Opportunities	• Significant sources of air pollutants and elevated levels, observed from space • Acquisition of multiple hotspots during one flight • more S-5p/TROPOMI pixels can be covered than in case of a mapping flight, assuming the same flight time • Necessary instruments and know-how available
Weaknesses / Threats	• Transect flights need a much better planning to synchronize with the satellite overpass and to closely follow the nadir-track. If the flight direction is not parallel to the S-5p orbit and/or the swath width of the imager is small, there is the risk that there is no coincident airborne data for full S-5p pixels. • Emission sources and their plumes are only covered partly • Cloud-free conditions might be more difficult to obtain over a 500 km distance than over a city

6.10 Airborne deployment for the validation of NO_2, HCHO and CO columns in the Italian Po-valley area

The proposed campaign concept addresses urban, industrial, and biogenic emissions of NO_x, CO and HCHO in the highly industrialised and densely populated region of the Po Valley in Northern Italy.

The Po Valley is one of the most important industrial and agricultural areas in Europe. It is characterized by a high density of anthropogenic emissions and by the frequent occurrence of stagnant meteorological conditions due to its enclosed nature. This area is one of the largest NO_2, CO and HCHO pollution hotspots in Europe, observed from the ground as well as from spaceborne data. The envisaged airborne and ground-based deployment would focus on the city of Milano (45°27'51" N, 09°11'24" E) and Ispra (45°48'14" N, 08°37'47" E). Milano has a population around 1.5 million and is the biggest source of anthropogenic pollution in the Po-Valley. Ispra is approximately 50 km northwest of Milano and in a background location at the foot of the Alps. However the area is subject to regular pollution events.

Currently, the S-5p cal/val consortium has little experience in flight operations over (Northern) Italy. During a previous campaign over the Po Valley organized as part of the EU FORMAT project (2003) with involvement of IUP-UB and MPIC, major problems arose to obtain flight approvals. Therefore adequate contacts with local partners and flight authorities need to be established to ensure success in a new airborne deployment. DLR/VITO have experience operating APEX over the Mantua area (which is located at approximately 150 km East of Milano) and this experience could eventually be reused. However, the APEX instrument is not sensitive in the UV and could therefore not be used for HCHO retrieval. In addition, airborne measurements of vertical profiles of NO_2, HCHO and CO would be needed for complete validation closure and this would require the deployment of a suitably equipped aircraft (e.g. the BN-2 aircraft from INCAS, Romania).

The EC Atmospheric Observatory, run by the Air and Climate Unit of the Joint Research Centre (JRC) of the European Commission is located in ISPRA. Campaign activities in this area could benefit from the existing instrumentation (in-situ analysers, sun photometer, aerosol lidar, etc.) used for routine measurements at the observatory, and additional ancillary instruments could be set up to support airborne operations. This could be further complemented by mobile-DOAS systems to be deployed from Milano or Ispra. Early spring would provide an ideal campaign window if the focus is on NO_2 and CO, providing a relatively high sun position but still a shallow PBL. Summertime is preferred if the focus is also on HCHO, since VOC oxidation is favoured at high temperatures.

Table 6.11: Po-valley campaign concept summary and SWOT analysis.

Addressed S-5p products	NO_2, CO and HCHO tropospheric columns and VMR profiles
Campaign teams	Ground-based and airborne operation teams TBD. Local support in Po Valley TBD
Campaign instruments	MAX-DOAS, mobile-DOAS, airborne imaging and in-situ sensors, EM27/SUN, sunphotometer, aerosol lidar, in-situ pollution monitoring stations
Strengths / Opportunities	• Significant sources of air pollutants (NO_2, CO, HCHO) and elevated levels, observed from space • Complex and relevant mixture of gaseous and particulate pollution • Necessary instruments and know-how available
Weaknesses / Threats	• Currently lack of local support and contacts for ground-based set up in the Po Valley, flight approvals. Collaborations are being established but not consolidated so far • Bad experiences to obtain flight approvals for flights over Po valley during FORMAT campaign (2003), however APEX operated successfully over Mantua

6.11 Airborne deployment for the validation of SO_2 plumes emitted by the Etna volcano, Sicily

Observations of volcanic SO_2 emissions from Etna (37°45'05" N, 14°59'35" E) are envisaged. Etna is degassing continuously (this is in fact the largest European source of SO_2) and SO_2 plumes can be observed on a daily basis in S-5p data under cloud-free conditions, mostly to the East of Sicily which is the main direction of the plume under prevailing wind conditions. Collaborations with the National Institute of Geophysics and Volcanology (INGV) are already established and a wide range of suitable instruments are available at the Etna observatory (e.g. UV, VIS and TIR cameras, UV scanning spectrometers, lidar). There are also regular campaigns on Etna to which S-5p validation activities could be linked. Airborne deployment using imaging DOAS to map the degassing plumes and in-situ sensors for vertical profiling would be of high interest for direct comparison with S-5p, since local ground-based measurements hardly allow for a direct comparison of measured columns. Ground-based measurements however can be used for indirect comparison of SO_2 flux estimates, as demonstrated in recent studies using S-5p. Therefore a combination of airborne and ground-based measurements would be highly valuable for end-to-end validation of both columns and fluxes of degassing SO_2.

Table 6.12: Etna campaign concept summary and SWOT analysis.

Addressed S-5p products	SO_2 emissions from degassing Etna volcano (vertical columns, profile and fluxes)
Campaign teams	Airborne operation team(s) TBD. Local support and ground-based facilities at INGV Catania
Campaign instruments	Airborne imaging DOAS and in-situ sensors, ground-based UV, VIS and TIR cameras, scanning DOAS and lidar
Strengths / Opportunities	• Possible validation of SO_2 S-5p product around the main source in Europe • Necessary instruments and know-how available at Etna observatory • Airborne deployment possible
Weaknesses / Threats	• Currently no experience with airborne operations in Sicily, local contact to be established

7 Instrumental deployment planned during 2019

In this section, we provide a concrete plan for a number of well-identified validation campaign activities, scheduled for deployment in 2019. This plan derives from a prioritization of the validation campaign concepts identified in section 6. The scientific, technical, logistical and costing details necessary to the implementation of the selected activities are further described in the following sub-sections.

The selection of campaign activities to be implemented in 2019 is based on various arguments, in particular:

- Maturity of validation concepts and available infrastructures
- Feasibility and costs
- Compatibility in terms of timing
- Balance between activities addressing different S-5p data products
- Balance between participating groups and institutions
- Complementarity and synergies between activities
- Adequacy of activities with respect to specific campaign requirements identified in section 4 (see also Table 6.1)

The validation campaign package proposed for deployment in 2019 implements the three first concepts listed in section 6, and links with the synergistic nationally funded activities, described in concepts 4 to 7. Four primary S-5p products are addressed (NO_2, HCHO, CH_4 and CO) with a conditional option for additional SO_2 activities as part of the German Methane-To-Go campaign. These products emerged as priority products because, for each of them, specific campaign validation requirements not achievable by MPC routine validation could be identified. Accordingly, campaign validation activities will concentrate:

- for NO_2 and HCHO: on a characterization of the small-scale horizontal variability of these short-lived pollutants using suitable airborne DOAS imagery, complemented by in-situ profiling and supporting static and mobile ground-based observations. Instrumental deployments will concentrate on two main target areas, Bucharest and the Jiu Valley in Romania, and the German Ruhr region in Northern Germany. Core activities will take place in September 2019, and June-July 2019 respectively.
- for CO and CH_4: the deployment of a range of distributed COCCON (COllaborative Carbon Column Observing Network) FTIR instruments, providing enhanced coverage of relevant geophysical parameters and different ground scenes, allowing for improved

characterisation of the S-5p performance under varying conditions of solar zenith angle, satellite line-of-sight, water vapour amount, ground albedo, fractional cloud cover or aerosol optical depth. In contrast to the airborne activities, which will be concentrated in core periods of one-month duration each, the COCCON campaign will be extended in time covering the full year 2019.

In addition to the main deployments described above, a set of complementary activities, nationally co-funded, will take place :

- at the super-site of Cabauw, The Netherlands (CESAR observatory)
- in Belgium (airborne operation of the APEX imaging spectrometer)
- as part of the MAGIC and Methane-To-Go campaigns

The main observational activities planned in Europe during 2019 are schematically illustrated in Figure 7.1. The decentralised concept of having several deployments serving different purposes is cost-effective in that it significantly reduces travel expenses, while allowing for more flexibility in the planning or activities. In particular flight operations have strong requirements on weather conditions, and it is therefore an advantage to plan campaign activities at proximity of the aircraft hosting entities and collaborating campaign teams.

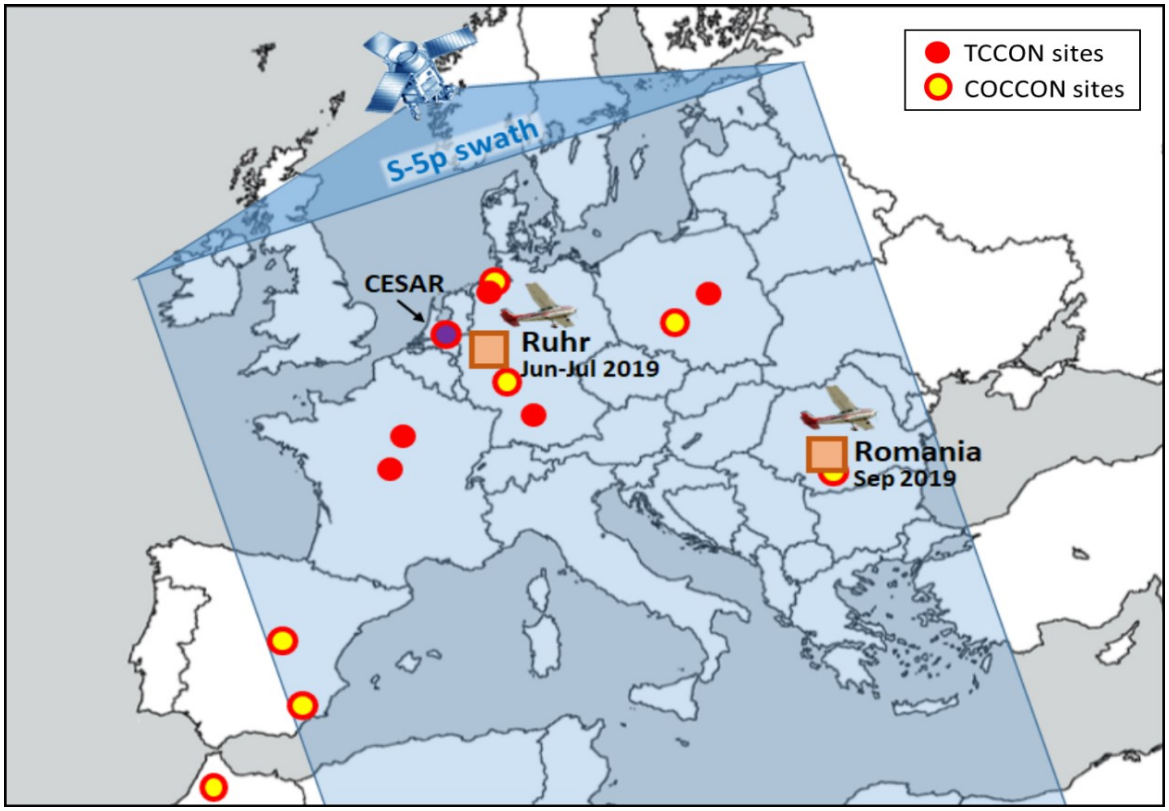


Figure 7.1: S-5p validation campaign deployment planned in Europe during 2019.

The following sections describe in the detail the planned practical implementation of the proposed activities, addressing:

- Identification of campaign site(s) and optimal time window(s)
- Identification of available platforms
- Identification of most relevant instruments for all available platforms
- Planning of deployment of airborne instrumentation
- Planning of deployment of ground-based instrumentation
- Estimation of costs for airborne and ground-based deployments
- Overall schedule

7.1 Airborne deployment in Romania

7.1.1 Objectives

This campaign deployment focuses on urban and industrial emissions of tropospheric reactive gases and aerosols in the Bucharest area (Romania). The main regions of interest are (1) the city of Bucharest, and (2) the large power plants around Turceni in the Jiu Valley. The campaign includes an airborne component, completed by ancillary ground-based observations. Both mapping flights (remote sensing observations) and vertical sounding flights (in-situ observations) will be performed at multiple days, in order to capture the high spatio-temporal variability and strong gradients of the target tropospheric pollutants.

The following S-5p geophysical data products will be addressed: NO_2, HCHO, SO_2 and Aerosol Layer Height, as well as input parameters in the retrieval algorithm such as the a-priori tropospheric profile of NO_2 and HCHO, surface reflectance climatology and aerosol impact on trace gas AMFs. Instrumental deployment is based on the experience gained during the successive AROMAT campaigns held in September 2014 (Merlaud et al., 2018) and August 2015, and the AROMAPEX campaign held in 2016 (Tack et al., 2018) and will largely make use of the infrastructure developed during the RAMOS project, which were/are being tested in 2017-2019. Note that the RAMOS test campaign planned over Bucharest in May 2019 will constitute the first airborne deployment for S-5p validation in Romania (see below).

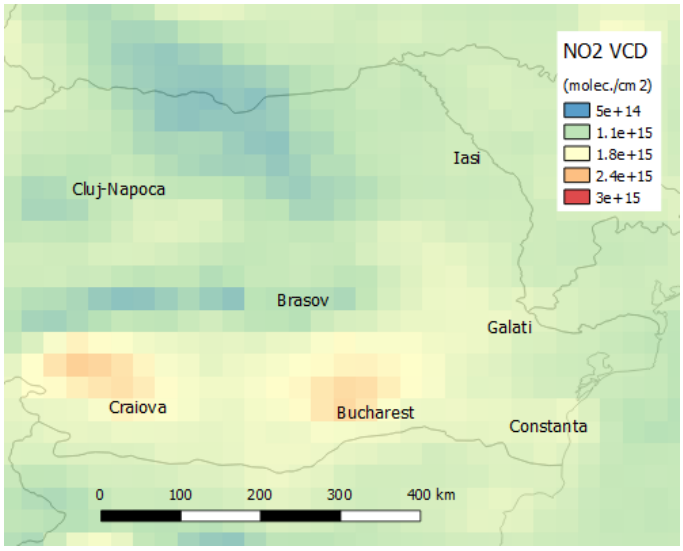


Figure 7.2: NO_2 VCDs retrieved from an OMI overpass over Romania on 12 September, 2014.

7.1.2 Justification

Both campaign sites have significant sources of air pollutants and elevated levels of NO_2 clearly detectable by S-5p. HCHO columns of up to 3.5e16 mol/cm^2 have been detected by ground-based and airborne instruments during the 2015 AROMAT campaign in Bucharest, and plumes of enhanced NO_2 (1e17 mol/cm^2) and SO_2 (4e18 mol/cm^2) columns were measured in the Jiu Valley. Both sources can be clearly idendified in OMI maps (see e.g. Figure 7.2), and initial results from S-5p show that they are detectable on a daily basis under cloud free conditions.

A strong asset is the expertise built during the AROMAT-1 and -2 campaigns, which took place in September, 2014 and August, 2015, respectively. The objectives of these campaigns were 1) to test and intercompare recently developed airborne observation systems dedicated to air quality studies, and 2) to prepare the validation programme of the future Atmospheric Sentinels, starting with S-5p. This gives a high maturity level to the planned campaign: a strong consortium was built, many issues were confronted and solved and the lessons can be extrapolated to future campaigns. The fact that already two AQ campaigns took place at the target areas, seriously reduces the preparation efforts (e.g. flight approvals, logistics, local support, etc.) and costs. Major bottlenecks for aircraft operations are the flight approvals. It was demonstrated, however, that this goes much easier once contacts with air traffic control (ATC) and the respective authorities are established.

An additional asset is the availability of the infrastructure developed during the RAMOS project, which includes ground-based (PANDORA, aerosol lidar, EM/27 SUN in-situ samplers, sun photometer, etc.) and airborne (INCAS BN-2 scientific aircraft with Environment SA AS32M analyzer, TSI nephelometer and Aerosol Particle Sizer, and a GHG PICARRO) facilities to support calibration/validation activities and geophysical algorithm development. Additionally, as a result of the transfer of knowledge during AROMAT and RAMOS, operations can be executed by the Romanian partners (INCAS, INOE, UGAL) which will also reduce costs and facilitate the preparation tasks (e.g. flight approvals).

A critical gap has been identified for S-5p SO_2 product validation. Although elevated levels of SO_2 were detected in the Jiu Valley during the AROMAT campaigns, the SO_2 emissions in this region are also known to have sharply decreased due to installation of desulfurization units. At the time of writing (July, 2018), the area does not seem to pop up as a hotspot in the currently scarce S-5p data sets.

7.1.3 Campaign site

Bucharest

The city of Bucharest (44°26' N, 26°06' E, population around two million) is the target site for the first phase of the campaign. The main source of NO_2 in this urban area is related to car traffic, however there is an additional contribution from several power plants, e.g. CET West Militari, CET South, located within the Bucharest ring road. During AROMAT, large plumes of NO_2 were observed, extending up to 25 km away from the city centre.

Jiu valley

The large power plants of the Gorj county (Turceni and Rovinari) are the targets of the second phase of the campaign. They are located along the national road 66, between the cities of Targu Jiu and Craiova. Although four power plants (from North to South: Rovinari, Turceni, Isalnita, and Craiova II) burning lignite for electricity production are potential candidates for measurements, the main focus will be on the Turceni power station (44°40'7.74" N, 23°24'24.00" E, see Figure 7.3) which is the largest producer of electricity in Romania and one of the largest thermal power plant in Europe. The Jiu Valley was one of the main target sites of the AROMAT campaigns and high levels of NO_2, SO_2, and aerosols were observed in the plume, both by ground-based and airborne instruments (see Figure 7.4).



Figure 7.3: Turceni powerplant in the Jiu valley.

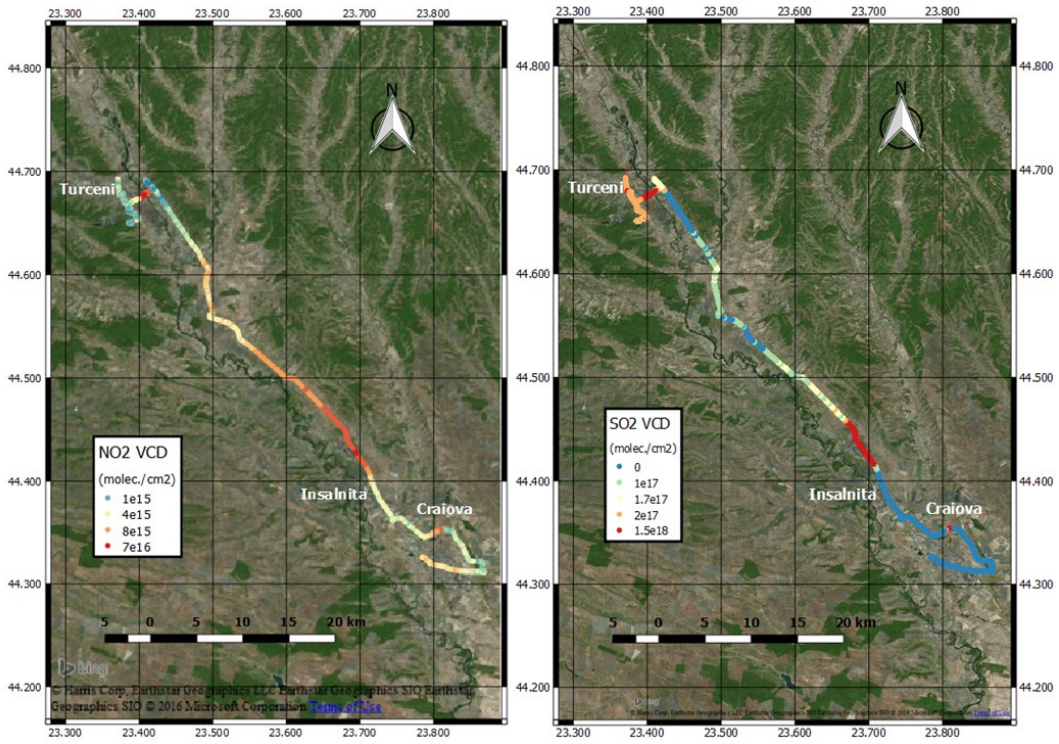


Figure 7.4: Car mobile-DOAS measurements of NO_2 and SO_2 VCDs in the Jiu Valley, performed on 28 August, 2015.

7.1.4 Campaign period

In addition to the RAMOS test deployment already planned in May 2019, we propose to organize the main campaign in late summer 2019 (September), for reasons of 1) flight clearance approval procedures, 2) favourable weather conditions and 3) clear pollution sources (larger signal from city traffic pollution since the holidays are over). A possible time frame could be e.g. to start on September 3, 2019 and end on September 28, 2019. In the first phase (Phase A, e.g. from 3 till 15 September, 2019) the focus will be on Bucharest. In the second phase (Phase B, e.g. from 17 till 28 September, 2019) the Jiu Valley will be the primary target. During these periods ground-based measurements will be performed with those instruments that can operate autonomously. The teams involved in airborne and mobile operations should be stand-by and perform measurements in case of clear-sky conditions. To capture the spatiotemporal variability of the reactive gases and to be able to validate multiple S-5p overpasses, flights on multiple days are envisaged, if weather permits. A daily update will be provided to all involved teams by INOE/BIRA to inform on possible aircraft operations on the following days depending on the weather. Note that the proposed timing of

the operations could be subject to changes depending on the weather forecast and flight approvals. Predicted golden days should be exploited as much as possible.

7.1.5 Campaign team and responsibilities

The anticipated consortium would consist of:

- The National Institute for Research and Development in Optoelectronics (INOE 2000)
- The Royal Belgian Institute for Space Aeronomy (BIRA)
- The National Institute for Aerospace Research Elie Carafoli (INCAS)
- "Dunărea de Jos" University of Galați (UGAL)

INOE will coordinate the campaign and will be responsible for the ground-based component both in Bucharest and the Jiu Valley.

BIRA will support INOE for coordination tasks and deliver NO_2 and SO_2 data sets from the SWING+ airborne imaging instrument.

INCAS will be responsible for the airborne operations of the BN-2A 27 aircraft and related administration for flight approvals. Both mapping and profiling flights will be conducted. INCAS will also have to responsibility over most of the instruments integrated in the BN-2 aircraft.

UGAL will be responsible for the car mobile-DOAS observations at the two campaign sites, providing 1) support for the airborne component to optimize the flight pattern in near-real time and 2) ground-based references for the observed NO_2 and SO_2 columns.

Table 7.1: Overview of institutes and participants.

Participants	Institute	E-mail address	Comments
Livio Belegante	INOE	belegantelivio@inoe.ro	
Doina Nicolae	INOE	nnicol@inoe.ro	
Dragos Ene	INOE	dragos.ene@inoe.ro	
Alexandru Dandocsi	INOE	alexandru.dandocsi@inoe.ro	
Michel Van Roozendael	BIRA	michel.vanroozendael@aeronomie.be	
Frederik Tack	BIRA	frederik.tack@aeronomie.be	
Alexis Merlaud	BIRA	alexis.merlaud@aeronomie.be	
Daniel-Eduard Constantin	UGAL	daniel.constantin@ugal.ro	
Andreea Calcan	INCAS	calcan.andreea@incas.ro	
Nicolae Sorin Vajaiac	INCAS	vajaiac.sorin@incas.ro	
Magdalena Ardelean	INCAS	ardelean.magdalena@incas.ro	
Sebastian Stefan Iancu	INCAS	iancu.stefan@incas.ro	
Octavian Angelo Voicu	INCAS	voicu.octavian@incas.ro	

Achieving fast and efficient communication between the different teams is critical for the success of the campaign but not always easy, once in the field. A WhatsApp group or use of another online application seems to be a good way to provide updates.

7.1.6 Campaign instruments and logistics

An overview of the relevant campaign instruments and the corresponding measured variables/species is provided in Table 7.2. A description of each instrument can be found in Annex A.

Table 7.2: Overview of the campaign instruments and corresponding measured variables/species.

Instrument	Owner organisation	Contact person	Measured variables	Platform	Platform operator	non-availability 2019
SWING+	ESA/INCAS	Alexis Merlaud, Angelo Voicu	NO_2, SO_2 column	BN-2A 27 aircraft	INCAS	May 2019 (GHG RAMOS campaign)
AS32M CAPS	ESA/INCAS	Andreea Calcan, Magdalena Ardelean	NO_2 VMR profile	BN-2A 27 aircraft	INCAS	May 2019 (GHG RAMOS campaign)
PICARRO G2401-mc	INCAS	Andreea Calcan	CO-CO_2-CH_4-H_2O VMR profile	BN-2A 27 aircraft	INCAS	May 2019 (GHG RAMOS campaign)
TSI Aerosol particle sizer 3321	INOE	Livio Belegante	Aerosol size distribution	BN-2A 27 aircraft	INCAS	May 2019 (GHG RAMOS campaign)
TSI Nephelometer 3563	INCAS	Andreea Calcan	(back)Scattering and angstrom coefficients	BN-2A 27 aircraft	INCAS	May 2019 (GHG RAMOS campaign)
ISAF HCHO analyzer	NASA/JPL	Tom Hannisco, Jim Gleason	HCHO VMR profile	BN-2A 27 aircraft	INCAS	Availability and Integration in BN-2 TBD
Pandora 2S	ESA\ESRIN	Alexandru Dandocsi	NO_2 column	Static	INOE	-
UV depolarization lidar	INOE	Livio Belegante	Aerosol	Static	INOE	-
Sun-lunar photometer CIMEL	INOE	Livio Belegante	Aerosol	Static	INOE	-

Mobile lab	INOE	Livio Belegante	Gas analyzers Horiba NO_x, SO_2, O_3, THC, CO, UV depolarisation lidar, weather station	van	INOE	-
Mobile-DOAS	UGAL	Daniel Constantin	NO_2, SO_2 column	Car	UGAL	-

Airborne infrastructures

The technical specifications of the INCAS Britten-Norman BN-2A 27 Islander can be found in [DR 15]. At the time of writing (July 2018), the integration of the instruments and inlet system on board of the BN-2 scientific aircraft and associated EASA certification are still ongoing under the responsibility of Enviscope GmbH. This is expected to be finished in September, 2018, including test flights near Frankfurt. A campaign to test the scientific instruments for observation of air pollutants is then planned in Romania in May 2019 in the framework of the RAMOS project. These campaign activities will be synchronized with S-5p overpasses allowing their integration into the overall validation analysis. A second campaign to test the instruments for monitoring greenhouse gases will take place in Poland in July 2019.

The BN-2 aircraft will be deployed from the Baneasa and/or Strejnicu Aerodrome airports (see Figure 7.6) for the first phase of the campaign. The aircraft will be based in Craiova for the flights over the power plants in the Jiu Valley.



Figure 7.5: INCAS BN-2A 27 aircraft.

ISAF HCHO analyser (supplied by NASA)

The JPL LIF HCHO analyser (ISAF) will be supplied by NASA for use in the campaign as part of an ESA-NASA cooperation agreement for S-5p validation. This instrument is highly sensitive and adequate to perform vertical soundings of the HCHO concentration in the troposphere (Cazorla et al., 2015). The integration of this instrument (for the duration of the S-5p campaign) in the INCAS BN-2 has been envisaged and needs to be further evaluated. One option would be to exchange the current PICARRO HCHO analyser by the ISAF instrument, using the same inlet line.

Ground-based supporting infrastructures in Bucharest and Jiu valley

In Bucharest, continuous ground-based measurements will be performed at the INOE/RADO atmospheric composition observatory in Magurele (see Figure 7.6; [DR 13]), a suburban area southwest of the city. The INOE observatory is fully equipped with ancillary ground-based instruments, e.g. sunphotometer and various aerosol measuring systems including aethalometer, nephelometer and a Raman lidar, compact DOAS instruments, wind profiler, etc. In Bucharest, INCAS offers a convenient place for (daily) campaign meetings since it has meeting rooms and is easily reachable by tram. Note that there is also a workshop and do-it-yourself/IT shops close by. The IBIS Gara de Nord hotel has a watched parking, which makes it interesting for car Mobile-DOAS instruments.

For logistic reasons, the main focus of the ground-based observations in the second phase of the campaign will be on the Turceni power station, while airborne activities will be extended to the complete Jiu Valley region. A small hotel, owned by the power plant company, could be at our disposal as it was the case during the AROMAT campaigns. It is very close to the center of the village and offers 16 rooms. During the AROMAT campaigns, the local authorities were very collaborative. Instruments (e.g. the UV depolarization lidar) could be installed on a soccer field, and its facilities could be used. The soccer field is approximately 2.4 km west of the Turceni power plant and there is a good visibility towards the power plant.

Car mobile-DOAS measurements will be performed along the external ring in Bucharest. Also transects to the city centre will be covered. In the Jiu Valley, mobile measurements will focus along the national road 66 and local streets around the power plants.

7.1.7 Campaign scenario (September deployment)

We propose a campaign baseline starting on 3 September, 2019 with a kick-off meeting at INCAS, including all involved teams. Phase A of the campaign will focus on operations in the Bucharest metropolitan area and will last until 15 September, 2019. On 16 September, 2019, phase B will start and instruments will be relocated to the Jiu Valley. The campaign will end on 28 September, 2019. Note that the general campaign scenario could be subject to changes

depending on the weather forecast and flight approvals. Predicted cloud-free days, which are rare, should be exploited as much as possible.

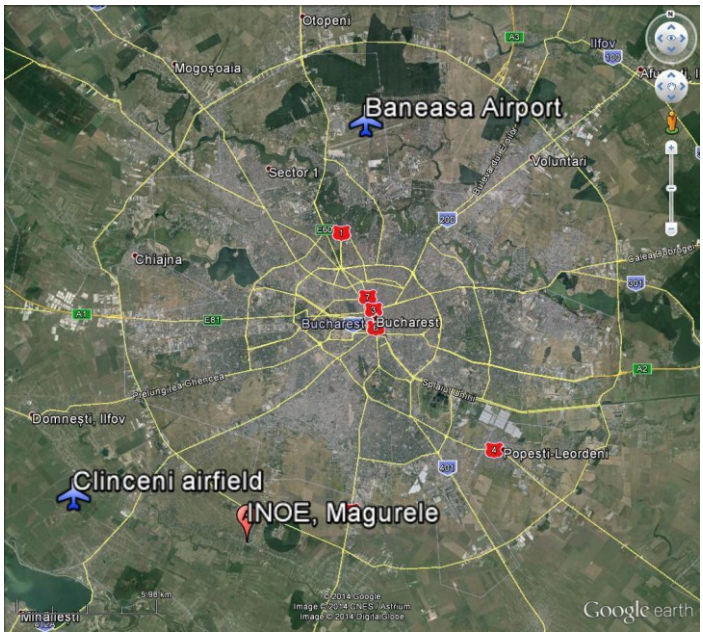


Figure 7.6: The Bucharest metropolitan area including the external ring, the Baneasa airport where the aircraft will be based, and the INOE observatory in Magurele, where the ground-based component will be set up.

Phase A: Bucharest

Phase A of the campaign will focus on Bucharest in the period from 3 till 15 September, 2019. During this period, static autonomous ground-based instruments will perform atmospheric measurements from the INOE/RADO observatory in Magurele. More specifically the ground-based set-up will include a Pandora 2S, UV depolarization lidar, Sun-lunar photometer CIMEL and a compact MAX-DOAS. Daily progress meetings will be organized in the late afternoon at the premises of INCAS or INOE, in order to discuss the progress and problems and to present quick looks for the collected data. Based on forecasts from meteorologists at INOE, a daily update will be provided to all involved teams to inform on possible aircraft operations on the following days.

Teams involved in aircraft and mobile operations will be stand-by during the campaign period and will perform measurements on days with clear-sky conditions. Note that flight operations should be avoided over the weekend as previous campaigns pointed out a clearly lower signal, especially on Sundays. Airborne operations will be performed using the INCAS BN-2A 27 scientific aircraft, deployed from the Baneasa or Strejnicu Aerodrome airport. The aircraft is equipped to perform 1) mapping flights, to map the horizontal distribution of reactive gases,

such as NO_2, HCHO, SO_2 and 2) profiling flights, to sample the vertical distribution of NO_2, HCHO and aerosols. The default scientific payload of the BN-2 aircraft includes a UV/Vis trace gas whiskbroom imager (SWING+) and in-situ instruments for trace gases and aerosols (an Environment SA AS32M analyzer, TSI nephelometer and Aerosol Particle Sizer, and a GHG PICARRO - G2401-mc). For the campaign, an additional highly-sensitive in-situ instrument from NASA (ISAF), dedicated to HCHO, might also be integrated in the BN-2.

Airborne remote sensing observations will focus on high resolution mapping of the NO_2, HCHO (and SO_2) field over Bucharest using the SWING+ instrument. Flights will be performed at 3 km altitude AGL. The angular and instantaneous FOV of SWING+ are tunable but are typically set to 50° and 6°, respectively, in order to have a good trade-off between coverage (3 km swath width) and spatial resolution (325 m). The flight plan consists of adjacent straight flight lines, alternately flown from south to north, and from north to south, with the first flight line in the west. Discussions with the Romanian flight authorities (CAA and ROMATSA) about the flight plan will be led by INCAS and should start at least three months in advance. A lesson learned from previous airborne campaigns is that the flight plan approved by the authorities should be initially larger than the actual area that will be covered, in order to have some flexibility to adapt the effective flight pattern to the predicted wind direction. Note that the North of Bucharest cannot be mapped as it is a restricted airspace due to the presence of the Otopeni international airport (See Figure 7.7).

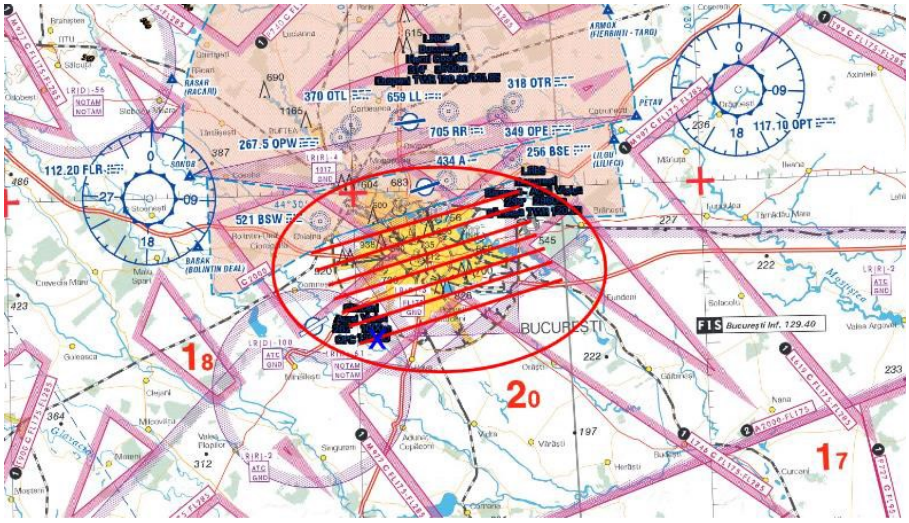


Figure 7.7: Airspace above Bucharest, indicating restricted areas in salmon color.

For this reason, the flight planning should avoid South wind conditions during the campaign. Downwind of the city, and thus the key sources, a maximum number of flight lines should be retained in order to catch the urban plume. The number of flight lines upwind can be reduced.

The acquired area should be sufficiently large in order to cover 1) the full plume, or at least a large part of it, 2) sufficient spatial gradients and 3) a large number of S-5p pixels in order to perform a quantitative intercomparison and analysis, being statistically relevant. The area should cover at least the whole city (with the exception of the restricted area in the North) and the Bucharest ring motorway, and obviously as well the INOE/RADO observatory in Magurele. This would be an area of approximately 25 by 25 km. Figure 7.8 shows a NO_2 VCD map, acquired over Bucharest with SWING during AROMAT-2, capturing the city plume around local noon. The flight was performed with a previous version of the SWING instrument, operated from the FUB Cessna 207T D-EAFU, carrying as well the AirMAP imager. Unfortunately the city plume, extending to the northeast, was not covered completely.

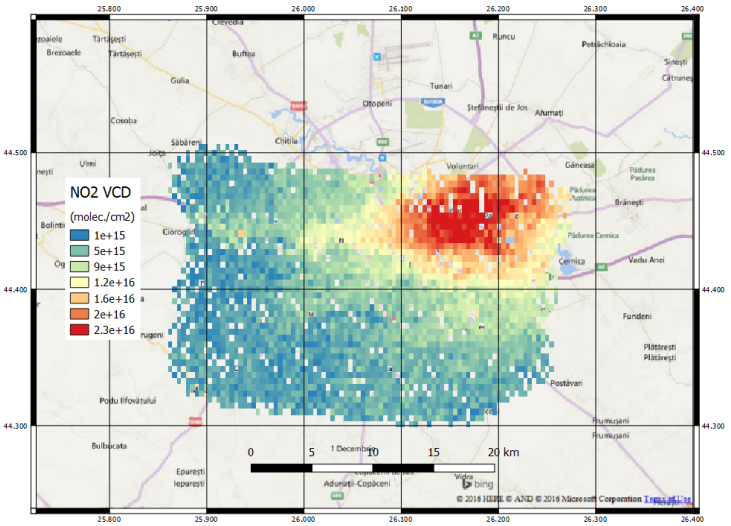


Figure 7.8: SWING NO_2 VCDs retrieved over Bucharest on 31 August, 2015.

The flights should be synchronized as much as possible with the satellite overpass. The S-5p overpass tool [DR 14], provided by EVDC, can be used for this purpose in order to predict the orbits and get the spatial overpasses. Daytime overpasses over Romania are typically between 10 AM and 12 AM UTC. This is also the most optimal flight time in terms of the maximum signal (largest sun elevation angle). Nevertheless, previous airborne campaign experience has proved that sometimes ATC, weather conditions and technical issues force us to operate at less optimal times of the day.

If weather conditions and ATC permit a choice, it should be discussed whether airborne observations should be performed on a day with one single satellite overpass at near-nadir or with two overpasses. In the latter case, one would sample the edges of the swath, which would imply coarser spatial resolution and lower SNR, but two co-located S-5p data sets.

Maybe both conditions could be sampled in order to study if there is an across-track dependency of the S-5p performance. Typically, the acquired area will cover 20 to 40 TROPOMI pixels. To capture the spatiotemporal variability of the reactive gases and to be able to validate multiple S-5p overpasses, flights on multiple days are envisaged, if weather permits. Ideally, 2 to 5 mapping flights should be performed. Note that the flight autonomy of the INCAS BN-2 aircraft is approximately 6 hours. However, the instrument battery lifetime is only two hours when all instruments are switched on. Test flights, planned in September 2018, will provide a clearer view on the instrument autonomy when only instruments for a mapping flight or profile flight are switched on.

The second type of flights will focus on sampling the vertical distribution of NO_2, HCHO and aerosols based on the in-situ instruments on board of the INCAS BN-2 aircraft. Soundings will be performed between a few hundred meters and 3 km altitude in order to collect in-situ data around the city, upwind and downwind and outside of the area encircled by the ring. A sounding down to the ground surface could potentially be performed above the Strejnicu Aerodrome or Baneasa airport. Operations at higher altitude are not possible as the BN-2 aircraft is unpressurized. Ideally (but not necessarily), soundings should be performed on days when mapping flights take place, as the profiles are valuable a priori input in the trace gas retrieval algorithms.

The static ground-based and airborne operations will be completed by mobile operations. The INOE mobile laboratory van, including in particular a scanning lidar and trace gas in-situ monitors, will be operated (preferably) downwind of the city. The UV depolarization lidar will be pointed vertically, in order to capture the vertical profile. Scans will be performed in continuous mode during flight operations. Two car mobile-DOAS systems from UGAL and BIRA will be operated in the city to provide ground-based references for the airborne remote sensing data. The two systems can perform different patterns in order to capture the spatial variability of the NO_2 field. For example, transects can be performed from and towards the city center with one system while the second system covers the Bucharest outer ring motorway. It takes on average 2.5 hours to cover the full loop of 80 km. Similarly as to the flight plans, the drive plans should be optimized shortly before the flights depending on wind forecast.

Phase B: Jiu Valley

Phase B of the campaign will focus on the large power plants in the Jiu Valley in the period from 16 till 28 September, 2019. The area is located approximately 200 km west of the city of Bucharest. September 16 is foreseen for the relocation and set up of the instruments. For logistic reasons, the main focus of the ground-based observations will be on the Turceni power station. Daily progress meetings will be organized at the hotel, owned by the power plant company in Turceni.

Static autonomous ground-based measurements (e.g. the UV depolarization lidar and compact MAX-DOAS) can be performed from the local soccer field in Turceni. Its facilities can be used as well. The soccer field is approximately 2.4 km west of the power plant and is providing a good visibility towards the power plant. Note that the soccer field will not be accessible during the weekend.

Teams involved in aircraft and mobile operations will be stand-by during the campaign period and will perform measurements on days with clear-sky conditions. Mapping flights with SWING+ will be performed in order to map the horizontal distribution of reactive gases, such as NO_2, SO_2 (and HCHO). The INCAS BN-2A 27 scientific aircraft will operate from the Craiova airport. Specifications of the flight plan will be similar as for campaign Phase A. However, two different mapping flights are proposed. The first flight plan will focus on the Turceni power plant in order to cover the full plume. Again, a large area around the power plant should be approved by ATC, and the effective flight plan should be optimized based on the forecasted wind regime. The second airborne activity will focus on the four power plants (from North to South: Rovinari, Turceni, Isalnita, and Craiova II) in the Jiu Valley region. The distance from Rovinari to Craiova is approximately 90 km, while the aircraft speed is roughly 60 m/s. Taking into account the time needed to take off, ascend to cruise altitude, descend and land, this will reduce the mapping flight to only a few long flight lines. This type of flight will capture the gradients from the four different sources, but will not capture the full plumes. The scanning set up will use the potential large field of view of SWING to optimize the covered area. Ideally, 2 to 6 mapping flights should be performed and the covered area should be sufficiently large to cover the spatiotemporal variability of the trace gas fields. The same criteria as for Phase A will be considered in order to synchronize the flights as much as possible with the satellite overpass.

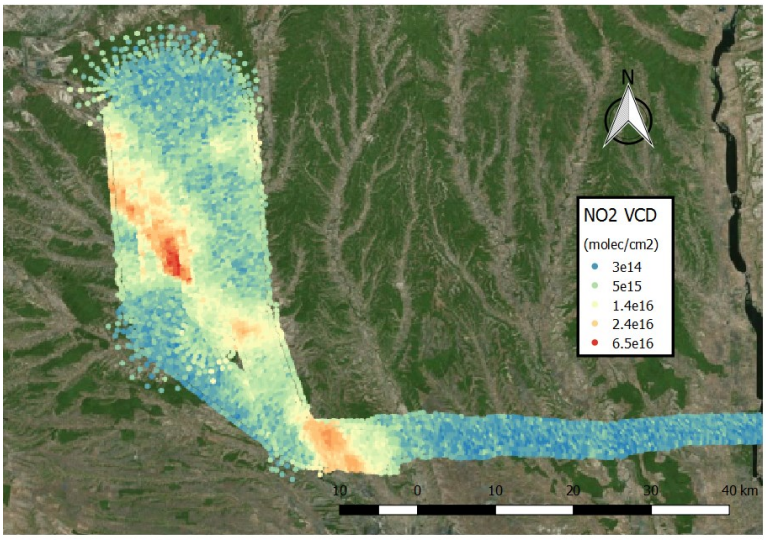


Figure 7.9: SWING NO_2 VCDs retrieved over the Jiu Valley on 28 August, 2015.

In-situ sounding flights through the exhaust plume are more critical in this area, because of the small spatial extent of the plumes. Suchlike flights will be performed if it appears feasible to adjust the flight plan in real-time based on the airborne CAPS data or based on ground-based data.

Two car mobile-DOAS systems operated by UGAL and BIRA will be deployed in the area and will largely cover, in opposite directions, the national road 66, interconnecting the four power plants. The systems will also operate on the local roads in the vicinity of the power plants.

7.1.8 Schedule and cost

The campaign will start on 3 September, 2019. Phase A of the campaign will focus on operations in the Bucharest metropolitan area and will last until 15 September, 2019. On 16 September, 2019, phase B will start and instruments will be relocated to the Jiu Valley. The campaign will end on 28 September, 2019.

Table 7.3: Campaign schedule.

Campaign phase	Dates	Comments
Campaign preparation and flight approvals	01-06-2019 - 02-09-2019	
Official campaign start	03-09-2019	
Phase A: Bucharest	03-09-2019 - 15-09-2019	
Switch to phase B (relocation + installation)	16-09-2019	
Phase B: Jiu Valley	17-09-2019 - 28-09-2019	

Table 7.4: Main campaign ROM costs.

Budget breakdown	Budget in Euro	Comments
Campaign preparation, organization and coordination	~15.000 €	Including flight approvals, etc.
Aircraft operations	~35.000 €	900 euro/ flight hour + cost of crew
GB and mobile instrument operations	~40.000 €	Including transport of instruments to Jiu Valley
Logistics + travel costs	~15.000 €	Travel to Jiu Valley + one person from BIRA to Romania
Data analysis (L0 to L2 product)	~25.000 €	
Total	**~130.000 €**	

7.2 Airborne deployment in the German Ruhr area

7.2.1 Objectives

This campaign focusses on industrial and urban emissions of NO_x, as well as assumptions made on a priori data in the retrieval of the S-5p NO_2 level-2 product. Emphasis will be given to the a-priori parameters aerosols and surface reflectance. For this purpose it is planned to deploy similar instruments as was done during the AROMAT-2 and AROMAPEX campaigns consisting of an airborne as well as a ground based component. With lower priority, HCHO and SO_2 columns will also be determined by a non-mapping nadir viewing DOAS instrument on the aircraft and by the mobile and stationary ground-based DOAS instruments.

Airborne component

The research flights will be carefully planned and optimized to coincide with the S-5p overpasses in order to fully cover multiple S-5p ground scenes with a short temporal offset.

It is planned to deploy the airborne imaging DOAS instrument AirMAP, and the airborne sun photometer FUBISS-ASA2 on the same aircraft. The AirMAP data products comprise the NO_2 VCD between aircraft and the ground at a spatial resolution of better than 100 m. The AirMAP measurements can thus be used to directly validate the S-5p tropospheric NO_2 product by averaging AirMAP measurements within the S-5p footprints.

A side product of the AirMAP NO_2 level 2 retrieval is the surface reflectance of each covered ground scene in the spectral region used for the DOAS analysis that can be used to study the impact of low spatial resolution a-priori surface reflectance data on the S-5p trace gas retrievals. In order to retrieve accurate NO_2 VCDs and surface reflectances, information about the vertical aerosol profile is required. Aerosol profile information can be retrieved from the FUBISS-ASA2 instrument, providing very useful input in radiative transfer simulations.

A nadir viewing Avantes spectrometer covering the spectral range from 300 to 550 nm will also be integrated in the airborne platform. This instrument is not imaging but integrates over a configurable stripe below the aircraft. Data from this instrument are useful for interpretation of the AirMAP measurements and under sufficiently homogeneous conditions, also for validation of S-5p HCHO and SO_2 columns. However, the target area is not a hotspot of these two gases in current S-5p data.

This configuration of the AirMAP instrument in combination with an Avantes spectrometer has been flown on multiple occasions on the Polar-5 platform as well as on the FUB Cessna as is proposed for this campaign. Target areas have been power plants and highways (Schönhardt et al., 2015), cities like Bucharest during AROMAT (Meier et al., 2017) or

Berlin (Vlemmix et al., 2017, Tack et al., 2018) but also shipping emissions (Seyler et al., paper in preparation).

Ground-based component

Several ground based instruments shall be deployed that can be used for support and the validation of the airborne remote sensing data and the S-5p data. During the research flights, multiple (mobile) MAX-DOAS instruments will be operated at the target sites aiming at capturing spatial gradients in the area covered by the aircraft. In addition, stationary MAX-DOAS measurements shall be performed to derive vertical NO_2 trace gas profiles.

Due to the larger spectral coverage and the higher sensitivity of the ground-based MAX-DOAS measurements, in comparison to AirMAP, the validation of further S-5p reactive trace gas products, such as HCHO and SO_2, could be addressed by the MAX-DOAS measurements.

The ground-based remote sensing measurements can possibly be extended to include also direct-sun Pandora instruments provided by NASA. This option is currently under discussion and would add several additional validation points, possibly covering a longer time period also before and after the airborne campaign.

The campaign shall take advantage of routinely operated infrastructure, such as the dense in-situ air quality network and an AERONET station.

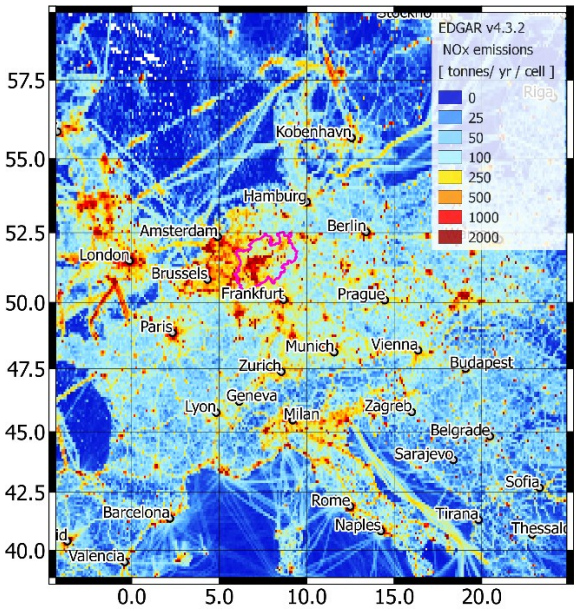


Figure 7.10: Annual average NO_x emissions from the EDGAR inventory on a 0.1° x 0.1° grid for the year 2012. The administrative boundary of North Rhine Westphalia is shown as a pink outline.

7.2.2 Justification

North Rhine Westphalia (NRW) is the most populous federal state of Germany, with a population of approximately 18 million [DR 19]. Large parts of NRW are characterized by contiguous urban agglomerations with many industrial sites, such as the Ruhr area in the north western part of NRW. The southern part of NRW accommodates some of the largest coal fired power plants in Germany, located south west of Cologne. Figure 7.10 shows a map of the annual average NOx emissions as listed in the EDGAR emission inventory (Crippa et al., 2018) for the year 2012 and illustrates, that this region is clearly a pollution hot spot in Europe.

Geometric NO_2 VCD retrieved from S-5p measurements on 28 November, 2017 are displayed in Figure 7.11 and indicate NO_2 levels of more than 2 x 10^{16} mol/cm^2 in the urbanized regions of NRW. Although the NO_2 lifetime in summer will be shorter, it can be expected that NO_2 levels are about one order of magnitude above the detection limits.

The short distance to The Netherlands, may enable a combination of German and the proposed Dutch target sites (e.g. Rotterdam ~ 200 km; Cabauw ~ 150 km) during the same campaign.

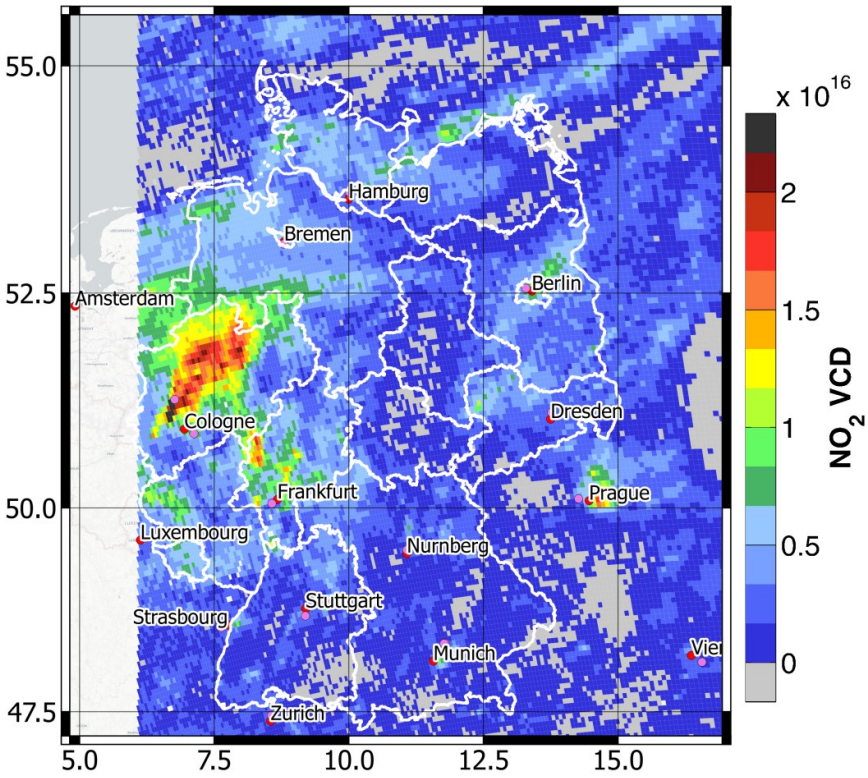


Figure 7.11: Geometric NO_2 vertical column densities in molec/cm^2 retrieved from S-5p spectra measured on 2017-11-28 above Germany.

Logistics

The envisaged industrial target sites have been the subject of the C-MAPExp campaign in 2012, where the airborne remote sensing instrument MAMAP was deployed for the detection of CO_2 from power plants (Krings et al., 2018).

During that campaign, the airport "Dinslaken / Schwarze Heide" was used as a base for the FUB Cessna and may also be used during the proposed campaign. However, multiple other airfields can be found in NRW, which may also be suited, cf. Figure 7.15.

Accommodation for scientists is not expected to be critical in this area.

Weather

Figure 7.12 shows monthly histograms of wind direction and speed for the area around Cologne for June, July and August of 2017. In this area, the wind is predominantly coming from south westerly directions, so that the spatial distribution of NO_2 shown in Figure 7.11 may be regarded as typical. It should however be noted, that the lifetime of NO_2 is shorter during the summer months, resulting in lower columns and less transport.

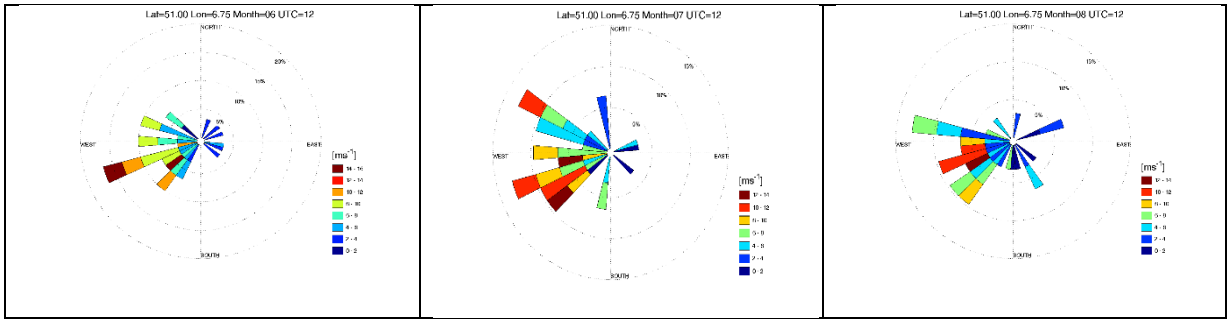


Figure 7.12: Wind histograms for three summer months (June, July, August) in 2017. The data was extracted from ECMWF ERA-interim reanalysis data.

7.2.3 Campaign site

Three different campaign sites are proposed which are less than 100 km apart. These sites are displayed in Figure 7.13 together with the locations of suggested airports and strong industrial emitters of NO_x that are listed in the E-PRTR. The target sites are shown as red boxes labelled with letters A-C. Each of these boxes covers an area of 40 x 40 km^2, which is about the maximum area that can be covered by AirMAP on board the FUB Cessna when flying at an altitude of about 3 km.

Box "A" represents a target area for industrial emissions as it covers three large lignite fired power plants.

Box "B" covers the city of Cologne, as well as some industrial sources south of the city.

Box "C" has a similar character as box "B" with a mixture of urban and industrial emitters of NO_x.

As it is desirable to capture strong horizontal gradients, the decision for a specific target area should be chosen according to the meteorological conditions during the campaign. This is to make sure, that clean areas upwind of the main sources are covered in addition to pollution hot spots. As the airborne imaging DOAS measurements generally require a background spectrum taken on the same flight, this avoids difficulties when estimating the NO_2 amount contained in the background spectrum. Online visualisation of AirMap results will be implemented to help adapting flight patterns if necessary and possible.

Box "A" would be chosen for winds coming from southern or western directions.

Box "B" would be chosen for winds coming from southern or eastern directions, whereas box "C" is suited for northerly or westerly winds.

Not all three proposed target sites must be covered during the campaign. It is however planned to cover at least one industrial and one urban site, as the urban sites show more variability on a priori parameters, such as surface reflectance, and are generally more complex with respect to adjacent multiple sources.

7.2.4 Campaign period

To judge the representativeness of one flight it is necessary to perform at least a second flight in the same area. To account for possibly unsuccessful flights, for example through instrumental failures or sudden cloud cover after take-off, a planning for three flights per target sites is recommended. As the research flights are aiming at the validation of S-5p, only single flights per day should be performed that coincide with the satellite overpass. If two target sites are covered, this results in a minimum of six days on which flights are performed. As the validation measurements should be carried out under clear sky conditions, the weather conditions are the main uncertainty in estimating the time required for successful measurements. Based on experience from previous campaigns, a window of 3-4 weeks should be expected for the campaign.

The summer holiday period in NRW ranges from 2019-07-13 to 2019-08-27. To circumvent complications with flight approvals, the holiday period should be avoided, as authorities may not be fully occupied. In addition, emissions are expected to be larger outside the main vacation period, which would be favourable for S-5p validation. Hence, the campaign should either start mid of June or end of August. As the campaign in Romania is planned for September we suggest the early date for the campaign in Germany to avoid a high workload for key personnel involved in both campaigns.

We propose a campaign period with a duration of 28 days from 2019-06-12 until 2019-07-10.

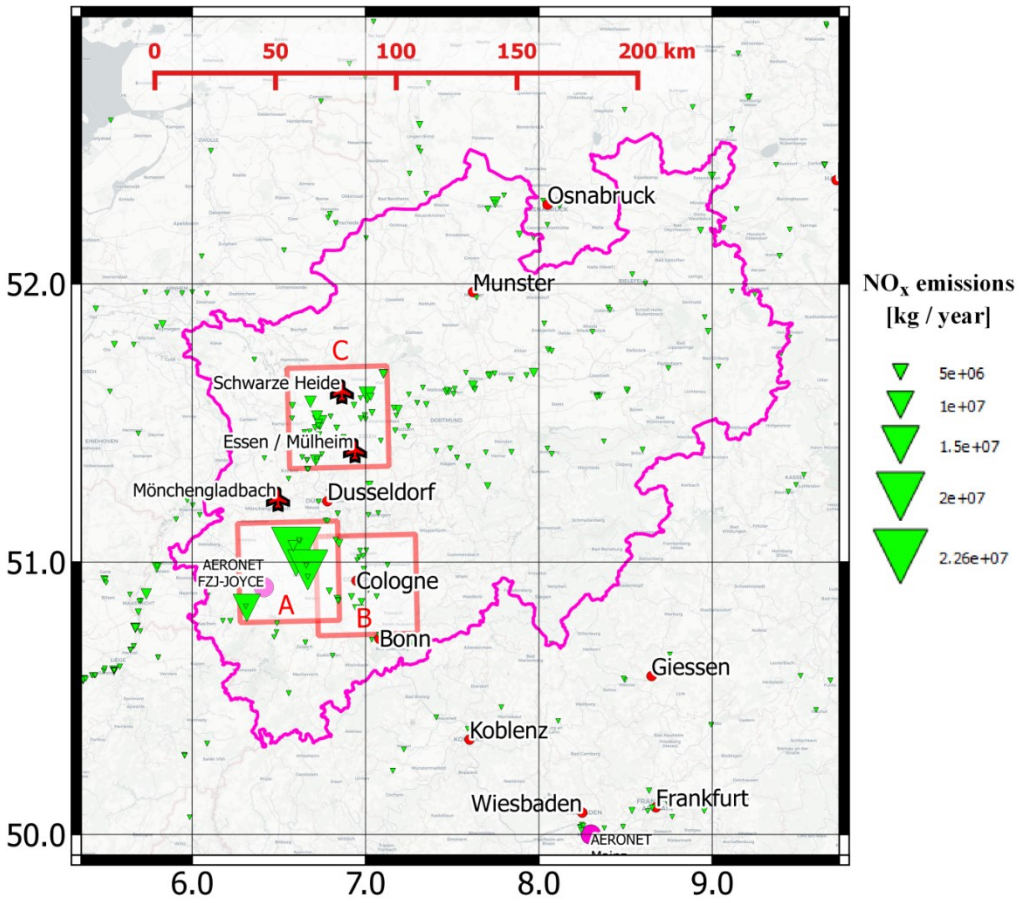


Figure 7.13: NOx emitters listed in the European Pollutant Release and Transfer Register (E-PRTR). The size of the markers provides a measure of the magnitude of annual NOx emissions [DR 17].

7.2.5 Campaign team and responsibilities

It is anticipated that the campaign consortium will consist of the following institutions:

- Institute of Environmental Physics, University of Bremen (IUP-UB)
- Freie Universität Berlin (FUB)
- Max Planck Institute for Chemistry Mainz (MPIC)
- Royal Belgian Institute for Space Aeronomy (BIRA)
- NASA / Luftblick and local hosts

Overall campaign responsibility will be shared by FUB (aircraft responsibility) and IUP-UB (planning and organisation responsibility).

IUP-UB will operate the AirMAP and Avantes instruments on the Cessna as well as a mobile DOAS instrument on the ground.

FUB is responsible for operation of the aircraft and the aerosol instrument FUBISS-ASA2.

MPIC will operate a mobile DOAS instrument on the ground.

BIRA will operate a mobile instrument on the ground.

NASA will potentially provide several Pandora instruments for a limited time period including the main airborne campaign days. These instruments would then be set-up at the premises of partners such as FZ Jülich, University of Cologne and University of Wuppertal and be operated for a longer time period.

7.2.6 Campaign instruments and logistics

Table 7.5: Overview of the campaign instruments and corresponding measured variables/species.

Instrument	Owner organisation	Contact person	Measured variables	Platform	Platform operator	non-availability 2019
AirMAP	IUP-UB	Andreas Meier	NO_2 column	Cessna 207T	FUB	-
FUBISS-ASA2	FUB	Thomas Ruhtz	AOD profiles	Cessna 207T	FUB	-
IUP-UB mobile DOAS	IUP-UB	Kezia Lange	NO_2, HCHO and SO2 columns	car	IUP-UB	-
MPIC mobile DOAS	MPIC Mainz	Thomas Wagner	NO_2, HCHO and SO2 columns	car	MPIC Mainz	-
BIRA mobile DOAS	BIRA	Alexis Merlaud	NO_2, HCHO and SO2 columns	car	BIRA	-

A description of each instrument can be found in Annex A.

Routinely operated infrastructure

Figure 7.14 displays a map of routinely operated instruments that can assist in the validation and interpretation of the campaign data set. A strong asset of the proposed location is the dense network of in-situ air quality stations and the AERONET station at FZJ, which provides information on aerosol properties required for an accurate DOAS retrieval from airborne and satellite remote sensing instruments.

Airports

For the refuelling of the FUB Cessna the availability of Avgas, a special fuel type, is required at the airport. In addition, the runway must be sufficiently long for landings of the Cessna (~1200 m). The three airports displayed in Figure 7.13 all fulfil these requirements. Figure 7.15 shows all airports located in NRW, which may possibly serve as an alternative.

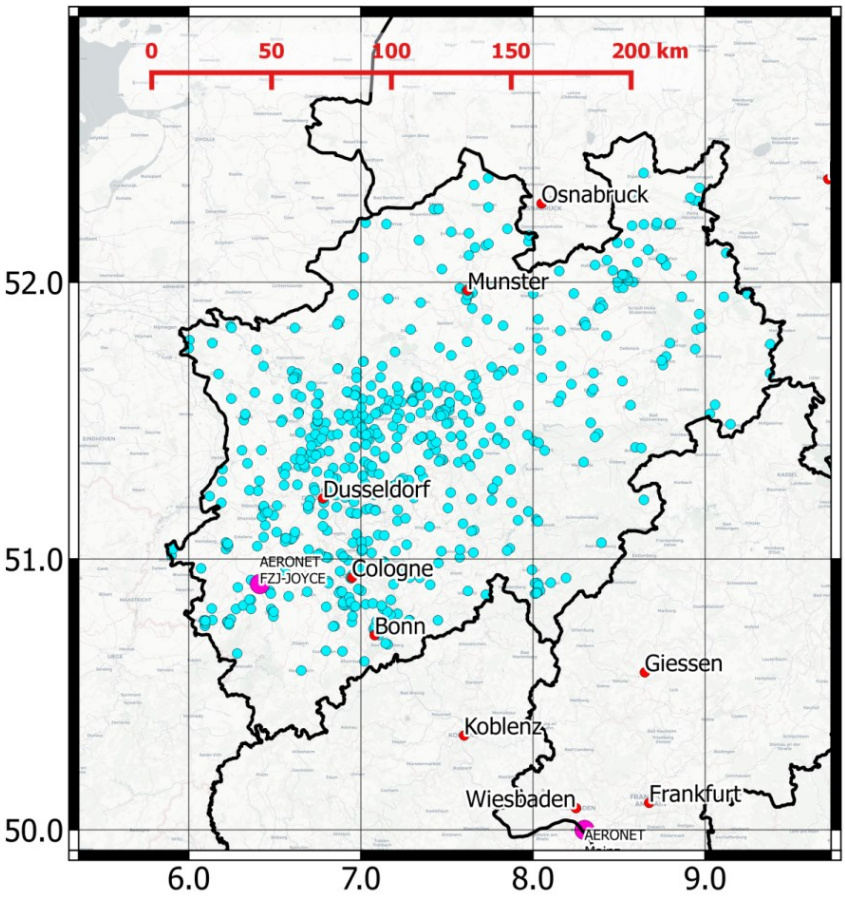


Figure 7.14: Map of in-situ air quality measurement stations (cyan) and AERONET stations (pink).

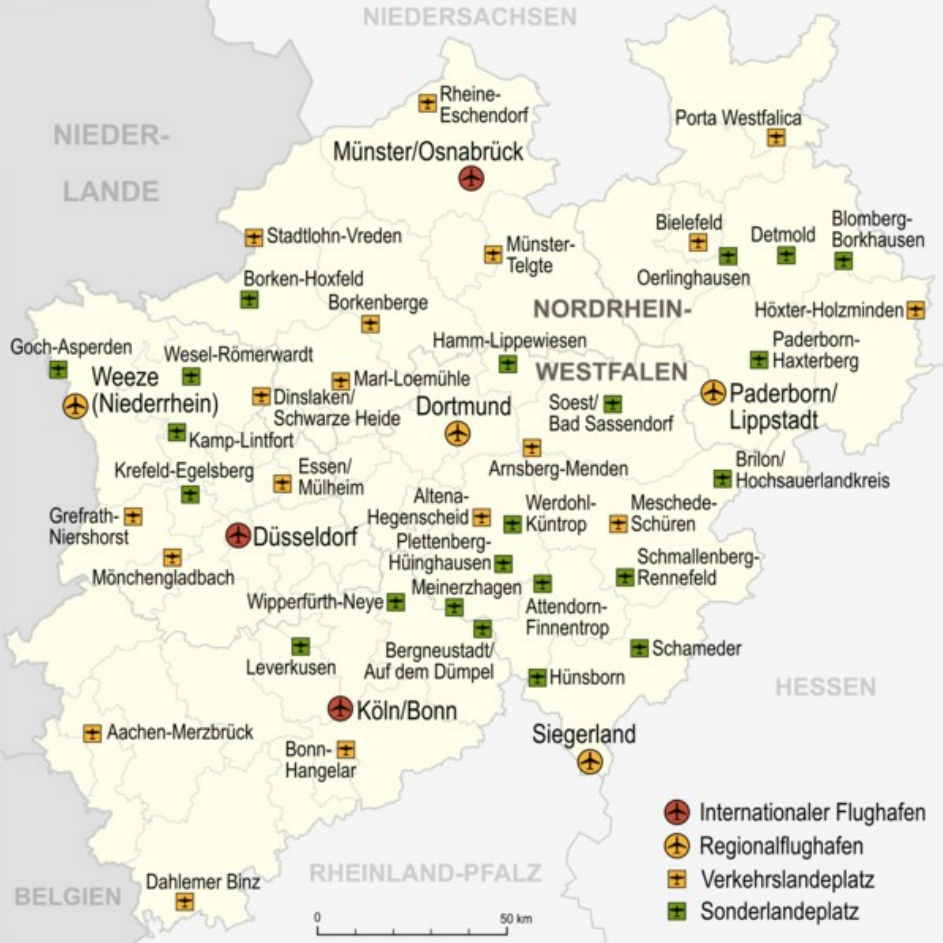


Figure 7.15: Map of airports in NRW. Yellow rectangles are candidates for landings of the FUB Cessna [DR 18].

7.2.7 Campaign scenario

We propose a campaign period from 2019-06-12 until 2019-07-10 in which the airborne and mobile instruments shall be ready to be operated at the proposed NRW target sites. This time frame of 28 days is anticipated to be long enough to be able to perform validation measurements under (nearly) cloud-free conditions during several S-5p overpasses. Installation of instruments on the respective platforms is to be performed before the campaign starts. Stationary instruments, such as Pandora or MAX-DOAS instruments shall be deployed about one month before and after the campaign period.

A kick-off meeting will be held on the first day of the campaign period that includes all teams. In case of persistent bad weather conditions it may be possible for some of the

campaign partners to join the meeting by a telephone conference, as the target sites are reachable from Mainz/Brussels within a few hours by car. This would save money, because costs for accommodation could be reduced. It should however be clear that if there are chances for successful flights, all instrument operators are instructed and on site.

Three target sites are proposed of which one is suitable for power plant mapping, whereas the remaining two sites have an urban character. As the target sites are in close distance to each other, a separation of the campaign targets by calendar dates is not necessary. Instead, the decision for a target site will be taken according to the forecasted meteorological conditions (wind and cloud cover). A relocation of the mobile campaign teams is not considered to be required. The procedure for the next day will be discussed in daily meetings that take place in the afternoon / evening. The exact location of these meetings is still to be discussed, but they could take place at the premises of local co-operators (e.g. FZJ or the Universities of Cologne / Wuppertal). As a fallback solution, meetings could be performed at the airport or at the scientists' hotel.

Phase A: Power plant mapping

In case of case of winds coming from the south west or westerly directions, box "A" will be chosen as target site. It includes three coal fired power plants from which a strong NO_2 signal is expected cf. Figure 7.13. Mapping flights with AirMAP will be performed by flying adjacent tracks with overlapping swath to acquire a gapless map of NO_2 VCD below the aircraft. The flight altitude will be above 3 km to capture the major tropospheric pollution and to have a large swath. The Avantes instrument will measure simultaneously with AirMAP and can assist in the interpretation of AirMAP measurements, but may also be able to detect SO_2 emissions from the power plants if levels are sufficiently large. The orientation of the flight tracks is to be discussed with Air Traffic Control (ATC). Preferably the fights tracks follow the course of the satellite or are orthogonal to it. As box "A" contains the AERONET station at FZJ and the airspace has only few restrictions, it is also well suited for vertical soundings of the FUBISS-ASA2 instrument.

Each of the three mobile car-DOAS instruments could encircle one of the power plants. A specific route however has to be chosen by the campaign team according to the wind conditions, road network and traffic situation.

If possible, stationary campaign instruments shall be overpassed during the transfers between airport and target site to validate the airborne instruments.

If the airspace restrictions permit, the flight tracks of the Cessna during ascend and descend from / to the airport shall be optimized for measurements of the vertical aerosol distribution.

Phase B: Urban mapping

In general, the procedure for the mapping of an urban site is similar to the mapping of the power plant site described above. Vertical soundings of the AOD will be performed during ascend / descend of the Cessna. Adjacent tracks with overlapping swath will be performed in the target area to provide a gapless map of NO_2 columns from the AirMAP measurements. The Avantes instrument will measure in nadir-only to assist the AirMAP measurements and may also be able to detect SO_2 and HCHO if their levels are sufficiently large. In the urbanized areas, the airspace is more restricted due to the vicinity of larger airports so that vertical soundings cannot easily be performed. When flying above FL100 (3 km) altitude however, little restrictions apply. The orientation of the Cessna flight tracks is to be discussed with ATC, but is in general parallel to the air corridor of the major airports.

Stationary instruments shall be overpassed on the way from the airport to the target sites. Mobile car-DOAS instruments will be deployed within the target area during the overpasses of the Cessna. The exact routes have to be determined based on route availability, traffic conditions and wind direction to capture strong spatial gradients.

Whether box “B” or “C” is chosen as the urban target site is again dependent on the wind conditions for the first planned urban flight. If successful measurements were performed above one of these sites, we propose to focus on this area also for the upcoming flights aiming at urban areas.

7.2.8 Schedule and cost

Table 7.6: Campaign schedule.

Campaign phase	Duration	Comments
Installation Pandora / MAX-DOAS		TBC
Installation AirMAP / Avantes	2 days	
Transfer Cessna to target sites	1 day	
Campaign execution	28 days	
Transfer Cessna to Berlin	1 day	
Unmounting AirMAP	2 days	
uninstallation Pandora / MAX-DOAS		TBC

Table 7.7: Main campaign ROM costs.

Budget breakdown	Budget in Euro	Comments
Campaign preparation, organization and coordination	~16.000 €	Including flight approvals, etc.
Aircraft operations	~60.000 €	1800 euro/ flight hour
GB and mobile instrument operations	~32.000 €	
Logistics + travel costs	~28.200 €	
Data analysis (L0 to L2 product)	~8000 €	
Total	**~144.200 €**	

7.3 COCCON ground-based FTIR deployment

7.3.1 Objectives

Achieve a significant validation of the column averaged abundances of methane and carbon monoxide derived from S-5p observations. A significant validation of these data products is not achievable by a spot test, instead a reasonable coverage of geophysical parameters and different ground scenes is required, therefore the validation activity needs to be extended in spatial and temporal domain.

S-5p is a sensor which delivers global data using passive sensor technique. Data derived from passive observation techniques are sensitive to the geophysical conditions of the observation, as solar zenith angle, nadir angle of the observation, columnar water vapour amount, ground albedo, fractional cloud cover (e.g. presence of cirrus clouds), and aerosol optical depth. A single validation campaign localized in time and space would obviously be inadequate, as it would sample only a minor part of the total variation range of the impacting interference factors. Therefore, for meeting the task of providing an encompassing characterization of the S-5p data products, we suggest in the following a range of distributed COCCON (COllaborative Carbon Column Observing Network) activities. The resulting validation campaign data set will be exploited as a whole in a synergistic manner for deriving the sensitivities of S-5p to the relevant impact factors listed above.

7.3.2 Justification

The COCCON is comprised of portable low-resolution EM27/SUN FTIR spectrometers. These spectrometers record solar absorption spectra in the near infrared spectral region. From these observations, column averaged trace gas abundances of H_2O, CO_2, CH_4, and CO can be deduced. The spectrometers within COCCON have been quality-checked and calibrated with respect to TCCON before going into operation at a central facility hosted by KIT, Germany. All spectrometers have identical design, and a very low scatter of instrument-specific residual characteristics. A review demonstrating the consistency between individual spectrometers and the long-term stability of the EM27/SUN spectrometer has recently been submitted to AMT (Frey et al., 2018).

A common preprocessing tool for the recorded interferograms is already available (deliverable in the framework of the ESA project COCCON-PROCEEDS), which allows immediate generation of spectra including quality selection by the operator. The subsequent trace gas analysis will either be done by the instrument operator using standardized code provided by KIT (this code is currently tested in the framework of ESA's FRM4GHG project), or ideally performed at a centralized data retrieval facility. In this case the operator

simply will submit the spectra resulting from the preprocessing together with required auxiliary information to the central facility. Whether the central facility will already be operational in 2019 for the COCCON campaign data depends on the further progress achieved in this respect before end of 2018. Independent from the chosen approach – preliminary distributed analysis with common code or the desired centralized processing scheme – the data processing chain will be identical for all spectrometers, to ensure strict conformity of results, not only with respect to hardware, but also with respect to processing algorithms.

Due to the fact that COCCON delivers column-averaged abundances of methane and carbon monoxide with consistent data quality at selectable sites, it becomes a highly promising component for the validation of these S-5p data products. Note that an infrared solar absorption measurement using direct solar light, as performed by COCCON, is insensitive to scattering. This makes COCCON an excellent tool for checking for possible biases of S-5p data products under partly cloudy or turbid conditions or in the presence of cirrus.

Below we list various individual proposed COCCON campaign activities which will deliver a set of data which in its entirety will cover all major validation aims.

(1) The data set will offer a wide latitudinal coverage for checking variations of S-5p data performance (scatter and bias) on a global scale.

(2) The data set will cover high- and low albedo sites for checking possible variations of S-5p data with respect to ground characteristics.

(3) The data set will contain observations of localized sources (large cities, ventilation shafts of Silesian coal mines, Australian bush fires, etc.), which will allow to deduce S-5p's detection limit for small-scale variations in the distribution of carbon monoxide and methane.

(4) The COCCON data collected across Europe for the purposes 1-3 will in addition be exploitable for detecting possible spurious variation of S-5p as function of the nadir angle of the satellite observation (systematic across-track dependency).

(5) As the COCCON spectrometers due to the short integration time and moderate spectral resolution can still be operated successfully under partly cloudy / hazy / cirrus conditions, the data set will also be exploitable for detecting problems of the S-5p data products under less-than ideal meteorological conditions.

7.3.3 Campaign sites and periods

The COCCON campaign activities cover a huge observation area (as shown in Figure 7.16) and span a major fraction of 2019 (see Table 7.8) instead of being concentrated at a certain location in space and time. This approach has been chosen not only for logistic reasons (consecutive activities allow to reuse a single spectrometer in several activities) and for

merging the largest number of potentially valuable contributions into a comprehensive validation data set, but also for making the COCCON contribution significantly more robust than a concentrated campaign (e.g. a campaign over a month duration held at a selected area in Central Europe using ground-based remote sensing devices could result in a very limited data set if weather is much poorer than climatological expectation suggests) and for taking into account the fact that S-5p is a global monitoring system. Finally, the temporal equalization of various campaign activities during 2019 will also corroborate the permanent long-term observations of TCCON (which are not part of the dedicated S-5p campaign) in the detection of drifts and assessing the seasonal variations of the satellite data.

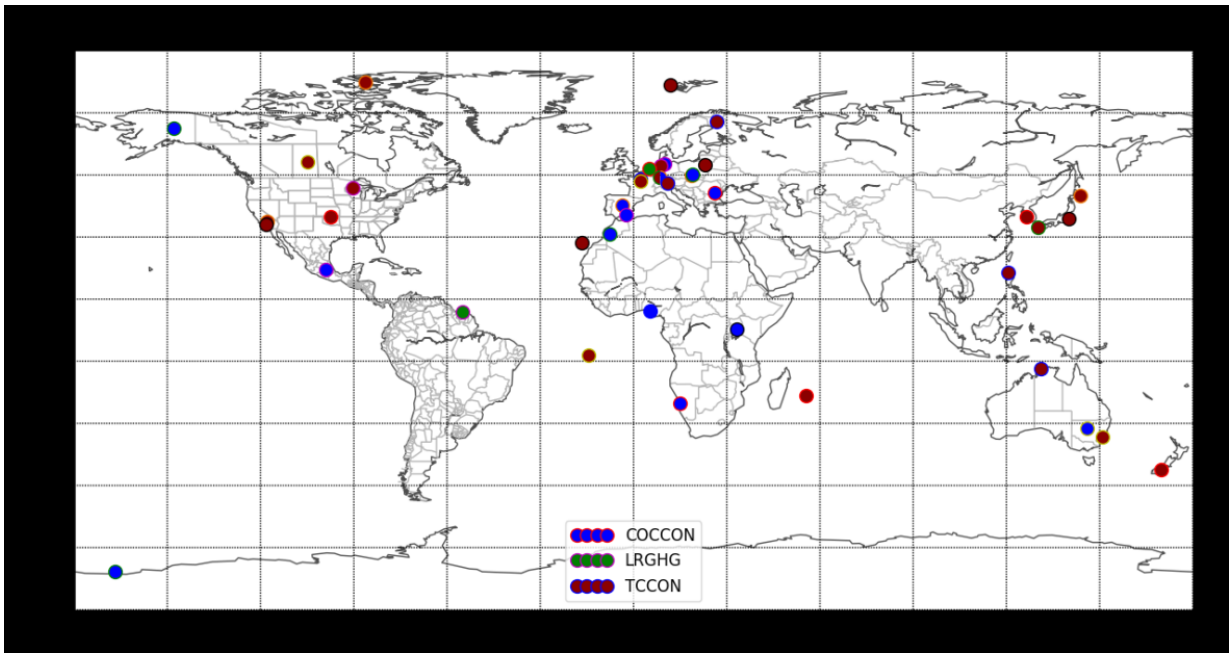


Figure 7.16: Distribution of proposed COCCON activities (blue) on a global map together with the existing TCCON stations and other proposed sites for CH_4 and CO observations under the CIP activities.

Table 7.8: Summary of the preferred periods for each of the COCCON activities during 2019.

Proposed activity	J	F	M	A	M	J	J	A	S	O	N	D
Operation of a pair of COCCON spectrometers for detecting CH_4 and CO emissions from Mexico City					*	*		*				
Operation of a pair of COCCON spectrometers in the high Arctic (Alaska), detection of CH_4 gradients			*	*	*	*	*	*	*	*		
Extension of COCCON activities planned across Europe for improving the capability of detecting spurious across-track variations in S-	*	*	*	*	*	*	*	*	*	*	*	*

5p data products, Provision of spectrometers for partners												
Operate one COCCON spectrometer in locations in France (Western Europe) throughout 2019 for achieving a denser across-track coverage in Europe.	*	*	*	*	*	*	*	*	*	*	*	*
COCCON observations of CH_4 city emissions from Hamburg							*	*	*			
COCCON observations at a high-albedo site (Gobabeb site, Namibia)	*	*	*	*	*	*	*	*	*	*	*	*
Operation of a COCCON spectrometer in Romania (Margurele site + campaign observations: mud volcanoes, landfills, refineries)					*	*	*	*				
Campaign operation of one COCCON spectrometer in high ground albedo region (desert)		*			*			*			*	
Campaign operation of one or several COCCON spectrometers in urban environment (Madrid)		*	*									
Deployment of a COCCON spectrometer for XCH_4, XCO_2, XCO measurements in Western Africa, associated to the LAMTO (Ivory Coast) and AM5 (Morocco) surface measurement sites.	L	L				M	M	M			L	L
Deployment of a COCCON spectrometer at NZ's Arrival Heights laboratory on Ross Island, Antarctica	*	*	*	*						*	*	*
Mobile EM27/SUN will be deployed in network configuration with 4 stationary COCCON spectrometers (KIT, TUM, INOE) in the Upper Silesian Coal Basin					*	*	*	*				
COCCON spectrometer in Jinja, Uganda to observe CH_4 and CO in tropical wetlands (and fire)	*	*	*	*	*	*	*	*				
Observation of bushfire plumes, enhanced CO (+ spectrally resolved optical thickness of biomass burning plumes) with two COCCON spectrometers										*	*	*

7.3.4 Campaign team and responsibilities

The PIs of each proposed activity are listed in Table 7.9. A specific detailed description of each activity including the involved team members is provided in the collection of factsheets in ANNEX B, which were kindly submitted by the PIs of each proposed activity. The responsibility for providing validation data in a timely manner (within 3 months after the measurement has been taken) is with the PI of each activity.

KIT will take responsibility for supporting the selected activities (provision of codes for data processing, provision of additional spectrometers, consultancy if problems with instrument operation occur).

Table 7.9: PIs and geographic location of activities.

Proposed activity	PIs (affiliation)	Geographic location
Operation of a pair of COCCON spectrometers for detecting CH_4 and CO emissions from Mexico City	Michel Grutter (UNAM)	19.4 N, 99.2 E
Operation of a pair of COCCON spectrometers in the high Arctic (Alaska), detection of CH_4 gradients	William R. Simpson (Univ. of Alaska, Fairbanks)	64.9 N, 147.4 W
Extension of COCCON activities planned across Europe for improving the capability of detecting spurious across-track variations in S-5p data products; Provision of spectrometers for partners	Frank Hase (KIT)	Central Europe
Operate one COCCON spectrometer in locations in France (Western Europe) throughout 2019 for achieving a denser across-track coverage in Europe	Caroline Bès	Target regions in France
COCCON observations of CH_4 city emissions from Hamburg	Jia Chen (TUM)	53.6 N, 9.9 E
COCCON observations at a high-albedo site (Gobabeb site, Namibia)	Matthias Frey (KIT)	15.0N, 23.5 W
Operation of a COCCON spectrometer in Romania (Margurele site + campaign observations: mud volcanoes, landfills, refineries)	Dragos Ene (INOE)	43.8 N, 24.9 E
Campaign operation of one COCCON spectrometer in high ground albedo region (desert)	Omaira Garcia (AEMET)	Southern Spain
Campaign operation of one or several COCCON spectrometers in urban environment (Madrid)	Omaira Garcia (AEMET)	40.4 N, 3.7 W
Deployment of a COCCON spectrometer for XCH_4, XCO_2, XCO measurements in Western Africa, associated to the LAMTO (Ivory Coast) and AM5 (Morocco) surface measurement sites.	Michel Ramonet (LSCE)	33 N, 7 E 7 N, 5 W
Deployment of a COCCON spectrometer at NZ's Arrival Heights laboratory on Ross Island, Antarctica	Dave Pollard (NIWA)	77.7 S, 167.1 E
Mobile EM27/SUN will be deployed in network configuration with four stationary COCCON spectrometers (KIT, TUM, INOE) in the Upper Silesian Coal Basin	André Butz (University of Heidelberg)	50.0 N, 18.7 E
COCCON spectrometer in Jinja, Uganda to observe CH_4 and CO in tropical wetlands (and fire)	Hartmut Boesch (University of Leicester)	0.4 N, 33.2 E
Observation of bushfire plumes, enhanced CO (+ spectrally resolved optical thickness of biomass burning plumes) with two COCCON spectrometers	Nicholas Jones (University of Wollongong)	34.4 S, 150.8 E

7.3.5 Campaign instruments and logistics

The logistic requirements of a COCCON spectrometer are extremely low. The operation using a portable inflatable solar cell array (in case an external power supply is not available on site) has been successfully demonstrated. The proposed activities are planned at sites which are developed and have been used before by the proposing teams for operation of other scientific equipment. Most of these sites are equipped with additional sensors. Details are listed in the appended activity factsheets in ANNEX B.

7.3.6 Cost estimate per activity

An estimate of the required funding for each activity is collected in Table 7.10. Several activities are already ensured by external funding. In these cases the funding requested from ESA mainly refers to the provision of data following the standardized data processing and delivery scheme mentioned above. The risks assigned to the proposed activities by the PIs are rated consistently low. In total, due to the distributed approach, the risk / vulnerability of the COCCON component in total seems extremely low.

Table 7.10: ROM cost of each COCCON activity.

Proposed activity	Institute	PI	Funding issues	Support requested from ESA
Operation of a pair of COCCON spectrometers for detecting CH_4 and CO emissions from Mexico City	UNAM, LSCE	Michel Grutter	collaboration with LSCE (France) ANR / CONACYT are funding a 3 years project dedicated to CO_2 measurements in Mexico-City	--
Operation of a pair of COCCON spectrometers in the high Arctic (Alaska), detection of CH_4 gradients	UAF, LANL, KIT	William Simpson	subject to the availability of national (NASA) funding	--
Extension of COCCON activities planned across Europe for improving the capability of detecting spurious across-track variations in S-5p data products, Provision of spectrometers for partners	KIT & COCCON partners	Frank Hase	PhD recruiting progress in 2018	40 kEUR (shipment of spectrometers, campaign travels, data processing + provision)
Operate one COCCON spectrometer in locations in France (Western Europe) throughout 2019 for	CNES	Caroline Bes	Part of MAGIC validation activities	5 kEUR (data processing and provision)

achieving a denser across-track coverage in Europe.				
COCCON observations of CH_4 city emissions from Hamburg	TUM & COCCON partners	Jia Chen	--	30 kEUR (shipment of spectrometers, campaign travels, data processing + provision)
COCCON observations at a high-albedo site (Gobabeb site, Namibia)	KIT, Gobabeb Research and Training Site	Frank Hase	PhD recruiting progress in 2018	10 kEUR (shipment of spectrometer, campaign travels, data processing + provision)
Operation of a COCCON spectrometer in Romania (Margurele site + campaign observations: mud volcanoes, landfills, refineries)	INOE	Dragos Ene	--	20 kEUR (shipment of spectrometer, campaign travels, data processing + provision)
Campaign operation of one COCCON spectrometer in high ground albedo region (desert)	AEMET	Omaira Garcia	--	10 kEUR (shipment of spectrometer, campaign travels, data processing + provision)
Campaign operation of one or several COCCON spectrometers in urban environment (Madrid)	AEMET	Omaira Garcia	This activity is proposed subject to the availability of national (AEMET) funding	30 kEUR (shipment of spectrometers, campaign travels, data processing + provision)
Deployment of a COCCON spectrometer for XCH_4, XCO_2, XCO measurements in Western Africa, associated to the LAMTO (Ivory Coast) and AM5 (Morocco) surface measurement sites.	LSCE	Michel Ramonet	The human resources to operate the instruments are available at both sites, and national funding to cover the travel/shipment of the instruments will be available.	5 kEUR (data processing + provision)
Deployment of a COCCON spectrometer at NZ's Arrival Heights laboratory on Ross Island, Antarctica	NIWA, KIT	Dave Pollard	High risk that EM27/SUN purchase will not be funded. Moderate risk of delays in travel/deployment to/from Antarctica	Letter of support for the purchase of an EM27/SUN

			due to weather or operational priorities.	
Mobile EM27/SUN will be deployed in network configuration with four stationary COCCON spectrometers (KIT, TUM, INOE) in the Upper Silesian Coal Basin	IUP-Heidelberg, KIT, TUM, DLR	André Butz	Activities in 2019 are subject to the availability of national or require ESA funding.	30 kEUR (shipment of spectrometers, campaign travels, data processing + provision)
COCCON spectrometer in Jinja, Uganda to observe CH_4 and CO in tropical wetlands (and fire)	U. o. Leicester, TUM	Hartmut Boesch	The activity is funded	5 kEUR (data processing + provision)
Total				**185 KEUR**

7.3.7 Campaign data analysis plan

The preprocessor provided by KIT to each site team includes a quality screening, removing raw data of poor quality. The retrieval code provided by KIT will generate the retrieved column-averaged abundances of methane and carbon monoxide in a simple, standardized ASCII column format. These data will be used by the CH_4/CO validation lead (see section 9) for performing the comparison with S-5p data products. This analysis will not only compare COCCON campaign data of individual sites with coincident S-5p data, but will make use of the high level of consistency of the COCCON validation data (uniform, quality controlled spectrometers and common data processing) and the large number of involved sites. This allows emphasizing the exploitation of this data set as a whole, e.g. check for systematic discrepancies as function of swath angle or as function of ground albedo. ESA will be informed about the results by end of November 2019 (preliminary report: by then, COCCON campaign data recorded until end of June 2019 should be available), and by end of May 2020 (final report: by then, all campaign data should be available).

7.4 Instrumental deployment at the CESAR super-site

7.4.1 Objectives

This campaign deployment at the supersite of Cabauw focuses on multiple species under realistic conditions of cloud cover. Activities will be developed along two lines of activities: 1) the measurement of CH_4 and CO from the surface till the top of the atmosphere using different techniques, and 2) NO_2, HCHO, aerosol and cloud measurements. Those measurements will be used to validate the corresponding S-5p level-2 products. In addition, a number of ancillary parameters will be measured to record the atmospheric state, so it will serve as a single site where different S-5p products are validated for the same topographic, meteorological and albedo conditions.

7.4.2 Justification

The Cabauw site is located about 25 km south-west of Utrecht in a polder 0.7 m below average sea-level. It has a long history of performing atmospheric measurement since its establishment in 1972. In particular, it has been used for monitoring of long term tendencies in atmospheric changes, studies of atmospheric and land surface processes for climate modeling and validation of space-borne observations. The site is equipped with a tall tower and performs in-situ measurements of CO_2, CH_4 and CO at four layers at 20 m, 60 m, 120 m and 200 m as part of the ICOS infrastructure. Drone flights can also be performed at the site.

The Cabauw site has been the stage for numerous field experiments in the past [DR 10], including OMI validation (DANDELIONS) and MAX-DOAS intercomparisons (CINDI, CINDI-2), while a number of other past campaigns have focused on aerosols and clouds. The unique capabilities of the station enable simultaneous in-situ and remote sensing observations. For many applications, including the retrieval of trace gases from hyperspectral instruments, the comprehensive suite of standard instrumentation is considered an important part of the campaign strategy for TROPOMI validation.

Added-value of the site for air pollution observations

For air pollution, and in particular NO_2, the Cabauw site is situated in a relatively rural area between the main port of Rotterdam, with petrochemical / industrial installations, and the cities of Amsterdam (population 820.000) and Utrecht (population 350.000). Therefore, plumes from the nearby urban areas, as well as the larger scale circulation from the clean North-Sea, as well as the long range transport from the German Ruhr area can be observed.

Added-value of the site for CO and CH_4 observations

Results from the PEGASOS campaign in 2012 have shown that the CO signal measured at the site is mostly from the anthropogenic contribution. It has a diurnal variation with the peak emissions occurring between 8 – 14h, but with some variability.

The annual averaged emissions of CH_4 and CO from the EDGAR inventory are shown in Figure 7.17. These show high emission sources in the regions of West-Germany, The Netherlands and Belgium. Figure 7.18 shows the total hourly concentration footprint of the 200 m and 20 m tower measurements (Vermeulen et al., 2011). Zhou, M. et al. (personal communication) has also shown, using FLEXPART backward trajectories, that the near surface footprint sources of 0-3.5 km CO above Cabauw originate from Europe, North America and South Canada. During the PEGASOS campaign period in 2012, the air mass came mainly from Western Europe, especially from The Netherlands and Germany.

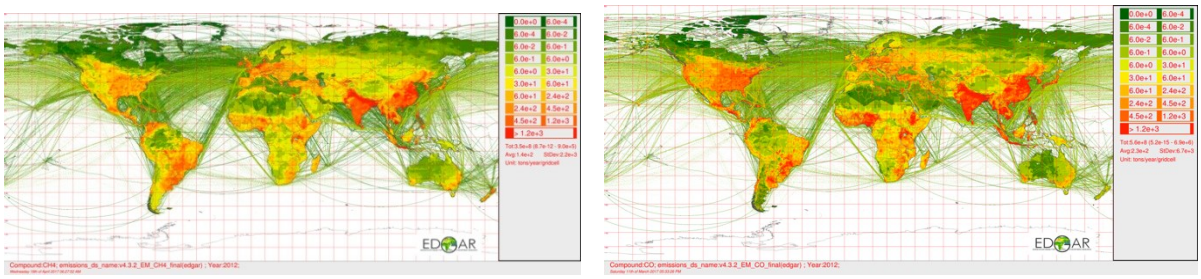


Figure 7.17: Annual average CH_4 (left panel) and CO (right panel) emissions from the EDGAR inventory for the year 2012.

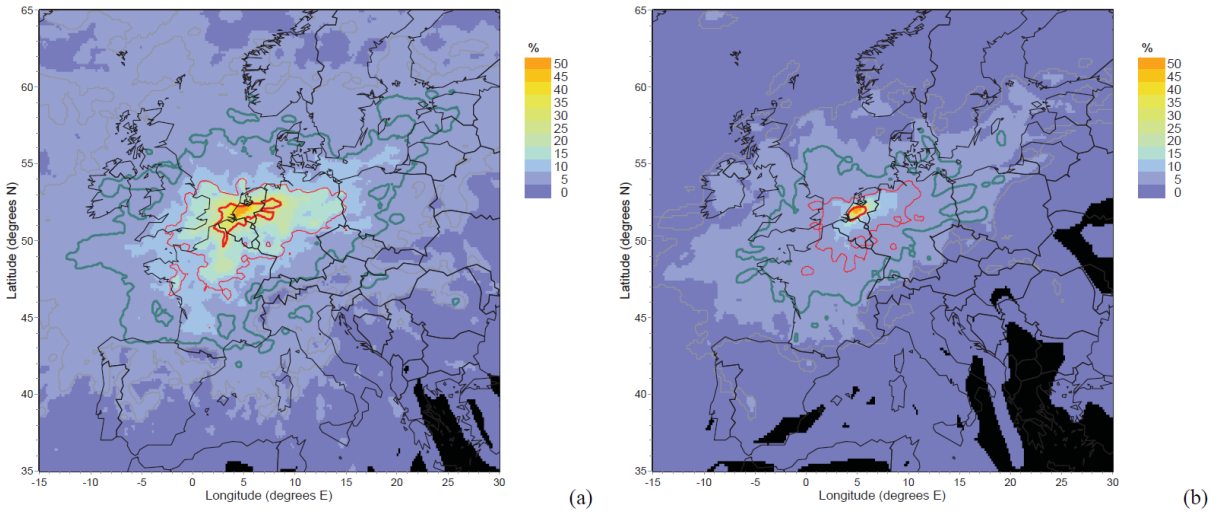


Figure 7.18: (a) Total hourly concentration footprint (annual averages of 2008) for Cabauw 200 m sampling level. (b) Total hourly concentration footprint (annual averages of 2008) for Cabauw 20 m sampling level (Vermeulen et al., 2011).

An example of a S-5p overpass file for XCO over Central Europe is shown in Figure 7.19. From this single overpass, we can already identify the high concentrations of CO values in Western-Germany (Cologne – Aachen industrial region) and central parts of The Netherlands. Such CO plumes, which can be monitored from FTIR observations in Cabauw, are expected to produce a large variability in the observed CO columns, therefore providing useful information for the validation of S-5p data.

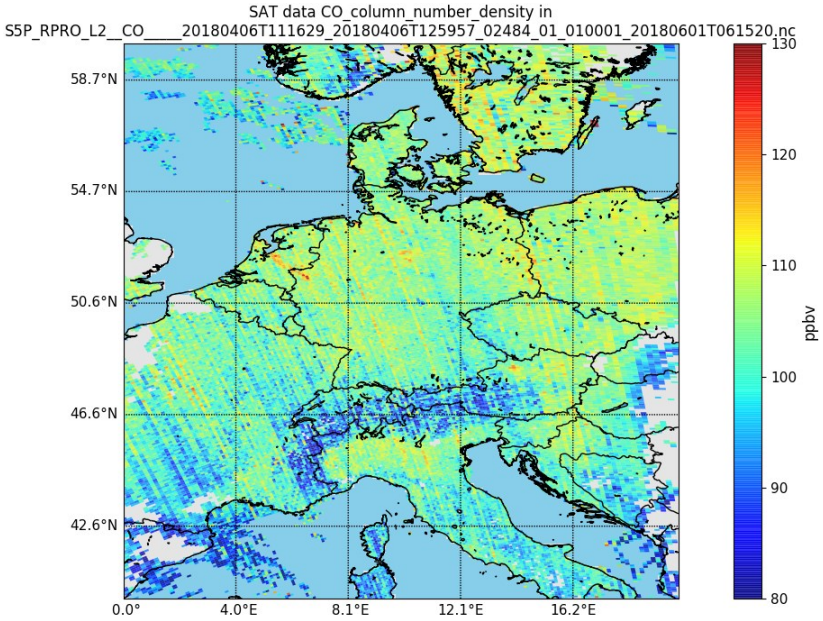


Figure 7.19: Single overpass file for CO total column over Central Europe. The high values indicate potential sources of CO over major industrial regions in Europe.

7.4.3 Campaign site

The Cabauw site is located in the western part of The Netherlands (4.927° E, 51.971° N, −0.7 m ASL). The population density is relatively low in the direct surrounding of the tower. However, the area within 100 km of the tower contains a population of more than 7 million people. Figure 7.20 shows the Cabauw site, marked by the yellow star, and the land use map of the surrounding area within approximately 300 x 400 km^2. The site layout and the location of the main instruments deployed during the CINDI-2 campaign (2016) are illustrated in Figure 7.21. A similar setup will be used in the Cabauw S-5p Core Validation Campaign.

The site has a long history of making atmospheric measurements of CH_4 and CO from the steel tower structure (height of 213 m AGL) at several layers. The FTIR instrument deployment at the site will be based on the experience gained during the PEGASOS campaign in 2012. The AirCore standard flights and the drone-based flights can also be launched easily

from the site as the local team has already some experience with these kinds of measurements, done in the past.

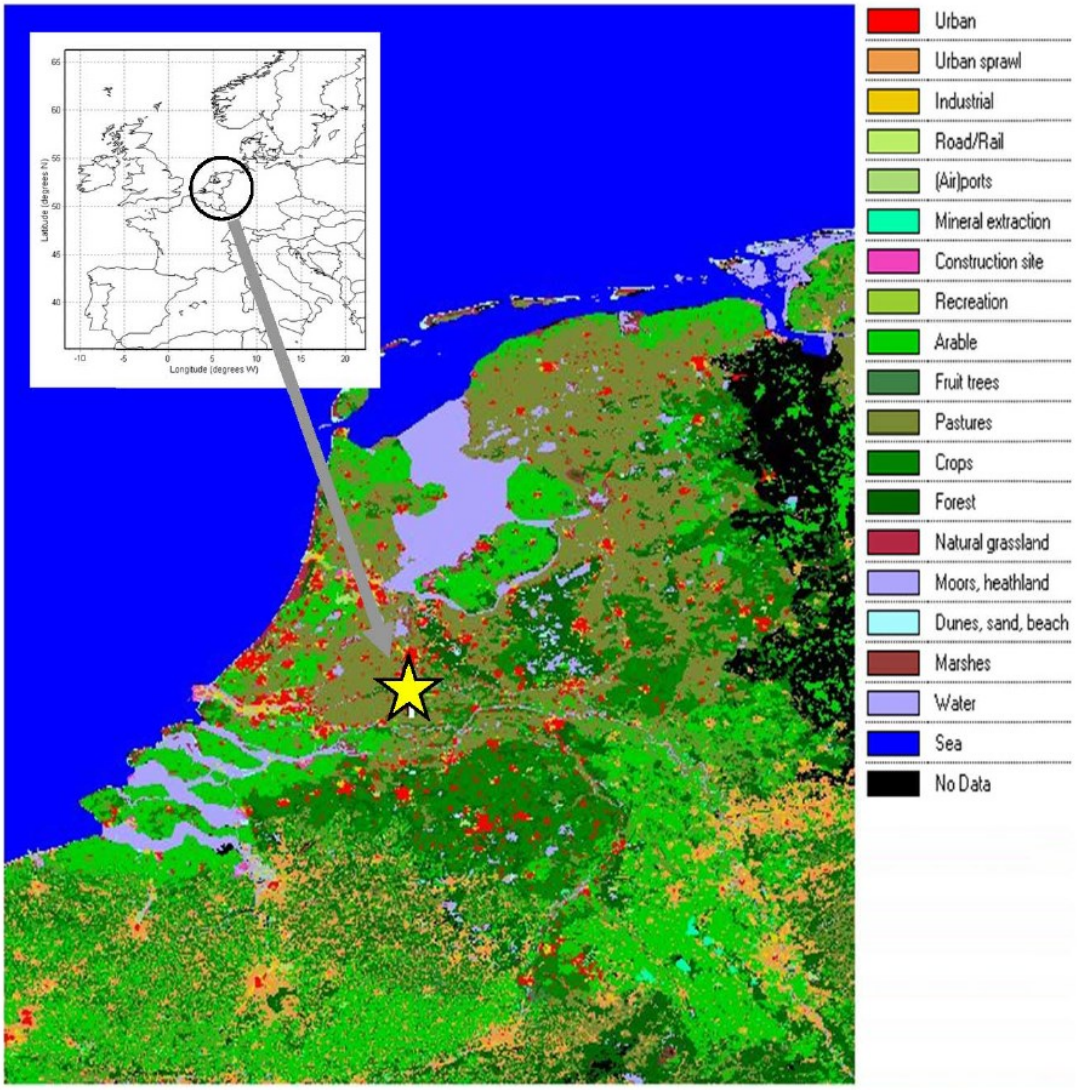


Figure 7.20: Cabauw site location (yellow star) and Corine 2000 [DR 20] land use map for the surrounding area. The area shown in the map is approximately 300 x 400 km^2 (Vermeulen et al., 2011).

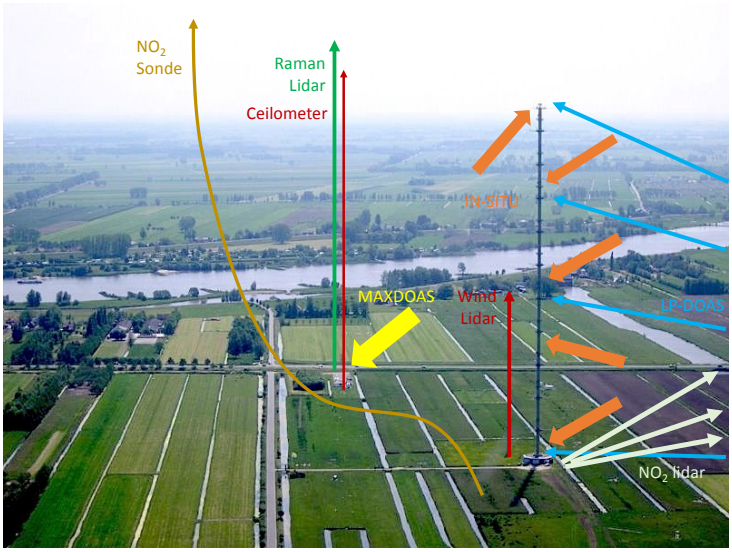


Figure 7.21: Cabauw site layout and main instrument locations during CINDI-2 (2016). A similar setup will be used in the Cabauw S-5p Core Validation Campaign.

7.4.4 Campaign period

A large number of the suite of standard instrumentation is operated automatically and provides data 24/7. In addition, a number of high performance instruments will be added for the S-5p validation.

Based on the experience gained from the PEGASOS and CINDI campaigns, we propose to start the campaign with the measurement setup for the FTIR system by the end of April and perform the measurement campaign for four months between May and August.

A number of periods will be selected in this timeframe to operate the additional instruments during the main campaign period. Furthermore, additional observations will be made to cover all seasons..

7.4.5 Campaign team and responsibilities

The anticipated consortium for the campaign would consist of:

- The Royal Belgian Institute for Space Aeronomy (BIRA-IASB)
- Institute of Environmental Physics, University of Bremen (IUP-UB)
- University of Groningen
- Royal Netherlands Meteorological Institute (KNMI) (as local support)

BIRA will be coordinating the campaign together will the local support from KNMI. BIRA and IUP-UB will be responsible for the FTIR measurements and retrieval of the data.

University of Groningen will be responsible for the AirCore launches and the analysis of the data.

KNMI and Dutch partners will provide the in-situ data, active remote sensing, measured as part of the ICOS network, and take care of local logistics.

7.4.6 Campaign instruments and logistics

Table 7.11: Overview of the campaign instruments and corresponding measured variables/species.

Instrument	Owner organisation	Contact person	Measured variables	Platform	Platform operator	non-availability 2019
Vertex70	BIRA / IUP-UB	Martine De Mazière, Justus Notholt	CH_4 and CO total column	Ground-based	BIRA	-
AirCore (standard & RUG-light)	Uni. Groningen	Huilin Chen	CH_4 and CO vertical profile	Balloon / drone	Uni. Groningen	-
ACTRIS/Cloud net - Lidar, radar, microwave radiometer	KNMI, TU-Delft	Henk Klein Baltink	Cloud vertical distributions and cloud typing masks	Ground-based	KNMI	-
ACTRIS/EARLINET – Raman lidar	KNMI	Arnoud Apituley	Aerosol vertical distributions and aerosol typing masks	Ground-based	KNMI	-
NO_2 sonde	KNMI	Ankie Piters	NO_2 profiles	Balloon	KNMI	-
NO_2 lidar	RIVM	Daan Swart	NO_2 profiles	Ground-based	RIVM	-

In addition, the continuous in-situ measurements of CH_4 and CO will be performed at 20, 60, 120 and 200 m AGL at the site under the ICOS infrastructure.

7.4.7 Campaign scenario

Air quality measurements

The NO_2 lidar instrument will be set up in the beginning of the campaign. A NO_2 sonde preparation station will be installed in the Cabauw site main building and a radio sonde receiving station will be installed. Since the setup of the campaign is already comprehensive, it offers the opportunity to link additional activities. It has been discussed to include for example a TOLNET tropospheric ozone lidar (from the US or Canada, TBC) at Cabauw.

CO and CH_4 measurements

The BIRA team will install the FTIR at the Cabauw site at the beginning of the campaign. During the campaign, the instrument will be operated automatically using the homemade BARCOS software and sun-tracker. The instrument operation will be monitored remotely on a regular basis by the BIRA team. In case of problems we have the possibility of manual intervention and testing of certain parameters remotely. In case the problem cannot be solved remotely then a technician will make a site visit to fix the problem. Due to the proximity of the site from the institute in Brussels the site visit can be planned and implemented relatively quickly. Upon successful completion of the campaign BIRA team will visit the site again to dismount and pack the experiment.

The AirCore setup and launch will be managed by the University of Groningen. Regular communications between the campaign teams will take place via WebEx or Skype or other means. Upon finding good favourable meteorological conditions we will launch few AirCore measurements covering well the time period of the measurement campaign. The AirCore launches will only be made when we have also FTIR measurements at the same time.

7.4.8 Schedule and cost

Table 7.12: Campaign schedule.

Campaign phase	Duration	Comments
Installation of FTIR	5 days	BIRA
Installation of AirCore	2 days	Uni. Groningen
Campaign execution	120 days	
Removal of FTIR	5 days	BIRA
Removal of Aircore	2 days	Uni. Groningen
Installation of NO_2 DIAL	2 days	RIVM
Installation of NO_2 sonde	2 days	KNMI
Installation of TOLNET	2 days	NASA (TBC)

Table 7.13: Main campaign ROM costs.

Budget breakdown	Budget in Euro	Comments
Campaign preparation, organization and coordination	~11.300 €	Only additional costs not covered by national funds are provided here.
Aircore operations	~30.000 €	
GB and mobile instrument operations	~22.000 €	
Logistics + travel costs	~3750 €	
Data analysis (L0 to L2 product)	~8500 €	
Total	**~75.550 €**	

7.5 APEX NO_2 deployment over key Belgian cities

7.5.1 Objectives

This campaign deployment focuses on urban and industrial emissions of tropospheric reactive gases of some of the largest and most heavily polluted Belgian cities, such as Brussels (50°51'02" N, 04°20'56" E, 1.2 million inhabitants) and Antwerp (51°15'37" N, 04°24'10" E, 0.5 million inhabitants). Flights are also foreseen over the port of Antwerp, one of the biggest (petro)chemical clusters in Europe. The horizontal distribution of the trace gas field will be mapped based on hyperspectral Airborne Prism EXperiment (APEX) observations. APEX was also one of the airborne hyperspectral imagers, operated during the AROMAPEX campaign over Berlin (Tack et al., 2018), alongside AirMAP, SWING and Spectrolite Breadboard Instrument. As the APEX instrument does not cover the UV band, the focus will be on the spatial distribution of tropospheric NO_2 solely. During previous flights with APEX over Brussels and Antwerp in the framework of the BUMBA project (Tack et al., 2017), clear NO_2 hotspots and strong horizontal gradients could be detected, related to traffic and industry. The city plumes can also be resolved in recent S-5p daily orbits. The flights will be carefully planned and optimized to coincide with the S-5p overpasses in order to fully cover multiple S-5p pixels (in the order of 10-30) with a short temporal offset, facilitating validation of the S-5p tropospheric NO_2 product. In addition to the airborne component there will be ancillary ground-based component consisting of MAX-DOAS and mobile-DOAS instruments.

Note that in order to avoid repetition, this deployment is discussed only in short. First of all, the campaign has similar objectives and applies a similar campaign strategy as the activities that will take place in Romania and the Ruhr area. Secondly, due to the recurrent nature of the APEX activities in Belgium, campaign procedures and contacts with (flight) authorities are well established, and the involved teams have acquired the necessary expertise and flexibility to organize successful campaigns, requiring only short preparations.

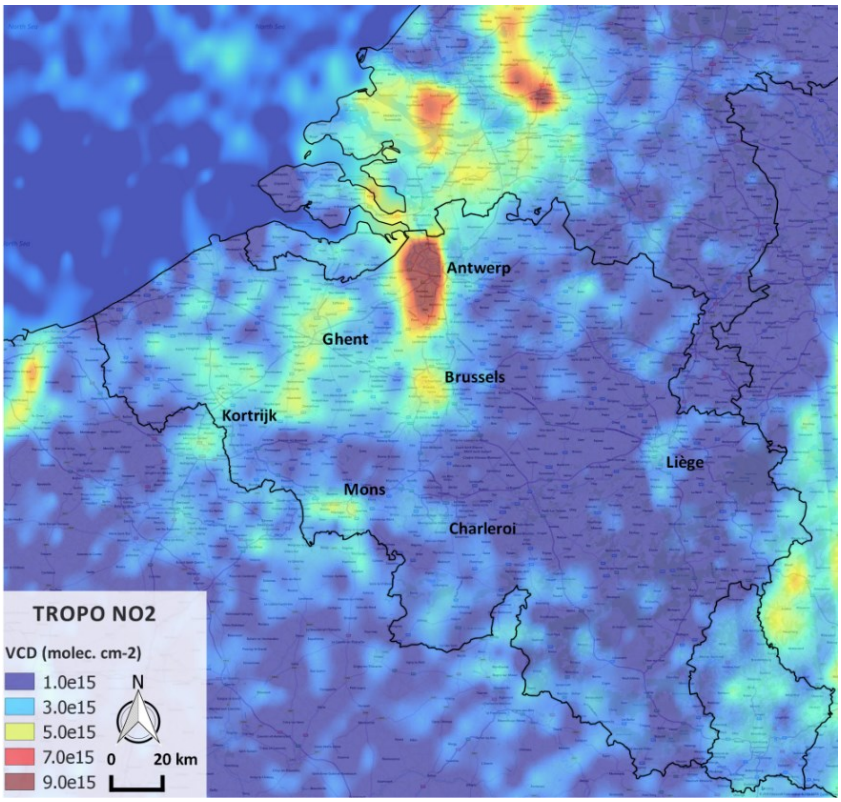


Figure 7.22: Tropospheric NO_2 hotspots observed over Belgium by TROPOMI based on a S-5p orbit on 08/07/2018.

7.5.2 Justification

Both cities, Antwerp and Brussels, have significant sources of air pollutants and elevated levels of NO_2, clearly detectable in daily S-5p orbits. A strong asset is the expertise built during the BUMBA project and the recurrent nature of the APEX activities in Belgium. Each spring and summer there are APEX flights over Belgium. They are, however, mostly conducted for land use / land cover applications. These data sets are acquired in spectral binned mode in order to increase the SNR, while retaining a very high spatial resolution of 3 by 4 m and are therefore not suitable for trace gas retrieval. Specific NO_2 mapping flights, at 100 m spatial resolution, were performed over the cities of Brussels, Antwerp and Liège in 2015, 2016 and recently again over Liège in 2018. Nevertheless, all APEX activities contribute to the establishment of good relations with air traffic control and the local authorities, increasing maturity, cost-effectiveness and flexibility of the operations. Ground-based and mobile infrastructure from BIRA will be used for ancillary measurements and validation. Similarly to the instrument deployment in Germany and Romania, the fact that the

campaign team consists of national partners seriously reduces costs (e.g. very limited costs for travel, hotels, etc.) and increases flexibility.

7.5.3 Campaign site

APEX flights are proposed over two of the largest and most heavily polluted urban areas in Belgium, namely Antwerp and Brussels. Flights are also foreseen over the port of Antwerp, one of the biggest (petro)chemical clusters in Europe with branches of BASF, ExxonMobil, Solvay, Total, etc. During previous flights over these areas, clear NO_2 hotspots and strong horizontal gradients could be detected. Further details of the target areas are provided in Table 7.14.

Table 7.14: Details of the campaign sites.

	Brussels	Antwerp
Lat (°N) / Long (°E)	50.8 / 4.4	51.2 / 4.4
Terrain altitude (m ASL)	76	10
Total population	1.175.173	513.570
Population density (#/km^2)	6751	2496

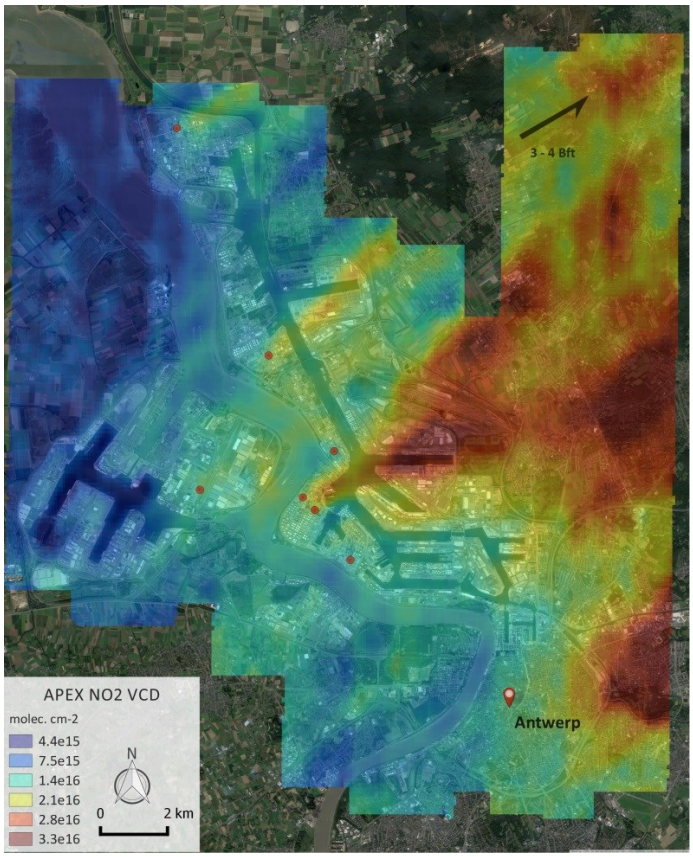


Figure 7.23: NO_2 VCD field mapped over Antwerp city and harbour, retrieved based on airborne APEX acquisition (~100 m spatial resolution) on 15 April, 2015 in the framework of the BUMBA campaign (Tack et al., 2017). Red dots indicate the chimney stacks in the harbour, emitting more than 25 kg of NOx per hour, according to the emission inventory of the Belgian interregional Environmental Agency.

7.5.4 Campaign period

The exact campaign window is difficult to estimate and depends largely on the weather conditions and other APEX activities in the region, but typically APEX flights can take place in Belgium from April till September. However, we prefer to avoid the period of 15 July to 15 August due to reduced (traffic) emissions. Usually APEX is integrated in the aircraft for a spring and a summer campaign in Europe and operations take place at different locations, depending on the weather forecast. It is possible that the planned flights over the campaign areas do not take place during one campaign period, in case weather does not permit, but are taking place during a spring and summer campaign. Ground-teams receive daily updates once APEX is installed in the aircraft and should be stand-by in this period.

7.5.5 Campaign team and responsibilities

It is anticipated that the campaign consortium will consist of the following institutions:

- The Royal Belgian Institute for Space Aeronomy (BIRA)
- Flemish Institute for Technological Research (VITO)
- Swiss Flight Service (SFS)

Together with BIRA, VITO will coordinate the flight operations. VITO will be responsible for the installation and operation of the APEX instrument and for the processing of the raw data to the level 1 product.

BIRA will be responsible for the NO_2 retrievals, level 2 product and comparison with coincident S-5p data. BIRA will also perform simultaneous mobile-DOAS and ground-based DOAS observations during the overpasses.

Swiss Flight Service will be responsible for the airborne operations of the Cessna Grand Caravan (HB-TEN) aircraft and flight planning.

Table 7.15: Preliminary overview of institutes and participants.

Participants	Institute	E-mail address	Comments
Michel Van Roozendael	BIRA	michel.vanroozendael@aeronomie.be	
Frederik Tack	BIRA	frederik.tack@aeronomie.be	
Alexis Merlaud	BIRA	alexis.merlaud@aeronomie.be	
Bart Bomans	VITO	bart.bomans@vito.be	
Daniel Iordache	VITO	marian-daniel.iordache@vito.be	

7.5.6 Campaign instruments and logistics

An overview of relevant campaign instruments and the corresponding measured variables/species is provided in Table 7.16. Auxiliary data will also be acquired from the Royal Meteorological Institute (RMI), e.g. wind data, boundary layer height, etc. More instruments could potentially be added when the campaign is planned effectively. A description of each instrument can be found in Annex A.

Table 7.16: Overview of the campaign instruments and corresponding measured variables/species.

Instrument	Owner organisation	Contact person	Measured variables	Platform	Platform operator	non-availability 2019
APEX	VITO (instrument), BIRA (retrieval algorithm)	Bart Bomans, Frederik Tack	NO_2 column, surface reflectance	Cessna Grand Caravan (HB-TEN)	SFS	-
Mobile-DOAS	BIRA	Alexis Merlaud	NO_2, SO_2 column	Car mobile-DOAS	BIRA	-
MAX-DOAS	BIRA	Michel van Roozendael	NO_2, SO_2, HCHO column	Static	BIRA	-

APEX is an airborne hyperspectral imager and was previously operated for mapping of the NO_2 field over Belgium in the framework of the BUMBA project (Tack et al., 2017) and it was one of the instruments operated over Berlin in the framework of the AROMAPEX campaign (Tack et al., 2018), alongside AirMAP, SWING and Spectrolite Breadboard Instrument. APEX used to be operated from DLR's DO-228 D-CFFU aircraft. However since summer 2018 it is operated from a Cessna Grand Caravan (HB-TEN) from Swiss Flight Service. More specifications about the SFS Cessna Grand Caravan (HB-TEN) can be found at [DR 23]. For the activities in Belgium, the aircraft will be deployed from Berchem airport, a small commercial airport, south-east of the Antwerp city center.

7.5.7 Campaign scenario

The proposed campaign builds on the airborne activities performed in the framework of the BUMBA project [DR 22]. NO_2 mapping flights were performed over the cities of Brussels, Antwerp and Liège in 2015, 2016 and recently again over Liège in 2018. Due to the recurrent nature of the activities, campaign procedures and contacts with (flight) authorities are well established, and the involved teams have acquired the necessary expertise and flexibility to organize successful campaigns, requiring only short preparations.

If weather conditions permit, we propose to organize two flights over each city in order to increase the representativeness. In order to optimize synchronization with the overpass of S-5p, only one flight should take place per day, resulting in four campaign days in total. Both target sites are close to each other (< 50 km), so the campaign teams do not need to be relocated.

In general, the flight path consists of adjacent straight flight lines, flown systematically in opposite directions, with overlapping footprints (approximately 20% overlap in the across-

track direction between consecutive flight lines) in order to have gap-free coverage. For example, the flight lines above Antwerp and Brussels were alternately flown from south to north, and from north to south, with the first flight line in the west during previous campaign. In total a data set consists of around ten flight lines, covering the full city. Additionally a number of flight lines will be extended to rural background sites with decreased levels of NO_2 for reference spectra. The total acquisition time is around 1.5-2 hours. Flights usually take place at a constant altitude of 6.1 km AGL, which is well above the planetary boundary layer (PBL) in order to capture the full tropospheric NO_2 column below the plane.

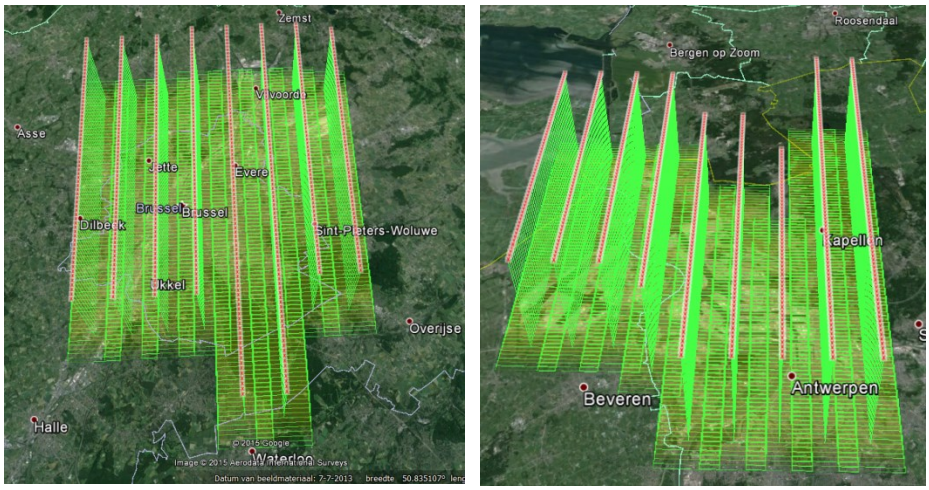


Figure 7.24: APEX flight plans over Brussels and Antwerp.

7.5.8 Schedule and cost

As discussed in Sect. 7.5.4, the exact campaign window is difficult to estimate and depends largely on the weather conditions and other APEX activities in the region. Therefore Table 7.17 must be considered purely indicative.

Table 7.17: Campaign schedule.

Campaign phase	Duration	Comments
Installation of APEX	2 days	
Transfer to target sites	1 day	
Campaign execution	21 days	Flights on clear-sky days only
Transfer to SFS base	1 day	
Unmounting APEX	2 days	

Airborne campaign costs would be covered by national BELSPO funding. However there is no formal agreement on this so far. Only ground-based operations and data analysis should be additionally funded within the framework of the S-5p Cal/Val activities.

Table 7.18: Additional campaign ROM costs.

Budget breakdown	Budget in Euro	Comments
Campaign preparation, organization and coordination	-	
Aircraft operations	-	
GB and mobile instrument operations	~5000 €	
Logistics + travel costs	-	
Data analysis (L0 to L2 product)	~16.000 €	
Total	**~21.000 €**	

7.6 Methane-To-Go campaign

7.6.1 Objectives of the core project

Since recently, the scientific community is aware of the extraordinary high emission rates of pollution (e.g. sulfur dioxide, nitrogen oxides) from the oil and gas industry in the Persian/Arabian Gulf region that are presently missing in global emission inventories (e.g. Fioletov et al., 2016; Krotkov et al., 2016; McLinden et al., 2016). This result was based on an emission-source detection algorithm applied to sulfur dioxide (SO_2) measurements from the Ozone Monitoring Instrument (OMI) satellite and is also supported by the DLR-IPA airborne SO_2 in-situ measurements carried out during the Oxidation Mechanism Observations (OMO) campaign (Klausner, 2016). In 2015, DLR-IPA performed the first detailed airborne SO_2 measurements in the Persian/Arabian Gulf region with the German research aircraft HALO (Figure 7.25), indicating extraordinary high SO_2 mixing ratios in the boundary layer in this region in accordance with the OMI satellite observations. Based on these recent findings, we propose to conduct an airborne in-situ field experiment in the Gulf region to measure the powerful greenhouse gas methane (CH_4), optional SO_2 and other trace species, which are known to be emitted in large amounts from the natural gas and oil operations. Up to now, no detailed trace gas measurements are available for this region. Such measurements are crucial to pin-point the location of the largest emitters, to quantify these emissions and to validate the current emission inventories used as primary input for global climate modeling.

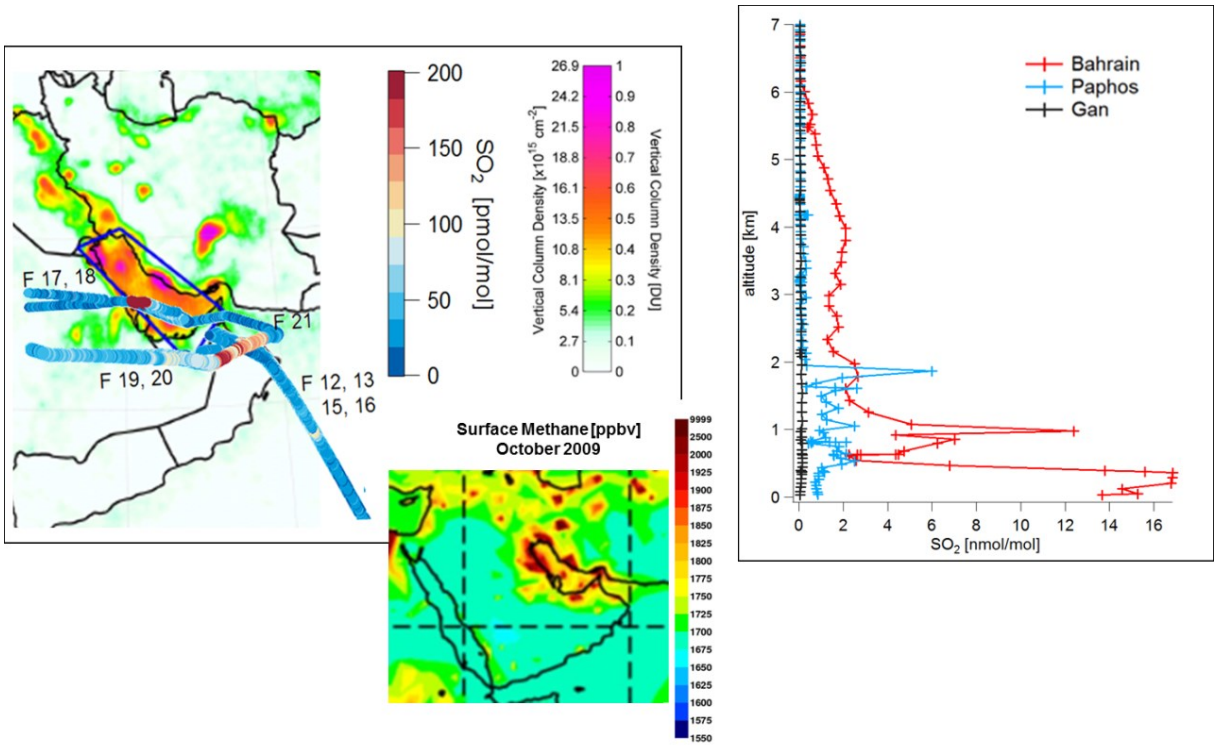


Figure 7.25: Left panel: HALO flight paths during OMO-2015 performed over the Saudi Arabian Peninsula (flights F 12, 13, 15 – 21 carried out mainly in the upper troposphere except during landing in Bahrain) and color-coded according to the measured SO_2 concentration (blue-red). Flight paths are superimposed on the OMI SO_2 PBL map (average of 2013 - 2015) from Krotkov et al. (2016). Right panel: Averaged vertical SO_2 profiles measured by HALO during ascent and descent in Bahrain (red line), Paphos (blue line), and Gan (black line) indicating ~10 times higher SO_2 mixing ratios in the Persian/Arabian Gulf PBL compared to e.g. Paphos (Cyprus). Both panels are modified from Klausner (2016). Center panel: Average surface methane distribution (October 2009) over the Arabian Peninsula from MACC (combination of atmospheric transport model calculations and SCIAMACHY satellite observations) indicating high CH_4 mixing ratios in the Persian/Arabian Gulf PBL.

7.6.2 Campaign site

Operating out of a campaign base located in the United Arab Emirates (UAE) or in Bahrain, the main target areas of the field experiment Methane-To-Go (CH4-To-Go) will be oil and gas operations in the southern part of the Persian/Arabian Gulf region, off- and on-shore of the UAE, Bahrain and Saudi-Arabia (see Figure 7.26).

Campaign Base:	UAE (Abu Dhabi) or Bahrain
Flight Regions:	Flight Information Regions of UAE, Bahrain and Saudi Arabia

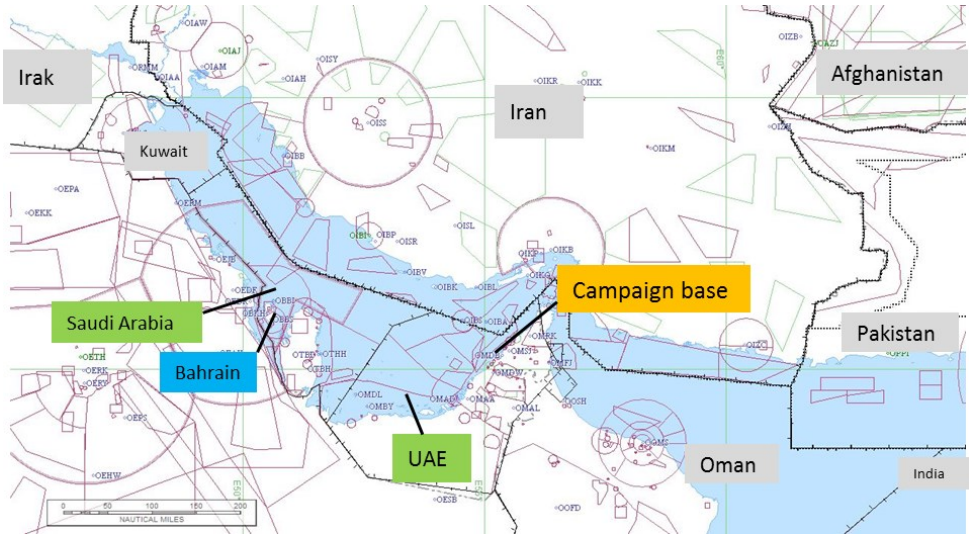


Figure 7.26: Overview of Flight Information Regions (FIRs). Areas of interest are located in the FIRs of Bahrain, Saudi Arabia and the United Arab Emirates (UAE).

7.6.3 Campaign period

Based on the necessity of stagnant meteorological conditions with stable weather (mostly cloud-free conditions with prevailing wind conditions), as well as availability of the DLR Falcon aircraft, the selected campaign period will be in October/November 2019.

7.6.4 Campaign team and responsibilities

The anticipated consortium for the campaign consists of:

- The Institute of Atmospheric Physics, DLR (DLR-IPA)
- The Department of Flight Experiments, DLR (DLR-FX)
- The Remote Sensing Technology Institute, DLR (DLR-IMF)
- The Institut für Umweltphysik, University of Heidelberg

DLR-IPA is responsible for the planning and coordination of the campaign, will conduct the measurements and will lead the technical and scientific data analysis. The logistical preparation of the campaign and the operation of the DLR Falcon during the deployment will be in close collaboration with DLR-FX.

Data analysis of the CH_4 and CO data set will be carried out together with the University of Heidelberg (specifically André Butz, S-5p expert and member of the L2 quality working group).

Furthermore, in case of the possibility to fly the SO_2 instrument, DLR-IPA will work in close collaboration with DLR-IMF (specifically Diego Loyola and Pascal Hedelt), who is responsible for improving the TROPOMI SO_2 vertical column retrieval algorithm, including the various retrieval steps as the slant column background correction scheme, the wavelength fitting windows, and the representativeness of a priori profiles (see Theys et al., 2017).

7.6.5 Campaign instruments and logistics

Besides the DLR-Institute of Atmospheric Physics (IPA) operation of a novel dual Quantum Cascade Laser (QCL) instrument based on laser absorption spectroscopy to measure CH_4 and CO, and related trace gases as CO_2 and C_2H_6 which can be used to distinguish between different CH_4 sources (flaring, venting and combustion), an ion-trap chemical ionization mass spectrometer (IT-CIMS) is envisaged for the measurements of SO_2. Both instruments operate with a high precision/accuracy and a temporal resolution of 0.5 to 1s which covers a horizontal distance of roughly 50-200 m during the flight. Furthermore, measurements of nitrogen oxides and aerosols are planned to pinpoint different sources (see Table 7.19).

Table 7.19: Specifications of the proposed DLR Falcon instrument package.

Instrument	Species/Parameter	Measurement Technique
Dual QCIs Aerodyne	CH_4, CO_2, CO, C_2H_6, N_2O, H_2O	Laser Absorption Spectroscopy
PICARRO	CH_4, CO_2	Cavity-Ringdown Spectroscopy
MET PACKAGE	Wind (3D), T, H_2O	Nose-boom, 5 hole probe
Optional:		
CIMS	SO_2	Chemical Ionization Mass Spectrometry
Aerosol	Vol.- and non.-vol. particles	Condensation Particle Counter plus Thermodenuder
ECO PHYSICS CLD	NO, NO_y	Chemiluminescence
CAPS	NO_2	Cavity-Attenuated Phase Shift

7.6.6 Campaign scenario

The proposed flight strategy of the core CH4-To-Go project (funded by EDF/UNEP and DLR-IPA) includes two different types of flight patterns:

- Regional survey (~3 flights of approximately 3.5 hours)

In the different areas of interest, detailed survey flights will be carried out to identify different kind of oil/gas facilities and their respective emissions, and to study the regional distribution of methane emissions and other trace species.

- Single plume study (~7 flights of approximately 3.5 hours)

A single plume study includes multiple stacked downwind legs perpendicular to the prevailing wind direction at appropriate downwind distances from the designated off- and on-shore oil/gas facility. This flight pattern will allow quantifying the integrated emission flux using different established methods. Depending on the local conditions (e.g. platform density) and the meteorological situation, different methods can be used to infer emission fluxes, such as the mass balance method assuming a fully mixed layer, the mass balance method using an interpolation kriging method, and/or particle dispersion modeling (e.g. Roiger et al., 2015). For the planning and analysis of the flights focusing on single plumes, we will run forecasts from different particle dispersion models as FLEXPART and HYSPLIT.

Extension of the Methane-To-Go campaign in the framework of S-5p validation

Measurements capabilities during CH4-To-Go provide a unique opportunity to support the S-5p validation activities. Specifically, the Persian/Arabian Gulf region is an extraordinary region for TROPOMI CH_4, CO and SO_2 validation because of:

- stagnant meteorological conditions with stable weather (mostly cloud-free conditions with prevailing wind conditions) during the selected campaign period (October/November)
- a variety of very localized, strong sources (partly missing in emission inventories)
- target region covers a wide range of different surface albedo (ranging from very bright desert to dark ocean surfaces)

The main focus of the extended flights will be on the performance of vertical profiles (spirals) covering 0-12 km altitude over highly polluted and less polluted regions which also can be used to determine the CH_4, CO (and SO_2) tropospheric columns in cooperation with DLR-IMF (as mentioned above). Depending on the flight permission situation, we may also conduct mapping or transect flights to follow the satellite near-nadir tracks and to study the intra- and inter-pixel variability in TROPOMI tropospheric columns. Exemplary Strawmen flight patterns are shown in Figure 7.27, however, the final flight patterns will be optimized

during the preparation phase of the measurement campaign. The flights will be carefully planned and optimized to coincide with the S-5p overpasses in order to fully cover multiple S-5p pixels. One main target region for the airborne measurements may also include the SO_2 hot spot "Das Island" (~25 °N, ~53 °E) located between Abu Dhabi and Bahrain, which is missing in the current emission inventories. In addition, the airborne measurements over desert, coastal and ocean areas will cover both high- and low albedo sites valuable for the validation of S-5p data with respect to ground characteristics. Due to the low CH_4 backscatter signal over water surfaces, the bulk of good-quality CH_4 satellite data will be located over land. Thus, we will focus on downwind CH_4 signals in the coastal regions of the southern Persian/Arabian Gulf. Furthermore, it is known that TROPOMI has a reduced sensitivity for SO_2 close to the surface, therefore the effect of pronounced inversion layers, which are common over the Gulf, on the TROPOMI SO_2 signal could be studied with airborne measurements.

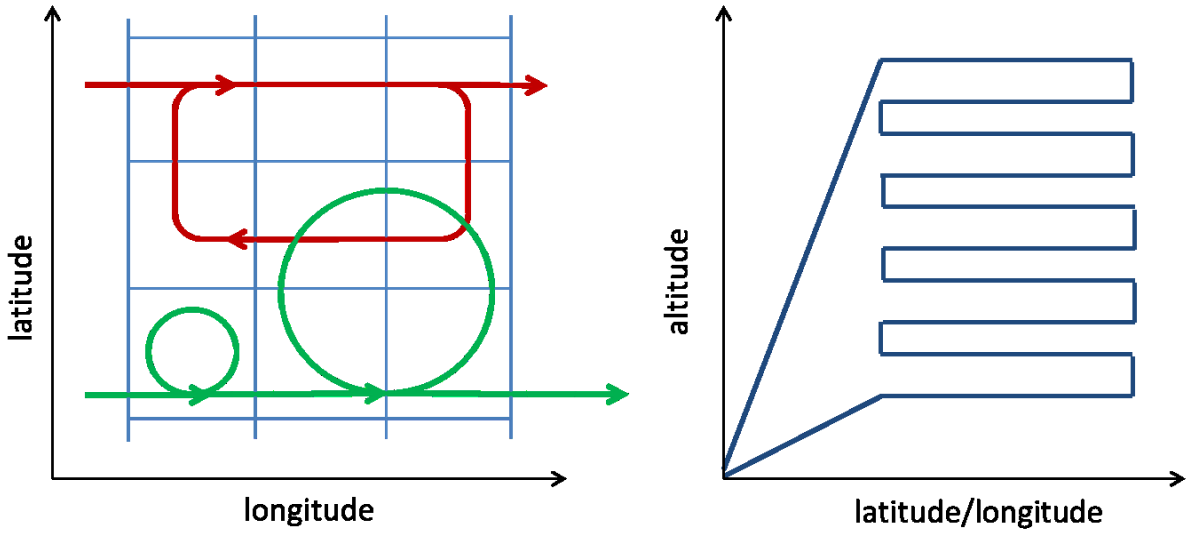


Figure 7.27: Strawmen flight patterns to study the intra- and inter-pixel variability in TROPOMI (left) as well as the tropospheric columns (right).

7.6.7 Cost estimate

We request ESA funding for additional DLR Falcon flight hours to perform the specific flight manoeuvers needed for S-5p validation purposes, for the related extension of the core campaign (2 days), as well as for the analysis of the various in-situ measurements. To allow for the gathering of a meaningful data set, we request two additional flights i.e. 7 flight hours (flight hours may also be split up between flights on different measurement days). In case of funding, we will also make the complete CH4-To-Go data set available to the S-5p community.

Table 7.20: Requested ESA-funding (ROM) for S-5p related tasks during CH4-To-Go.

Budget breakdown	Budget in Euro	Comments
Campaign preparation, organization and coordination	~5000 €	
Aircraft operations	~60.000 €	
Logistics + travel costs	~10.000 €	
Data analysis	~25.000 €	
Total	**~100.000 €**	

7.7 MAGIC campaign

7.7.1 Campaign plan for 2019

In 2019, a MAGIC campaign, close to the one performed in May 2018, will be carried out. It will involve about 40 scientists from 5 laboratories (LMD, LSCE, GSMA, LOA, LERMA), CNES and SAFIRE. The planned instruments are:

- Falcon20 from SAFIRE equipped with Picarro G2401-m in-situ analyzer for CO_2/CH_4/CO/H_2O, as well as drop-sondes and instruments dedicated to the measurements of hydrometeors and aerosol particles (size distribution and backscattering with CIMEL/lidar)
- AirCore-light (3 kg) developed at LMD; will be launched at Aire-sur-l'Adour and Trainou site
- Amulse (3 kg) from GSMA that will be launched at Aire-sur-l'Adour
- Radiosondings from Aire-sur-l'Adour
- CHRIS portable FTS from LOA
- 2 EM27/SUN operated by CNES with the support of LERMA, and by LSCE.

7.7.2 Currently funded activities

MAGIC-2019 is funded by CNES, CNRS and EUMETSAT. The current plan is the following: The Falcon20 will fly along the track of IASI/GOSAT from Aire-sur-l'Adour (ASA) to Trainou (TRN) in order to compare the latitudinal evolution of airborne and satellite measurements. Along its flight, three profiles will be made: at ASA, TRN and around Cognac.

The hours of release of balloons carrying AirCore and Amulse at ASA and TRN will be phased with the passage of the Falcon 20. Additional balloon launches will be phased with three satellites of interest: IASI (local passage time at 10h / 22h), GOSAT and OCO-2 (local time of passage at 13:30). Co-localization with satellites will make it possible to compare the total and partial CH_4/CO_2/CO columns estimated from space with those deduced from the airplane/balloon profiles.

At ASA, a specific flight pattern will be made by the Falcon20: in a radius of 40 km, more than 20 dropsondes will be released in phase with IASI/Metop-A/Metop-B overpassing, in order to study the sub-pixel heterogeneity in temperature and water vapour. At the same time, three releases of AirCores and Amulse will be made.

Concerning the EM27/SUN and CHRIS, two deployments are envisaged:

- A deployment together around ASA to study the subpixel variability of the total columns, at the passage of Falcon20 making its measurements in a radius of 40 km
- A deployment along the track of a satellite, overflown by the Falcon20

The campaign is planned either in July 2019 in order to improve the odds of non-cloudy conditions and to insure the availability of Falcon20, with a back-up in September.

7.7.3 Proposed S-5p validation activities

In order to benefit from the MAGIC2019 organization and team deployment, we propose to ESA to include three specific activities for the validation of S-5p products:

- To perform a second flight with the Falcon20 under the track of S-5p starting from ASA (with 0-11 km profiling close to the overpass time of S-5p) and following an across-track SW→NE and then an along-track SE→NW flight. A flight from ASA following a North-West direction and ending over the Golfe de Gascogne (Atlantic Ocean) with a profiling above the sea might be possible as well, if of interest
- To perform additional AirCore and Amulse flights co-located with S-5p overpassing time at ASA and TRN, as well as with the Falcon20 profiling at ASA
- To perform CHRIS ground-based total column measurements in co-location with the previous measurements.

7.7.4 Budget plan for 2019 as requested for S-5p validation

- Additional Falcon20 flight (6 hours + flight regulation and authorization): 10.500 €
- Additional AirCore launches at ASA (3 flights including balloons, parachutes, radiosoundings and helium): 1500 €
- Additional Amulse launches at ASA (3 flights including balloons, parachutes, radiosoundings and helium): 1500 €
- Additional measurement with CHRIS FTS (full days measurements, including running the retrieval code and providing resulting trace gas abundance): 2000 €.

Table 7.21: Additional campaign ROM costs.

Budget breakdown	Budget in Euro	Comments
Campaign preparation, organization and coordination	-	
Aircraft operations	~10.500 €	
Aircore operations	~3000 €	
GB and mobile instrument operations	~2000 €	
Logistics + travel costs	-	
Data analysis (L0 to L2 product)	-	
Total	**~15.500 €**	

8 Coordination plan with external interfaces

8.1 MPC and S5PVT

MPC validation activities are performed routinely during the operational S-5p mission and rely primarily on the usage of Fiducial Reference Measurements, being a limited suite of independent, fully characterized, and traceable ground measurements. Interactions between the MPC and the S-5p campaign team are expected at different levels: e.g. relevant data sets, available on the Atmospheric Validation Data Centre (EVDC), will be collected by the campaign team and analysed as an ensemble together with the acquired campaign data, e.g. CO and CH_4 columns from TCCON and COCCON sites. Furthermore, the acquisition of the co-located S-5p overpass data will be done with the support of the MPC VDAF.

The S5PVT is complementary to the MPC VDAF. The ESA Announcement of Opportunity (AO) call (2014) aims to engage leading expertise for the calibration and validation of S-5p in the mission validation team, providing independent experimental data, analysis and recommendations to critically assess the end-to-end performance of the instrument and its products. A list of S5PVT accepted projects that can potentially be linked or are already linked to the activities planned in the CIP is provided in Table 8.1. In order to foster collaboration between the different scientific teams, all acquired campaign data will be copied to the EVDC server so they become available to the S5PVT members. Vice versa, data acquired by relevant S5PVT projects, e.g. NASA airborne deployment for the validation of NO_2 and HCHO tropospheric columns in the New York City Area, should be collected by the ESA campaign team and further exploited as part of a coordinated validation approach, as discussed in section 9.

Links are made as well with relevant existing field campaigns, providing essential independent data for S-5p validation, e.g. the RAMOS campaign taking place in Romania in May-July, 2019. A non-exhaustive list is provided in Table 5.4. Note that some campaigns are part of the S5PVT accepted projects.

Table 8.1: List of S5PVT accepted projects that can potentially be linked to the activities proposed in the S-5p CIP. An extended summary of each accepted S5PVT project can be found at [DR 23].

ID	Project name	Institution	PI
40202	Participation in S5PVT to assess TROPOMI NO_2 products using NASA data	NASA	Lamsal Lok
40030	NASA 2018-2019 Airborne Tropospheric Composition Campaigns Contributing to S-5p Validation	NASA	Al-saadi Jay
28329	Participation in S5PVT to validate SO_2 and HCHO Products	NASA	Krotkov Nickolay
28651	Validation and Verification of S-5p NO_2 using ground-based, airborne and satellite data (VVS5P)	IUP-UB	Richter Andreas
28633	Heidelberg Sentine5 precursor validation with a ground-based and airborne DOAS Network (HeiSent-Network)	IUP-UH	Pfeilsticker Klaus
28691	United Kingdom Collaborative S-5p Validation Team (UKCVTS5P)	Uni. Leicester	Hartmut Bösch
28687	Campaign for comparing TCCON to complementary instruments for S-5p validation (TCCONcomp)	BIRA	De Maziere Martine
28675	AirCore vertical profile measurements for validation of the S-5p CO and CH_4 products (AirCoreS5P)	Uni. Groningen	Chen Huilin
28579	Methane and CO validation and verification for S-5p (MECOVAL-S5P)	IUP-UB	Buchwitz Michael
28630	Validation of the S-5p CO and CH_4 total column product	SRON	Landgraf Jochen
28632	SNITCH (SeNtInel 5P validaTion by Comet Halo)	DLR	Andreas Fix
28622	GLORIA for Sentinel-5P Validation (GASVal)	JCNS	Kaufmann Martin
28603	Validation of S-5p Methane and Carbon Monoxide with TCCON Data (TCCON4S5P)	BIRA	Mahesh Kumar Sha
28596	S-5p/TROPOMI L2 products validation using the Cabauw Experimental Site for Atmospheric Research CESAR	KNMI	Apituley Arnoud
28659	EC-ACTS: Earlinet and Cloudnet - Aerosol and Cloud Team for Sentinel-5 Precursor Validation	Istituto di Metodologie per l'Analisi Ambientale - Consiglio Nazionale delle Ricerche	Mona Lucia

8.2 S-5p satellite planning

The foreseen activities need proper synchronization with S-5p overpasses. To predict the orbits and overpasses over a certain location, the Orbit Predictor and Overpass Tool (OPOT) [DR 14] will be the key application for campaign planning. The OPOT is a tool that allows users to specify an area of the Earth's surface and a time window, select a list of satellites, and apply a query to verify, if and when the satellite will perform observations in this region, matching, for example, specific ground based measurement observations. Given a location or a region of interest (defined as a polygon) the OPOT produces a list of overpasses for that region and satellite for a future time range. Besides time synchronization of the activities with the overpass of S-5p, choices will need to be made related to the position of the campaign area with respect to the S-5p nadir track. There will be days where the campaign area is only covered by one overpass. However, when the area is at the edge of the swath it can be covered by two subsequent overpasses.

8.3 Model data providers

Model data will provide key information for both the planning of the campaigns and the analysis/interpretation of the acquired campaign data. For most of the (airborne) activities, clear-sky conditions are required. Weather forecast models will be key to plan optimal campaign days during the campaign window. Chemistry-transport models such as listed in Table 5.2 will be very useful for the interpretation of validation results. Some of them can also be run in forecast mode, so they can be used to provide air quality forecasts. In particular the predicted location of the emissions plumes can be an essential input for campaign planning. An example of modeled NO_2 surface concentrations from the EURAD model (which is part of the CAMS air quality regional Ensemble model) is provided in Figure 8.1.The forecasts images, at an hourly resolution, are routinely published by University of Cologne and FZJ. The underlying data is available through the Copernicus Atmospheric Modeling Services (CAMS) [DR 16].

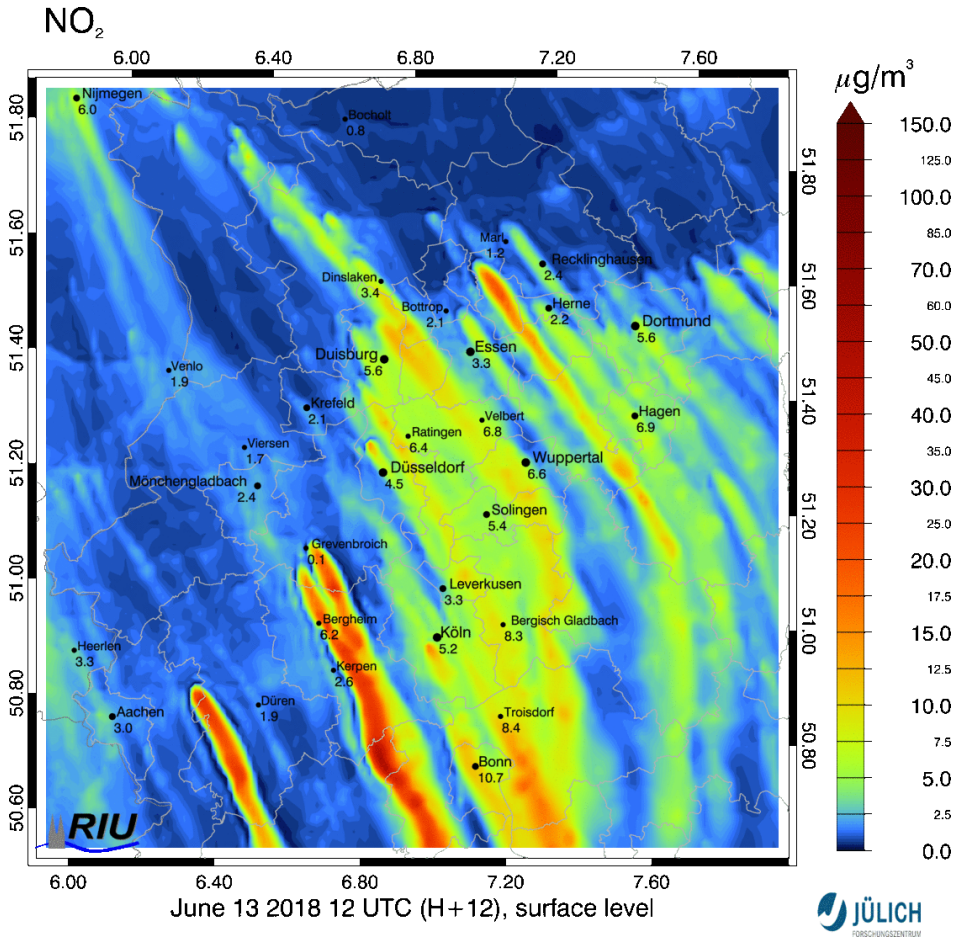


Figure 8.1: Example of modeled NO_2 surface concentrations from the EURAD model. (Images available in hourly resolution [DR 20]).

8.4 EUMETSAT Metop-C

The EUMETSAT Polar System (EPS) programme consists of a series of three polar orbiting Metop satellites, planned to be flown successively for more than 14 years, from 2006. While Metop-A (launched on 19 October 2006) and Metop-B (launched on 17 September 2012) are still operating in a lower polar orbit, at an altitude of 817 kilometres, Metop-C is planned to be launched in November 2018.

Validation campaign activities planned for S-5p in 2019 might therefore provide interesting validation means for the GOME-2 and IASI atmospheric sensors on board of Metop-C. Upon interest from EUMETSAT to be associated to the S-5p campaign activities, the planning of airborne and ground-based deployments might be adjusted to provide a limited number of relevant observations synchronized with the overpass time of the Metop-C platform (9:30 Local Solar Time equator crossing, descending node).

9 Campaign data analysis plan

The various airborne and ground-based instrument deployments, performed as part of the CIP, will produce an important ensemble of valuable independent reference data sets to be used for the purpose of validation of S-5p products. The reference data sets follow the requirements for validation that have been set in Sect. 4 and highlight requirements that can only, or most efficiently, be addressed by a validation campaign as compared to the MPC routine validation activities or in the frame of the S5PVT. The following sections present our plan for a coordinated geophysical validation of a number of key S-5p products, i.e. NO_2, HCHO, CH_4 and CO, using coinciding L2 data from the various CIP activities organized in 2019. For each data product, one core team will coordinate validation tasks and reporting duties, making use of data collected in all relevant instrumental deployments.

9.1 Coordinated validation of NO_2 and HCHO products

Proposed lead: BIRA and IUP-UB

All relevant NO_2 data will be collected from the airborne and ground-based deployment in Romania (Sect. 7.1), Germany (Sect. 7.2), The Netherlands (Sect. 7.4), and Belgium (Sect. 7.5) during a period of 6 months after the end of the campaign. Pre-processing will be applied as necessary so that the various collected data sets are prepared in a common data format, easily ingestible in the various data analysis tools that will be developed at BIRA and/or IUP-UB. The validation campaign data will also be copied to the EVDC server such that they are available to other S5PVT teams.

The S-5p overpass data, needed to perform the validation work, will be acquired with the support of the MPC VDAF. Although existing and well-validated tools will be used as much as possible, additional more specific tools might have to be designed to allow for the generation of fully suitable overpass files around the campaign locations.

The coordinated validation work will make use of the expertise available within the operational VDAF environment, complemented with experience from the AROMAT, AROMAPEX and RAMOS projects. Since the characteristics of TROPOMI pose new validation challenges, mostly related to the much finer spatial resolution of TROPOMI in comparison to past sensors such as OMI or GOME-2, some new development and adaptation of existing validation strategies (including adaptation of tools) will be required. These new developments and the overall interpretation of the validation data will be discussed together with the participating campaign teams.

The proposed campaign activities address in priority a key problem in the analysis of tropospheric data products from satellite observations: the effect of vertical and horizontal

gradients of the trace gases within the satellite ground pixel. While vertical profiles are important for the calculation of satellite air-mass factors, horizontal gradients further complicate the quantitative comparison of satellite column measurements with correlative measurements. Here we will focus on observations of tropospheric NO_2 and HCHO, but similar problems may arise with other short-lived species such as SO_2 or glyoxal. Airborne imaging-DOAS sensors deployed in Romania and Northern Europe, will sample tropospheric NO_2 and HCHO fields close to strong emission sources where strong spatial gradients exist. The main aim of this part of the validation campaign will be to characterise these spatial gradients and their effects on the satellite retrievals. It is expected that close to strong emission sources, horizontal gradients of NO_2 (and probably also HCHO) will be found on scales similar or even smaller than the dimensions of the S-5p ground pixels. Ancillary measurements of NO_2 and HCHO vertical profiles, as well as surface albedo and aerosol content, performed as part of the airborne deployments, will be used to refine the analysis, and better understand the contribution from different error sources under different observational conditions.

Results from NO_2 and HCHO validation activities will be disseminated in various ways, e.g. through presentations at ESA workshops, and international scientific conferences.

The cost of these coordinated validation activities is estimated to be approximately 8 person months.

9.2 Coordinated validation of CH_4 and CO products

Proposed lead: BIRA

The validation activity will be performed by the leading entity in collaboration with the various campaign leads. The COCCON activities comprise 13 individual campaign deployments with data coming from about 33 spectrometers. This will be complemented by additional instruments operated in Cabauw. The campaign data will be collected by the validation lead immediately after they are made available by the respective campaign leads.

It is anticipated that the reference validation data set will sample a wide range of varying conditions e.g.:

- wide coverage of high to mid latitude regions
- wide coverage of different ground albedo conditions
- wide coverage of aerosol and pollution levels
- wide coverage of satellite nadir angles with the setup of several reference spectrometers simultaneously

- coverage of different seasons at several locations covering also time periods where measurements are performed under less than ideal meteorological conditions.

These differences also pose challenges in the interpretation of the validation results. The validation of the S-5p products using these data will be the first of its kind as none of these data was previously used.

The data management for all of the campaign data will be in charge of the validation lead. Data sets from each campaign will be collected centrally, e.g. on a ftp server from which the validation work will be performed. The data will be pre-processed such that they are ready for the validation study. The campaign data will also be copied to the EVDC server such that they are available to other S5PVT teams.

S-5p overpass files operationally generated within the MPC VDAF will be used for the validation campaign study, as much as possible. However, it is anticipated that more specific satellite overpass files will have to be generated for each (non-standard) campaign location. For this purpose, the validation lead will make use of its existing tool to generate the overpass files around the campaign locations.

To complete the coordinated validation work, all existing expertise will be used, in particular the expertise gained during ongoing S-5p validation projects such as TCCON4S5P or the MPC-VDAF operational system. However, the measurements scenarios and conditions of the S-5p campaigns are new and therefore it may require some development or adaptation of existing validation strategies (including adaptation of tools) which will need to be discussed with participating teams. Results from CH_4 and CO validation activities will be disseminated in various ways, e.g. through presentations at ESA workshops, and international scientific conferences.

The cost of the coordinated validation activity is estimated to be approximately 8 person months.

10 Campaign cost estimate

In order to provide an overview of the overall cost for all planned 2019 activities, key ROM costs of the different activities for both the data acquisition and data analysis (L0 to L2 processing and validation of S-5p data) are summarized in Table 10.1.

Table 10.1: Main ROM costs for all 2019 activities.

Budget breakdown	Campaign activity (all costs in €)									Total ROM cost (€)
	Airborne deployment					Ground-based deployment		Coordinated validation		
	RO	DE	APEX	CH_4-TO-GO	MAGIC	COCCON	CESAR	NO_2, HCHO	CO, CH_4	
Non-ESA co-funding?	No	No	Yes	Yes	Yes	Yes	Yes	No	No	-
Campaign preparation, organization and coordination	15.000	16.000	-	5000	-	-	11.300	-	-	**47.300**
Airborne operations	35.000	60.000	-	60.000	13.500	-	30.000	-	-	**198.500**
GB and mobile operations	40.000	32.000	5000	-	2000	185.000	22.000	-	-	**286.000**
Logistics and travel costs	15.000	28.200	-	10.000	-	-	3750	-	-	**56.950**
Data analysis	25.000	8000	16.000	25.000	-	-	8500	80.000	80.000	**242.500**
Total ROM cost (€)	**130.000**	**144.200**	**21.000**	**100.000**	**15.500**	**185.000**	**75.550**	**80.000**	**80.000**	**831.250**

11 Secondary campaign objectives

Although the ESA-coordinated campaign will address in first priority the validation of S-5p operational data products (see list in Table 4.1), it is anticipated that the instrumentation deployment will allow to perform additional validation studies, or investigate research topics of interest.

In particular, the various instruments deployed in the field might provide interesting additional reference data addressing non-operational (scientific) S-5p data products that will be generated by research experts in various institutes or universities. A non-exhaustive list of scientific data products retrievable from S-5p is given in Table 11.1.

Table 11.1: List of non-operational geophysical data products retrievable from S-5p spectra.

Parameter	Data Product	Vertical Resolution
Glyoxal	Total CHOCHO	Total column
Water vapour	Total H_2O	Total column
Water vapour isotopic composition	HDO/H216O ratios	Column-averaged
BrO	Total BrO	Total column
	Tropospheric BrO	Total tropospheric column
SO_2	SO_2 plume height	Altitude of SO_2 plume emitted by volcanoes
IO	Total iodine monoxide	Total column
OClO	OClO slant column	Total slant column
AOD	Aerosol optical depth	Total optical depth
Surface albedo	Lambertian surface reflectance	N/A
Chlorophyll fluorescence	Fluorescence radiance at the surface (Fs)	N/A

In the following, we provide a tentative analysis of the capacity of each validation campaign concept, presented in section 6, to deliver measurements addressing non-operational data products. Table 11.2 lists for each concept case, the different species that are planned to be measured using the deployed instrumentation. It is important to note that there is no commitment from the teams to deliver measurements addressing non-operational data products. These activities will be performed in research mode, upon availability of national funds or on a best effort basis.

In addition to fulfilling validation objectives, campaign measurements might be further exploited for research activities, e.g. in relation to atmospheric composition chemistry and transport or the investigation of emission sources. The deployment of multiple instruments might also provide opportunities for intercalibration exercises. It must be noted that the planned activities will not be optimized towards the secondary objectives, but simply used to the benefit of them.

Table 11.2: Assessment of the atmospheric trace gases relevant for S-5p validation, to be measured as part of the various campaign concepts proposed in section 6.

ID	Validation campaign concept	Target S-5p operational products	Additional measurable species
1	Airborne deployment for the validation of NO_2, SO_2 and HCHO tropospheric columns in high emission regions in Romania	NO_2 , HCHO, SO_2	Total O_3, glyoxal, H_2O, AOD, surface albedo
2	Airborne deployment for the validation of tropospheric NO_2 point sources and plumes in the German Ruhr area	NO_2 , HCHO, SO_2	Total O_3, glyoxal, H_2O, AOD, surface albedo
3	COCCON ground-based FTIR deployment for the validation of CH_4 and CO columns	CH_4, CO	H_2O
4	CO, CH_4, NO_2, HCHO, cloud and ALH validation at the CESAR super-site [partly funded by national contribution]	NO_2, HCHO, CH_4 CO, S-5p cloud, ALH	Total O_3, O_3 profile, glyoxal, BrO, H_2O, HDO, AOD
5	APEX NO_2 deployment above major Belgian cities [partly funded by national contribution]	NO_2	AOD, surface albedo
6	Methane-To-Go campaign in Persian/Arabian Gulf [partly funded by national contribution]	CH_4, CO, SO_2	--
7	MAGIC: a multi-instruments campaign for greenhouse gases and validation of space missions	CH_4, CO	--
8	Airborne deployment for the validation of CH_4 (and CO) gradients in Upper Silesian Basin (Poland)	CH_4, CO	--
9	Airborne deployment for the validation of NO_2, SO_2 and HCHO spatial distribution using transect flights	NO_2, HCHO, SO_2	AOD, surface albedo
10	Airborne deployment for the validation of NO_2, HCHO and CO columns in the Italian Po-valley area	NO_2, HCHO, CO	Total O_3, O_3 profile, glyoxal, H_2O, CH_4, AOD, surface albedo
11	Airborne deployment for the validation of SO_2 plumes emitted by the Etna volcano, Sicily	SO_2	NO_2, total O_3, BrO, surface albedo

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ANNEX A: Instrument descriptions

AirMAP

The Airborne imaging Differential Optical Absorption Spectroscopy (DOAS) instrument for Measurements of Atmospheric Pollution (AirMAP) has been developed for the purpose of trace gas measurements and pollution mapping at the Institute of Environmental Physics of the University of Bremen (IUP-UB). AirMAP is a push-broom UV/vis imager with a wide field-of-view of around 52° across track, leading to a swath width of about the same size as the flight altitude. Due to its large swath and the use of a frame transfer charge coupled device (FT-CCD) detector, gapless maps of horizontal trace gas distributions can be acquired within a relatively short time. During previous campaigns, the AirMAP collects scattered Sun light from below the aircraft with a wide field of view objective in nadir geometry. The light is coupled into an imaging grating spectrograph via a sorted fibre bundle, retaining the spatial information. The dispersed light is imaged onto a FT-CCD. The CCD images are stored on a PC. From a maximum of 35 individual viewing directions, created by 35 single fibers, the number of viewing directions used can be adapted to each situation by averaging according to signal-to-noise or spatial resolution requirements. The single fibres are stacked vertically at the spectrometer entrance slit and are oriented across flight direction in the focal point of the telescope. The spectrometer is an Acton 300i imaging spectrograph with a focal length of 300 mm, and an f-number of f/3.9. The spectrometer is temperature stabilized at 35°C. The wavelength region can be chosen according to the chemical species of interest, with a spectral coverage of around 64 nm, using a 400 g/mm grating blazed at 400 nm. The table below lists some relevant properties of the experimental setup during the latest campaigns (AROMAT-2 / AROMAPEX).

Property	UV-setup	VIS-setup
Spectral range	303 – 367 nm	429 - 493 nm
Spectral resolution	0.8 – 1.5 nm	0.8 – 1.5 nm
Typical integration time	0.5 sec	0.5 sec
Field of View	44°	51.7°

The instrument is further equipped with an optional camera for scene photography. These photographic images are triggered by the spectroscopic measurements and can be used, e.g., for position control and interpretation of the observed scene. The AirMAP instrument as well as the aircraft is equipped with an Attitude and Heading Reference System (AHRS) and GPS sensor. The instrument measures spectra of scattered sunlight. The spectra are analyzed using Differential Optical Absorption Spectroscopy (DOAS) in order to derive column densities of

trace gases. In addition, the effective surface reflectance is derived for each ground scene. A detailed description of the instrumental setup, its performance, the viewing geometry and the georeferencing is described in Schönhardt et al. (2015). The retrieval of vertical column densities, considering a variable surface reflectance, as well as an explicit aerosol correction, is described in Meier et al. (2017).



Figure 0.1: AirMAP installed on the FU Berlin Cessna 207-Turbo D-EAFU aircraft.

SWING+

SWING+ is a custom-made instrument developed by Royal Belgian Institute of Aeronomy, designed and optimized to be functional on BN-2A 27 aircraft. As the previous version of SWING - Small Whiskbroom Imager for atmospheric compositioN monitoring, developed for UAVs (Merlaud et al, 2018), this imager is based a compact UV-VIS spectrometer from Avantes, scanning mirrors driven by a servomotor, optical fibres, and a compact PC which controls the measurements and store the data. The field of view of 6° and typical integration time of 0.5 s yields a spatial resolution of around 300 m when flying at 3 km. Its weight is 3.8 kg and the power consumption is 15 W. Its output parameters are the column densities of NO_2, SO_2 and HCHO (differential slant columns densities-DSCDs) retrieved from the spectra of backscattered radiation on the ground of the or in the atmosphere below the aircraft (Level 0).

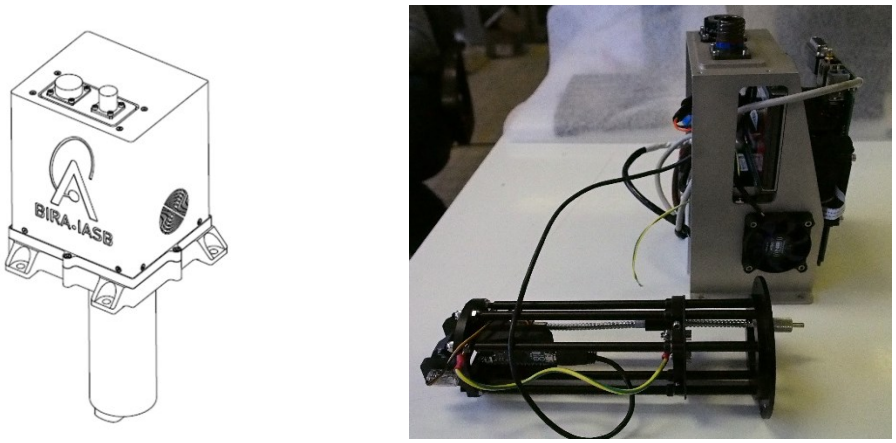


Figure 0.2: SWING+ instrument developed by BIRA.

APEX

Airborne Prism EXperiment (APEX) is a pushbroom imaging spectrometer developed by a Swiss-Belgian consortium (the Flemish Institute for Technological Research (VITO) and the Remote Sensing Laboratories (RSL) at the Department of Geography of the University of Zürich) on behalf of ESA (Itten et al., 2008; D'Odorico, 2012; Schaepman et al., 2015). Although APEX is initially designed as an airborne remote sensing instrument for land use – land cover (LULC) applications, several studies have demonstrated that the instrument is suitable for atmospheric trace gas retrieval applications, and in particular NO_2 (Popp et al., 2012; Kuhlmann et al., 2016; Tack et al., 2017). APEX records data in the visible, near infra-red and infrared regions of the electromagnetic spectrum, covering the wavelength range between 370 and 2540 nm. The radiance is spectrally dispersed by a prism, while the three other imaging instruments are equipped with a grating spectrograph. Because of the use of a prism dispersion element, the full width at half maximum (FWHM) is a non-linear function, broadening with wavelength. In the visible wavelength range, the spectral resolution increases from 1.5 to 3 nm FWHM. APEX has an across-track field of view (FOV) of 28˚ and records data in 1000 across-track pixels. A swath width of 3.1 km is obtained at a typical flight altitude of 6.2 km AGL In order to obtain a favorable signal-to-noise (SNR) for trace gas retrieval, spectra are spatially binned by 20 pixels along- and across-track resulting in a spatial resolution of approximately 80 by 60 m^2. Differential Optical Absorption Spectroscopy (DOAS) is applied to the spectra to retrieve NO_2 column densities.



Figure 0.3: APEX instrument on board of DLR's DO-228 D-CFFU aircraft.

Spectrolite

Spectrolite is a compact, UV/VIS imaging spectrometer that has been developed at TNO for future space application. The design philosophy (relatively light-weight and low-cost modular system for spaceborne remote sensing of the Earth and atmosphere) and instrument specifications are described in detail in de Goeij et al. (2016). The Spectrolite airborne Breadboard Instrument (SBI) version has a weight of 8 kg (which includes the flight box of 4 kg) and a volume of 310 × 420 × 190 mm^3. It has a spectral coverage from 300 to 490 nm with a spectral resolution smaller than 0.3 nm for all wavelengths above 400 nm. The initial wavelength grid (grating function) was determined using several spectral line sources that illuminated a small integrating sphere. The same measurements were used for determining the slit function. During the entire flight the instrument and detector are kept at a temperature of 25°C with a stability of 0.5°C. A glass transmission window was added in order to prevent contamination from outside air. With the SBI optical lens system used for the AROMAPEX campaign – a microscope objective that will not be part of the final design for deployment of Spectrolite from space – an across-track field of view of 8.3° was achieved. At a flight altitude of 3 km above the surface, this corresponds to a width of 435 m. This was divided in 74 viewing directions, such that each ground pixel has an approximate across track width of 6 m. With an integration time of 0.14 s, and the airspeed of around 70 ms^{-1} this corresponds to a Level 0 pixel size in along track direction of approximately 10 m. Processing of raw data to spectral radiances consisted of the following steps: bad pixel removal, electronic offset and dark current removal, followed by flat fielding and radiometric calibration. With respect to the latter, de Goeij et al. (2016) report an uncertainty of 2-5% assuming no degradation of the integrating sphere (these values apply for un-polarized light). The radiometric calibration also resulted in a pixel to wavelength mapping, which was further refined in the DOAS processing. With a SNR for the breadboard set-up of approximately 70 per CCD pixel, considerable spatial binning is needed in order to retrieve NO_2.

ULM-DOAS

The ULM-DOAS system (Constantin et al., 2017) consists on a compact Czerny-Turner spectrometer (AvaSpec-ULS2048XL-USB2, of 175 × 110 × 44 mm dimensions and 855 g weight) placed in ULM (UltraLight Motor). The spectral range of the UV-Vis spectrometer is 280–550 nm with 0.7 nm resolution (FWHM) with a focal length of 75 mm. The entry slit is 50 μm and the grating is 1200 L/mm, blazed at 250 nm. A flexible device (a piece of wood with a hole cached in a small metallic plate), mounted under the wing of the aircraft , holds the telescope achieving a 1.2° field-of-view with fused silica collimating lenses. The spectrometer is connected to the telescope through a 400 μm chrome plated brass optical

fiber. Each spectrum is recorded by a laptop and georeferenced by a GPS receiver. The spectrometer and the GPS receiver are powered by the laptop USB ports. The entire set-up is powered by 12 V of the aircraft through an inverter. Each measurement is a 10-second average of 10 scans accumulations at an integration time between 100–250 ms. All observations were performed only in nadir geometry. The ULM-DOAS system can be used to determine the column densities for NO_2, SO_2 and HCHO.

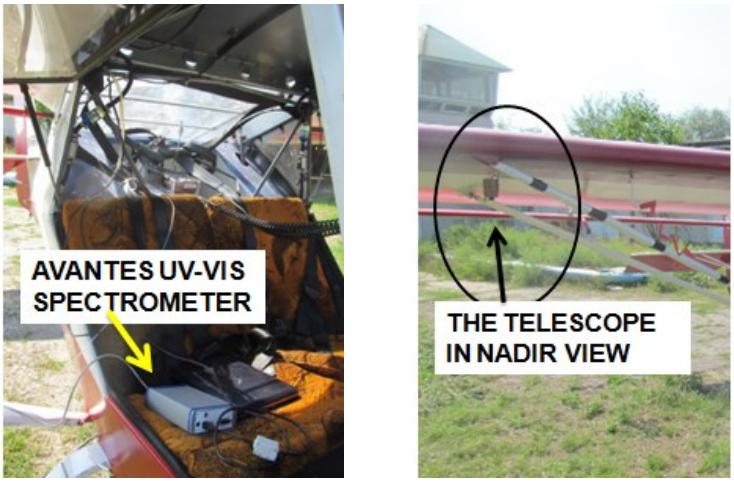


Figure 0.4: The UV-Vis spectrometer inside the ULM and the telescope installed under the wing.



Figure 0.5: Apollo Fox ULM.

MAMAP

In 2006 the IUP Bremen and GFZ Potsdam jointly initiated a research cooperation to develop and build a flexible high altitude airborne spectrometer system, the "Methane Airborne Mapper" (MAMAP). This instrument is capable to perform direct and quantitative remote measurements of atmospheric CH_4 and CO_2 column mixing ratios as well as retrieval of the column averaged dry air mole fractions of XCH_4 and XCO_2 by airborne passive NIR/SWIR absorption spectroscopy (see Gerilowski et al. 2011). The retrieval algorithm was developed and continuously refined at IUP-Bremen (Krings et al. 2011). The method was further developed to quantify CH_4 emissions from coal mine ventilation shafts (Krings et al. 2013). During the last years MAMAP was flown in two campaigns one in summer 2012 focusing on CO_2 emissions from power plants in Germany (Krings et al. 2018), and another in summer 2014 focusing on CH_4 emissions from different source types (Oil & Gas-Industry, Waste Management) in the greater Los Angeles area and the San Joaquin Valley (Krings et al. 2017, Krautwurst et al. 2017).

The results demonstrate that the MAMAP instrument is able to detect and retrieve gradients with a precision of ~ 0.3% (1-sigma) in the background normalized dry column of the greenhouse gases CH_4 and CO_2 at local scales and that MAMAP is an appropriate tool for detection and inversion of localized GHG emissions from different aircraft. Based on successful design studies, IUP currently is building a follow-on sensor, MAMAP2D.

The MAMAP instrument measures similar to SCIAMACHY the earth surface reflected and scattered solar radiation in the short wave infrared (SWIR) and near-infrared (NIR) spectral range at moderate spectral resolution. The NIR channel around 0.76 μm measures the atmospheric O2-A-band absorption with a resolution of ~ 0.46 nm. The SWIR channel yields measurements of atmospheric absorption bands of CH_4 and CO_2 in the spectral range between 1.59 μm and 1.69 μm at a spectral resolution of ~ 0.9 nm. The retrieval algorithm used for MAMAP (Krings et al., 2011) was derived from the Weighting Function Modified Differential Optical Absorption Spectroscopy (WFM-DOAS) retrieval algorithm (Buchwitz et al., 2000). The column averaged dry air mole fraction of CH_4 (XCH_4) is computed thereby by normalizing the CH_4 column to the column measurements of CO_2 or O_2 (denoted as $XCH_4(CO_2)$ and $XCH_4(O_2)$). CO_2 column averaged dry air mole fractions (XCO_2) were derived by normalizing CO_2 column measurements of CH_4 or O_2 (denoted as $XCO_2(CH_4)$ and $XCO_2(O_2)$), see also (Gerilowski et al. 2011). These data can then further be used for the top-down inversion of fluxes of local sources via inverse modeling (Krings et al.2011).

The MAMAP instrument comprises two thermally stabilized grating spectrometer systems having a focal length of F = 300 mm and a f-number of f/3.9. Both spectrometers are operated currently in non-imaging mode. The first spectrometer system measures in the SWIR in the

spectral interval from 1590 nm to 1690 nm to enable simultaneous retrieval of CO_2 (1590–1620 nm) and CH_4 (1630–1675 nm) columns. The second spectrometer system measures in the NIR in the spectral interval from 756 nm to 769 nm for the detection of the oxygen (O_2) absorption using the O_2-A band. Both spectrometers have one common telescope, collecting electromagnetic radiation, and pointing towards nadir. Optionally the instrument can point also upwards to zenith-sky direction. A fold-mirror allows switching between the nadir and zenith-sky observation modes. This permits sequential measurement of the diffuse up-welling and down-welling radiance. Optionally, cosine diffuser plates can be installed on top of the zenith sky telescopes. In this configuration the instrument can perform direct solar irradiance measurements and diffuse down-welling (ir)radiance measurements in zenith-sky mode. From these nadir and zenith-sky measurements total and/or partial vertical columns can be retrieved (Gerilowski et al., 2011; Krings et al., 2011). Both spectrometer systems and electronic components fit in two "standard Falcon racks" with ~120 kg weight of each rack.

In 2014, real time retrieval capabilities were implemented in the MAMAP instrument data acquisition chain enabling the operation and guidance of the remote sensing measurements over complex terrain, as well as detection and characterization of unknown sources/source clusters and their spatial distribution (Thompson et. al. 2015, Gerilowski et al, 2014).

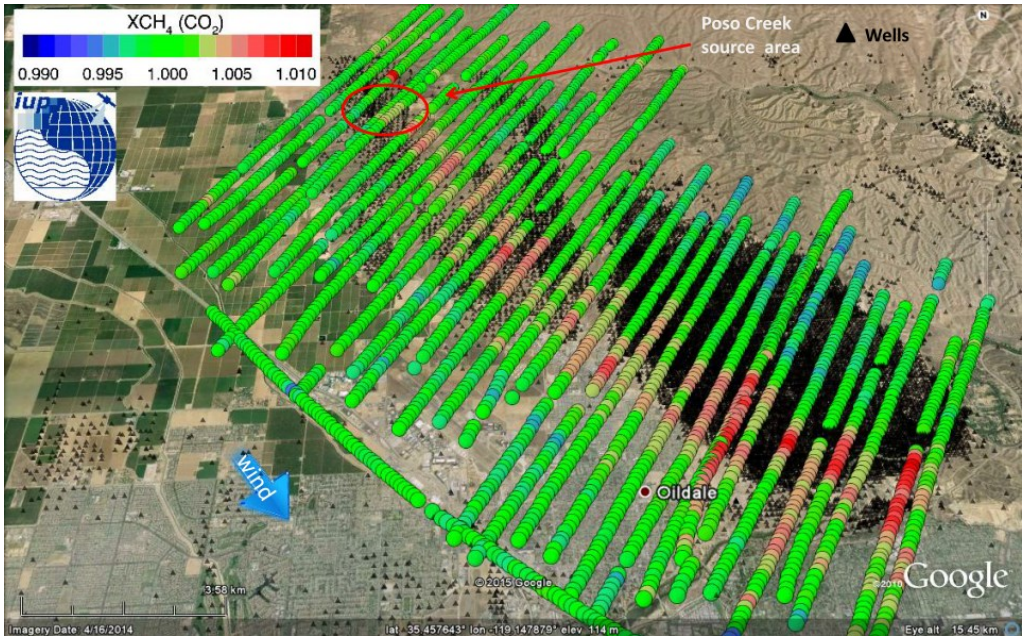


Figure 0.6: MAMAP measurements over the Kern-River, Kern-Front and Poso-Creek Oil Fields. The measurements reveal the existence of an unexpected large-scale methane plume extending several kilometers over the western area of the main fields. The measurement was performed on September 04, 2014. The plume was traced by the MAMAP real-time retrieval capability implemented in the MAMAP data acquisition chain before the campaign (Thompson et al, 2015; Gerilowski et al. 2014).

GHOST

GHOST is a compact shortwave infrared grating spectrometer (non-imaging), designed for remote sensing of tropospheric columns of CO, CH_4 and CO_2 from an airborne platform. It observes solar radiation at medium to high spectral resolution (better than 0.3 nm) which has been reflected by the Earth's surface, using similar methods to those used by polar orbiting satellites such as the JAXA GOSAT mission, NASA's OCO-2, and the Copernicus Sentinel-5 Precursor. By using an original design comprising optical fiber inputs along with a single diffraction grating and detector array, GHOST is able to observe CO_2 absorption bands centered around 1.61 µm and 2.06 µm (the same wavelength regions used by OCO-2 and GOSAT) whilst simultaneously measuring CH4 absorption at 1.65 µm (also observed by GOSAT) and CH_4 and CO at 2.30 µm (observed by Sentinel-5P). More details can be found in Humpage et al. (2018).

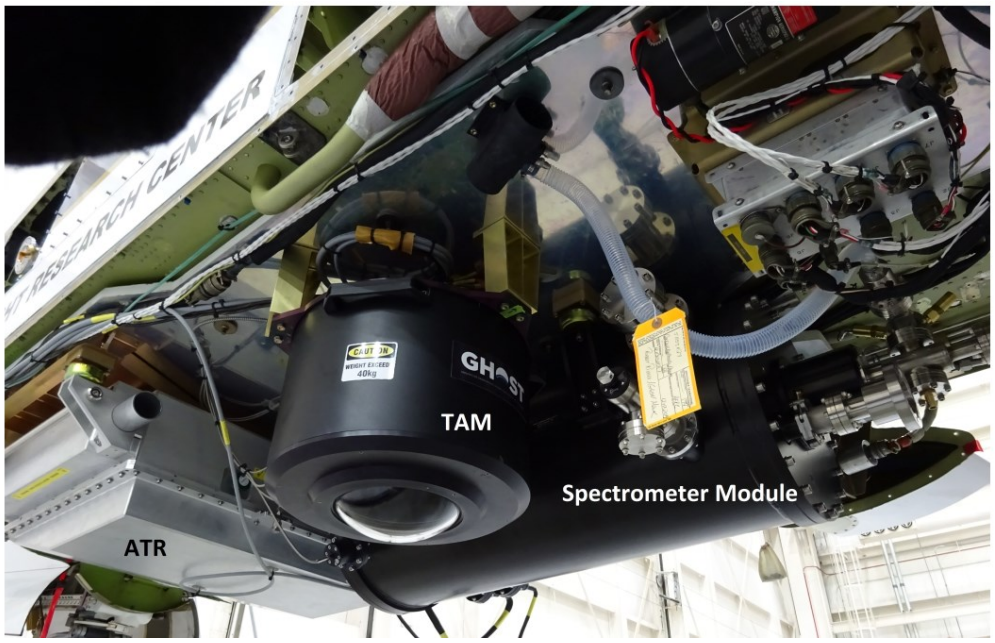


Figure 0.7: GHOST components as mounted in the lower instrument bay of the NASA Global Hawk, Photograph taken from below showing the installation (Humpage et al. 2018).

FUBISS-ASA2

The airborne spectrometer system FUBISS-ASA2 (Zieger et al., 2007) provides simultaneous measurements of the direct solar irradiance and the aureole radiance in two different solid angles. The high resolution spectral radiation measurements are used to derive vertical profiles of aerosol optical properties. Combined measurements in two solid angles provide better information about the aerosol type without additional and elaborated measuring geometries. It is even possible to discriminate between absorbing and non-absorbing aerosol types. Furthermore, they allow to apply additional calibration methods and simplify the detection of contaminated data (e.g. by thin cirrus clouds). For the characterization of the detected aerosol type a new index is introduced which is the slope of the aerosol phase function in the forward scattering region. The instrumentation is a flexible modular setup, which has already been successfully applied in airborne and ground-based field campaigns.



Figure 0.8: FUBISS-ASA2 installed on the FUB Cessna D-EAFU.

Measurements during the AROMAT campaigns were aiming at providing AOD (Aerosol Optical Depth) profiles in the vicinity of the measurement area (Bucharest / Berlin) and the discrimination between background and tropospheric AOD.

TD-LIF

The airborne Thermal Dissociation Laser Induced Fluorescence (TD-LIF) is a custom-built four channel instrument for real-time direct in-situ measurements of NO_2 and total peroxy nitrate (∑PNs), total alkyl nitrates (∑ANs) and HNO_3 after thermal dissociation. The TD-LIF was developed at the University 'G. D'Annunzio' of Chieti-Pescara (Italy) for airborne and ground-based measurements. The detection limits of the TD-LID are 9.8, 18.4, 28.1 and 49.7 pptv (1 s, S/N =2) for detection of NO_2 by the NO_2 cell, ∑PNs cell, ∑ANs cell and HNO_3 cell, respectively. The time resolution of the TD-LIF is 10 Hz, allowing a flux retrieval of the NO_2 and speciated NO_y (∑PNs, ∑ANs and HNO_3) flux, via eddy covariance technique. Detailed information on instrument performance and operational details can be found in Di Carlo et al. (2013). The TD-LIF measured the above compounds in different aircraft campaigns: nighttime observations above the ocean in UK (RONOCO) (Stone et al., 2014), above a megacity in London (SEPTEX) (Aruffo et al. 2014), boreal forest fire study in Canada (BORTAS) (Parrington et al., 2013), SONATA (Italy) and ground-based campaigns working continuously without interruption and failure for months: Borneo (Malesia) forest emission study (OP3) (Hewitt et al., 2009; Fowler et al., 2015), ACTRIS Auchencorth Moss (UK), Cape Verde. The system is currently operating in our campus in Central Italy, Adraitic coast. For summer 2019 it is already planned and funded the use the TD-LIF during a summer campaign in Innsbruck (Austria).



Figure 0.9: On left: The TD-LIF instrument on board the BAe-146 aircraft of the FAAM. On right: the TD-LIF on the ground Auchencorth Moss (UK) observatory.

CAPS (Environnement S.A., AS32M)

Based on Cavity Attenuated Phase Shift (CAPS) technology (Kebabian et al, 2007), this instrument operates as an optical absorption spectrometer for measuring direct NO_2 densities with high precision and sensitivity (limit of detection of 0.01 ppb). Taking into consideration that NO_2 is a broadband absorber of light in the visible region of the spectrum, the instrument uses a blue light-emitting diode (LED) as a light source, a near-co focal arrangement of two high reflectivity (R~0.9999) mirrors in tandem with an enclosed sample cell of 26 cm in length and a vacuum phototube detector. The shape of the luminous signal emitted by the LED is square, and the shape of the signal received by the detector is a succession of increasing and decreasing exponential curves. This distortion is measured as a phase shift θ (that depends on the speed of light - c, coefficient of mirror reflectivity - R, modulation frequency - f of the LED, length of optical cavity - L, concentration of absorbent species - N and absorption cross section - σ of absorbent species), comparable to the measurement of the decay time τ in the optical cavity.

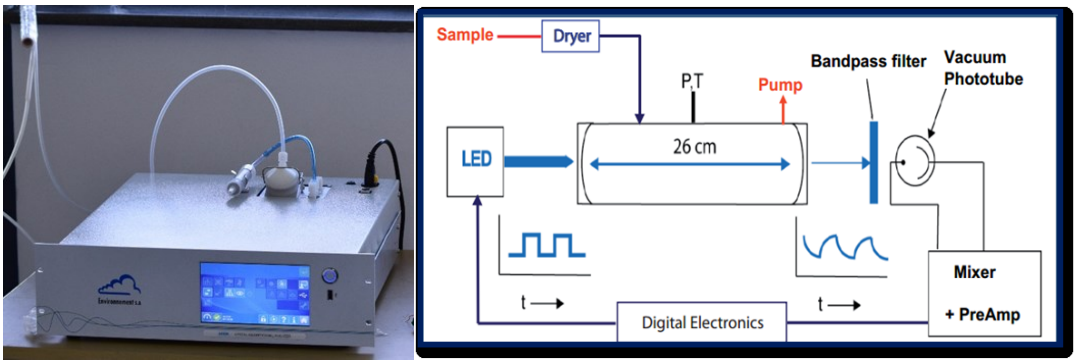


Figure 0.10: NO_2 analyser (left) and its operation principle (right).

For ensuring accurate measurements, the sample cell contains both pressure and temperature sensors that correct both the nitrogen dioxide absorption coefficient and also the baseline subtraction. Also, prior to each measurement session, it is required to do a complete check of sample cell's parameters and of MUX signals to be in conformity with the values indicated by the manufacturer.

NO_2 sonde

The NO_2-sonde can measure vertical NO_2-profiles flying on board of a research aircraft. The NO_2 sensor's measurement principle is based upon the chemical reaction between Nitrogen dioxide and Luminol. This is a chemiluminescent reaction, that produces a faint blue light. The reaction chamber contains Luminol dissolved in (alkaline) water. Ambient air is pumped through a Teflon pump, and bubbled through the sensing solution. The light that is produced by the reaction is detected by an array of photodiodes that is glued to the reaction chamber. The electric current from the photodiodes is converted into a voltage with a highly sensitive operational amplifier (OPAMP), and passed through a filter that removes high frequency fluctuations.

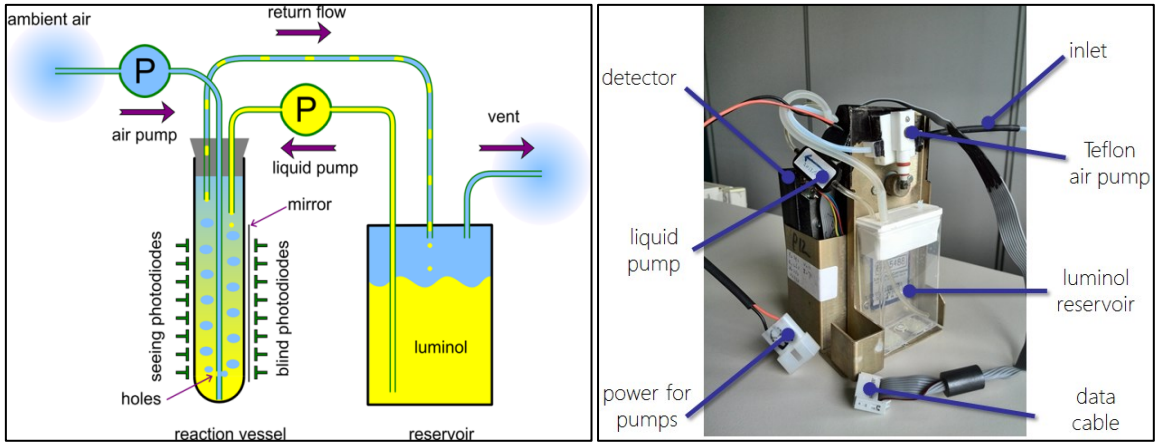


Figure 0.11: left: Schematic overview of the measurement principle behind the KNMI NO_2-sonde. right: Overview of NO_2-sonde components normally inside of a black cardboard and a Styrofoam box painted black on the inside during measurement.

IT-CIMS

In-situ measurements of atmospheric SO_2 VMRs can be made at altitudes between ground level and 12 km using chemical ionization mass spectrometry. IT-CIMS is a very sensitive and fast-response aircraft-based ion trap CIMS (chemical ionization mass spectrometry) instrument. The sensor was deployed successfully in several airborne campaigns.

ISAF

The NASA In Situ Airborne Formaldehyde (ISAF) instrument (Cazorla et al., 2015) is a high-performance laser-based detector for gas-phase formaldehyde (HCHO). ISAF uses rotational-state specific laser excitation at 353 nm for laserinduced fluorescence (LIF) detection of HCHO. A number of features make ISAF ideal for airborne deployment, including (1) a compact, low-maintenance fiber laser, (2) a single-pass design for stable signal response, (3) a straightforward inlet design, and (4) a stand-alone data acquisition system. The accuracy of reported mixing ratios is 10% based on calibration against IR and UV absorption of a primary HCHO standard. Precision at 1 Hz is typically better than 20% above 100 pptv, with uncertainty in the signal background contributing most to variability at low mixing ratios. The 1 Hz detection limit for a signal = noise ratio of 2 is 36 pptv for 10mW of laser power, and the e fold time response at typical sample flow rates is 0.19 s. ISAF has already flown on several field missions and platforms with excellent results.

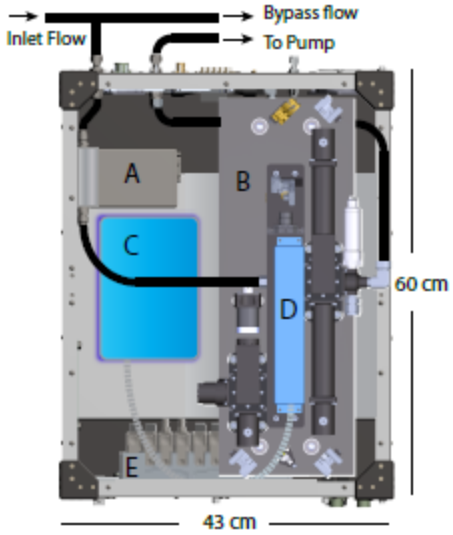


Figure 0.12: A top view of the ISAF instrument layout. The instrument chassis is 60 x 43 x 35 cm and 25 kg. The major subsystems are labeled: (A) pressure controller, (B) optical bench, (C) tunable fiber laser, (D) harmonic generation housing, and (E) data acquisition system.

Picarro gas analysers (G2401-mc, G2107)

Both Picarro gas analysers (G2401-mc, G2107) are based on the same technology: near–infrared cavity ring down spectroscopy (Crosson, 2008). By tuning the laser with a known wavelength (usually the specific absorption wavelength of these gases) for quantifying the spectral features of gas phase molecules in an optical cavity (including tree mirrors of 99.9% reflexivity) the voltage decay over time is recorded. By employing improved electronics, the concentration profiles are displayed in real time. Thus, simultaneous and continuous measurements of CO, CO_2, CH_4, water vapours (G2401-mc) and HCHO (G2107) are performed. Sensitivities of parts-per-billion (ppb) with negligible drift are reached for both analysers (e.g. for 5 min average time the precision is 0.5 ppb for CH_4 and 15 ppb for HCHO). Periodic calibrations are required for ensuring high data quality. G2401-m analyser automatically performs water vapours corrections (already validated by several laboratories) and reports both normal and dry mole fraction of volume mixing ratios.



Figure 0.13: Picarro gas analysers: G2107 (left), G2401-mc (right).

BBLIFF

The Broad-Band Laser Induced Fluorescence to measure Formaldehyde (BBLIFF) is a new instrument which is going to be developed in the framework of the Joint Research Activity of EUFAR. The aim is to develop a very compact system to be used in different aircraft platform using the non-resonant laser induced fluorescence technique (NR-LIF). The new laser source is compact and has an UV output at 355 nm, the pulse width (FWHM) is <15 ns, and the bandwidth is ~ 1 nm. The laser head dimensions are 16.5 cm x 9.5 cm x 5.4 cm (0.9 kg) and power supply dimensions 16.4 cm x 13 cm x 6.6 cm (1.2 kg). Another advantage compared with previous systems, is that the pump will be much more compact, dry and oil free. The system will be controlled with a custom program using LabVIEW (NI Instruments) that allows continuous measurements without control by an operator, and very low maintenance: about one per year. The instrument does not need a specialized inlet, and combined with its low weight, dimension, power consumption and the case (19''aviation rack housing), it will be a multi-platform instrument that can be deployed on a wide-range of research aircrafts. The plan is to have it ready for summer 2020 for a ground-based campaign in Innsbruck and for an aircraft campaign at the same site in summer 2021.

AirCore

AirCore name	Length, Tubing diameter, Wall thickness	Weight package (kg)	Volume (ml)
RUG03	100 m 4 mm + 50 m 1/8, 0.1mm	3.0	1400.00
RUG-light	37 m 3/16" m + 39 m 1/8" m	2.0	850

Aerodyne Dual Quantum Cascade Laser System

DLR's The Aerodyne dual Quantum Cascade Laser (QCL) system offers high precision airborne in-situ measurements of VMRs of CH4, CO2 ,N2O, CO, and C2H6. It was already flown on a NASA C-130 during the ACT-America campaign and is planned to be flown during the COMET campaign in late spring 2018.

APS (TSI, 3321)

It provides high-quality measurements of each particle: aerodynamic diameter by using time-of-flight technique for 0.5-20 μm range, and relative light-scattering intensity for 0.37 -20 μm range with the help of an integrated patented double-crest optical system with two partially overlapping laser beams (655 nm laser diode, 30 mW). Output parameters are particle size raw counts from 52 channels, number, diameter, surface, volume and mass particle size calculated with the aid of its software program. For ensuring data quality, periodic maintenance and inter-calibration procedures using ground based gravimetric measurements are performed. In this context, internal parameters as inlet flow, laser diode energy, inlet temperature and pressure are also continuously monitored.

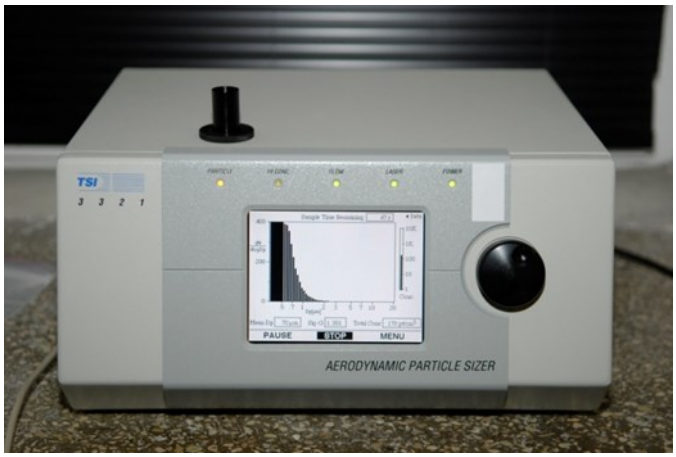


Figure 0.14: Aerodynamical Particle Sizer – APS (INOE).

Nephelometer (TSI, 3563)

Used for high accuracy measurements of both total and backscatter signals of aerosols light scattering for three wavelengths: 450 nm (blue), 550 nm (green) and 700 nm (red), the instrument shows good efficiencies for both short and long-term measurements of aerosol optical properties. Having temperature, humidity and pressure sensors, heater and high vacuum integrity, as well as additional options for selecting time average and flow rates from 20 to 200 l/min, make this instrument suitable for precision measurements in cleaner or more polluted areas, including aircraft measurements (Tsekeri et al, 2017). For 60s averaging time, sensitivities of light scattering coefficient as 1x10-7 m-1 (blue and green) and 3x10-7 m-1 (red) are reached. In term of data quality, angles smaller than 7° and larger than 170° of aerosol scattered light or variable humidity may lead to uncertainties during measurements or

condensation occurred on optical elements of the instrument. Thus, using corrections (Massoli et al., 2009) to improve the retrieve signal and performing measurements according to manufacturer recommendation are desired.



Figure 0.15: Nephelometer, TSI-3563.

Pandora 2S

The Pandora 2S system is capable of measuring the O_3 and NO_2 vertical column concentrations in Dobson Units (1 DU ≈ 2.7 × 10^{16} molecules cm^{-2}). The system has two spectrometers, first ranging from 290 nm to 500 nm with a 0.6 nm resolution and the second one with a range from 400 nm to 900 nm with a resolution of 1 nm. With a field of view of 1.5^0, an elevation ranges from -10^0 to $+90^0$ and azimuth range of 360^0, the system is capable of pointing anywhere in the sky in order to perform direct sun, zenith sky, principal plane, or almucantar observations. Complimentary control software allows automated measurements and virtual monitoring and data transfer over the internet.



Figure 0.16: Pandora 2S during AROMAT-2 campaign.

Pandora – 2S observations cannot be used in the presence of clouds, because of their high albedo. Uncertainties during cloudy sky and precipitation are large.

4-azimuth MAX-DOAS

The MPIC 4 azimuth MAX-DOAS consists of 4 Tube-MAX-DOAS instruments (see above), which are operated simultaneously looking into 4 different azimuth angles. From the derived spectra not only vertical profiles, but also horizontal gradients of trace gases (SO_2, NO_2 and HCHO) and aerosols can be retrieved. The 3-D-inversion of trace gases and aerosols is performed using a simple model function of the 3-D-distribution in combination with 3-D radiative transfer simulations using the Monte-Carlo model McARTIM-3.

IMPACT Imaging DOAS instrument

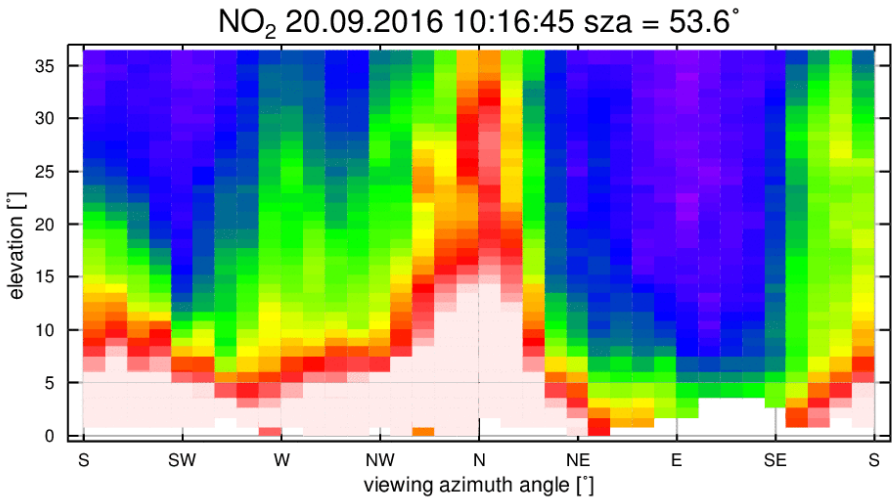


Figure 0.17: Example of one azimuthal scan of the azimuthal distribution of NO_2 slant columns on September 20, 2016 during CINDI-II.

The IMPACT instrument is a rack mounted DOAS instrument using an imaging spectrometer in combination with a sorted quart fiber bundle and an objective to take measurements at up to 50 elevation angles in parallel. The telescope is mounted on a Pan-Tilt-Head enabling horizontal scanning in addition to the vertical imaging. A single measurement takes about 45 s resulting in 30 minutes for a 360° scan at 10° steps.

The IMPACT instrument is optimized for NO_2 observations under polluted conditions and can map spatial gradients around a station with high temporal resolution. It was first deployed during the CINDI-2 campaign and later on the ship-borne cruise during AQABA. While the instrument is transportable, it needs an indoor location for installation in combination with access to an outdoor mounting point for the telescope with as much free horizon view as possible.

PMAX – Polarization Sensitive MAX-DOAS Instrument

Instrument still in development. Measures spectra of direct- and scattered sunlight at different polarizations between 300 and 1100 nm with adjustable range/resolution of 60/0.3, 140/0.7 or 280/1.4 nm, respectively (acton spectrometer with motorized grating turret). Delivers NO_2-, HCHO- and aerosol extinction profiles, aerosol optical thickness and microphysical properties. All quantities derived with OEM retrieval. Exact information contents have still to be investigated.

Instrument components are:

- Telescope unit on pan-tilt stand, required space: 1m x 1m x 1m (w x l x h), ca. 15 kg
- Spectrometer in temperature controlled housing, 0,8m x 0,6m x 0,5m, ca. 15 kg
- Computer for control and data analysis

Requirements for installation:

- Weatherproof shelter (building or container) for spectrometer and computer, with feedthrough to the outside for cables/optical fiber. We (IUP-Heidelberg) might be able to provide a small container but already present building would be much more appreciated.
- Maximum cable-/fiber length from/to telescope: 6 m
- Telescope needs stable ground to stand on, free view to the horizon in as many azimuth directions as possible (e.g. roof of building).
- Power requirements: 230V, about 200 W
- Internet connection appreciated for remote maintenance and data streaming
- Working table appreciated
- Typically, remote maintenance is sufficient

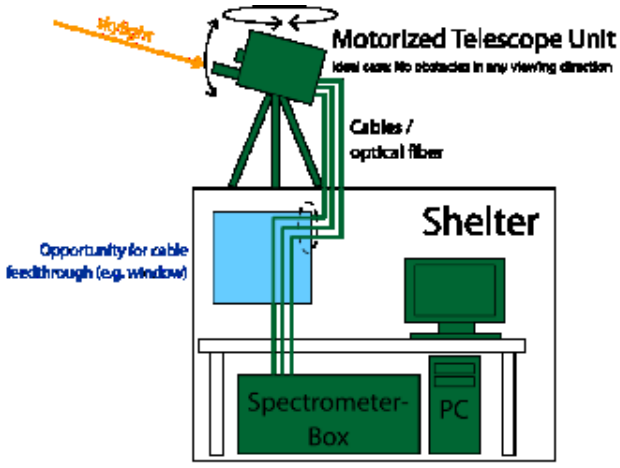


Figure 0.18: Sketch of measurement system (photo not yet available).

BIRA double channel visible Mobile DOAS system

The BIRA double channel mobile-DOAS instrument is based on a double channel Avantes spectrometer installed on a car. The entry slit is 50 µm, the focal length 75 mm and the grating is a 600l/mm, blazed at 300 nm. The spectral range is 200-750 nm with a 1.2 nm resolution (FWHM). The CCD detector is a Sony2048 linear array with a Deep-UV coating for signal enhancement below 350 nm. An optical head, mounted on the car window, holds the two telescopes achieving a 2.5° field-of-view with fused silica collimating lenses. One telescope points zenith while the other is directed 30° above the horizon. Two 400 µm chrome plated brass optical fibers connects the telescopes to the spectrometer. The integration time is around 5ms. Each measurement is an average of (typically) 10 seconds of 10 scans accumulations. A GPS antenna is used for georeferencing the measurement, the whole set-up is powered by the car 12V through an inverter. While measuring, the instrument is recording spectra continuously and simultaneously from the two directions (Piters et al., 2012).



Figure 0.19: BIRA Aeromobil with both the UV (optical head on car window) and double channel visible system (optical heads and GPS integrated in dome on car roof). the double channel DOAS system is integrated in the trunk of the car (right).

BIRA UV zenith-only Mobile-DOAS system

The BIRA UV zenith only Mobile DOAS system is based on an Avantes spectrometer installed on a car. The spectrometer has a single channel. The entry slit is 50 µm, the focal length 75 mm and the grating is a 1200l/mm, blazed at 250 nm. The spectral range is 200-450 nm with a 0.8 nm resolution (FWHM). The CCD detector is a 2048 linear array Hamamatsu S11155 with pixels of 14*500 μm^2. An optical head, mounted on the car window, holds the telescope in zenith, achieving a 2.5° field-of-view with fused silica collimating lenses and uses a 400 µm thick optical fiber. The integration time is around 150ms. Each measurement is an average of (typically) 10 seconds of 10 scans accumulations. The system uses a GPS antenna for georeferencing the measurements and is powered by an inverter plugged on the car 12V. Differential Optical Absorption Spectroscopy (DOAS) can be applied to the spectra to retrieve column densities for NO_2, SO_2 and HCHO.

UGAL UV-Vis Mobile-DOAS

The UGAL mobile DOAS instrument (Consantin et al., 2013; Dragomir et al., 2015) is based on a compact Czerny-Turner spectrometer (AvaSpec-ULS2048XL-USB2, of 175 × 110 × 44 mm dimensions and 855 g weight) placed in a car. The spectral range of the spectrometer is 280–550 nm with 0.7 nm resolution (FWHM) with a focal length of 75 mm. The entry slit is 50 µm and the grating is 1200 L/mm, blazed at 250 nm. A flexible device (a piece of wood with a hole cached in a small metallic plate), mounted on the top of the road vehicle, holds the telescope achieving a 1.2° field-of-view with fused silica collimating lenses. The spectrometer is connected to the telescope through a 400 µm chrome plated brass optical fiber. Each spectrum is recorded by a laptop and georeferenced by a GPS receiver. The spectrometer and the GPS receiver are powered by the laptop USB ports. The entire set-up is powered by 12 V of the car through an inverter. Each measurement is a 10-second average of 10 scans accumulations at an integration time between 50–150 ms. All observations were performed only in zenith geometry. The CAR- DOAS system can be used to determine the column densities for NO_2, SO_2 and HCHO.

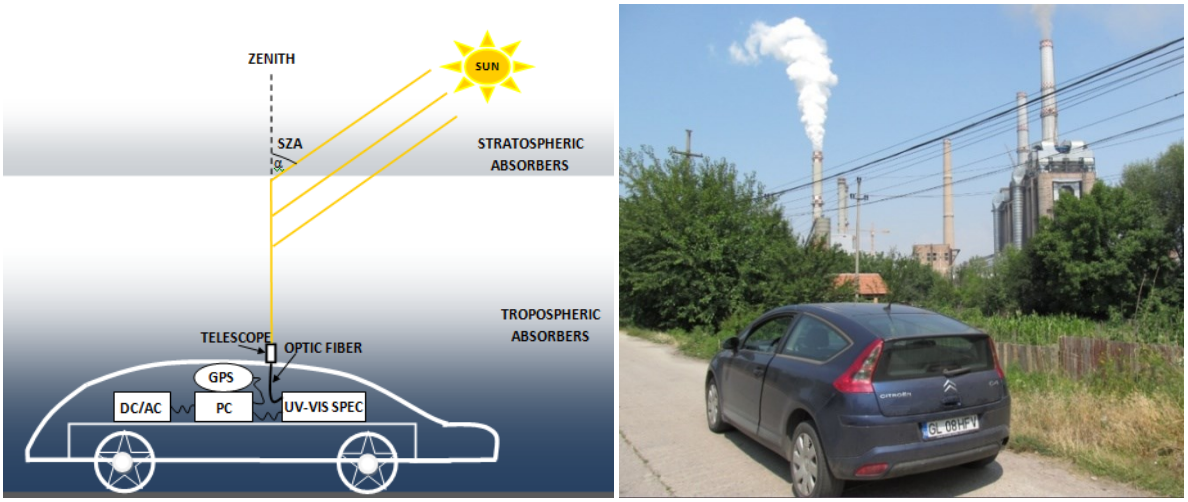


Figure 0.20: The mobile DOAS system (sketch and artistic photo).

Boku/IUP-UB UV-Vis zenith-only Mobile-DOAS system

The Boku/IUP-UB UV zenith only Mobile DOAS system is based on an Avantes ULS2048x64 spectrometer installed in a car. The spectrometer has a single channel. The entry slit is 50 µm, the focal length 75 mm and the grating is a 1200l/mm, blazed at 250 nm. The spectral range is 300-550 nm with a 0.65 nm resolution (FWHM). An optical fibre is connected to the instrument and the other side is attached to the window of the car. As no collimating lens is used, the FOV is about 8°. Each measurement is an average of (typically) 2 - 15 seconds. The system uses a GPS antenna for georeferencing the measurements and is powered by an inverter plugged on the car 12V. Differential Optical Absorption Spectroscopy (DOAS) can be applied to the spectra to retrieve column densities for NO_2, SO_2 and HCHO.

MPIC mobile-DOAS

The MPIC MAX-DOAS (so called Tube MAX-DOAS) is a new self-built MAX-DOAS, which covers the UV and part of the visible spectral range using an AVANTES spectrometer. The instrument is separated into a telescope unit and a spectrometer unit. Both are connected via a 12 m long fibre bundle. The spectrometer is thermally stabilised by a combined cooling/heating unit. Measurements are taken at 90° elevation and at a second low elevation angle (between 20 and 30°). From the measured spectra the column densities of SO_2, NO_2 and HCHO are retrieved. Because the instrument measures at two elevation angles, the absolute tropospheric trace gas VCDs can be directly determined from the measurements. The Tube MAX-DOAS was successfully operated at several measurement campaigns, e.g. AROMAT-2, AROMAPEX, CINDI-2.

BIRA UV-Vis Bike-DOAS system

The UV-Vis Bike-DOAS is a compact DOAS-system that is primarily designed to mount on a bike but it can be used as a static instrument as well or be mounted on other type of platforms. The system consists of an Avantes AVASpec-US2048x64 spectrometer, a raspberryPi RPi-3 microcumputer and a powerbank battery of 10400 mAh providing 5-6 hours of measurement time. The entry slit of the spectrometer is 50 µm, the focal length 75 mm and the grating is a 1200l/mm, blazed at 250 nm. The spectral range is 300-550 nm with a 0.65 nm resolution (FWHM). Although the radius of use of the instrument is smaller when compared to the car mobile-DOAS systems, the instrument can be complementary, e.g. it offers more flexibility in city centers with heavy traffic and many one way streets for the cars. After successfully testing a first version during the CINDI-2 campaign in summer 2016, the system is currently further developed. A weatherproof box with an universal rear carrier mount is currently designed. The new version of the system offers also the possibility to control the acquisition program and log the data acquisition through a smartphone application.

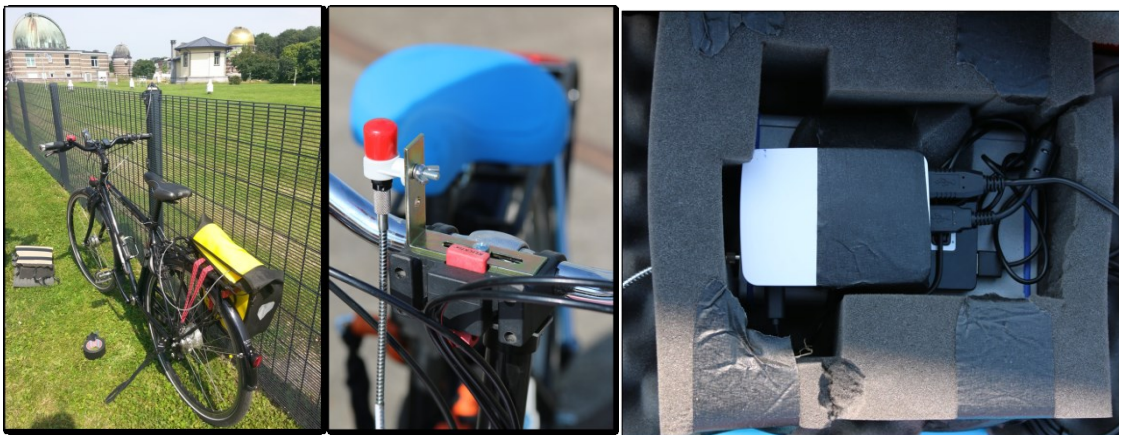


Figure 0.21: The Bike-DOAS with a universal steer mount for fiber (middle), which can be pointed to 90° and 30° and the instrument in a temporary foam-cardboard box (right).

EnviCam 3

EnviCam 3 a commercial camera system from Nicarnica Aviation (https://nicarnicaaviation.com/technology/envicam-3/) for measuring SO2 gas emissions from volcanoes and industry. It features dual UV cameras (16 fps, FOV 11.7° x 15.4°), a spectrometer (250-400 nm, FOV 0.5° * 0.03°, spectral resolution 0.8 nm), an integrated computer and hard drive storage, all housed inside a aluminum, weather resistant casing. The instrument can be easily operated using a tablet computer which mounts to the side of the case.

The SO_2 imaging camera measures the absorption of light by SO_2 in the UV spectrum between 280 – 340 nm (Bluth et al, 2007). SO_2 strongly absorbs UV light at 310nm, while for the 330nm filter the SO_2 absorption is approximately 30 times lower (Kern et al, 2013). The intensity of incident solar light is attenuated according to the Beer-Lambert-Bouguer law, whenever SO_2 is encountered along the optical path. The difference between absorption intensities of two filters (with strong and low SO_2 absorption characteristics) is proportional with absorber's concentration along the optical path.

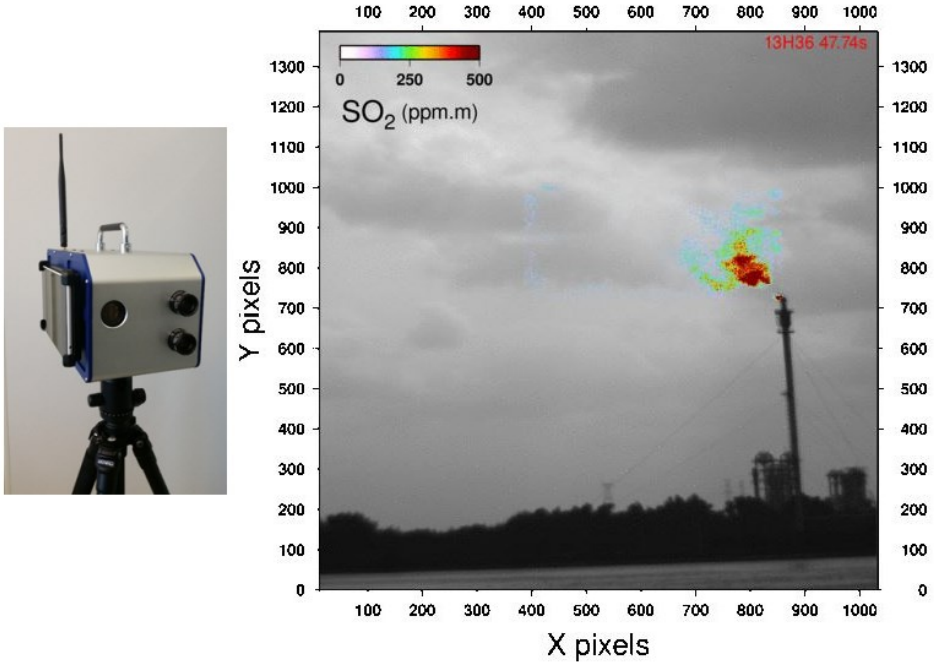


Figure 0.22: Envicam3 SO_2 camera (left) and example of measurements in Antwerp Harbour (June 2016).

COCCON (Collaborative Carbon Column Observing Network)

COCCON is comprised of quality-checked and calibrated EM27/SUN portable FTIR spectrometers. The recorded spectra are analysed with common code developed in the framework of the ESA project COCCON-PROCEEDS. The EM27/SUN has been developed by KIT in cooperation with Bruker (Gisi et al., 2012) and is commercially available since 2014. The spectrometer allows the measurement of column-averaged abundances of H_2O, CH_4, CO_2, and CO with high precision and accuracy. The spectrometer has demonstrated its usefulness for the detection of local sources of greenhouse gases, trace gas gradients, and as a travel standard in the hands of various investigators (Hase et al., 2015; Chen et al., 2016; Hedelius et al., 2017). The stability of the device is sufficient to allow remote deployment and even operation on moving platforms (Klappenbach et al., 2015; Butz et al., 2017).

For ensuring consistent results from different spectrometers, each COCCON spectrometers undergoes an acceptance test at KIT and is calibrated with respect to a collocated TCCON spectrometer before delivery. The work by Frey et al. (2015) provides an overview over the QC procedures concerning instrumental line shape characterization and reports a side-by-side comparison (before and after transport to a campaign) demonstrating the high level of stability achieved with these devices.



Figure 0.23: EM27/SUN portable FTIR spectrometers.

Sun-lunar photometer CIMEL

The Sun-photometer CE 318 automatic sun tracking photometer is capable of measuring sun and sky radiance in order to derive total column water vapour, ozone and aerosols properties using a combination of spectral filters and azimuth/zenith viewing. The direct sun measurements are made in eight spectral bands: 340, 380, 440, 500, 670, 870, and 1020 nm. Optical depth is calculated from spectral extinction of direct beam radiation at each wavelength based on the Beer-Bouguer Law. The processed data provide a wide number of parameters and characteristics that are important for the comprehensive interpretation of the aerosol retrieval. The output includes both retrieved aerosol parameters (i.e., size distribution, complex refractive index and partition of spherical/non-spherical particles) and calculated on the basis of the retrieved aerosol properties (e.g. phase function, single scattering albedo-SSA, Angstrom exponent, spectral and broad-band fluxes, etc.). Accurate retrievals of SSA (with accuracies reaching 0.03) can be obtained for high aerosol loadings and for solar zenith angles >50 degrees. The instrument is part of the Aerosol Robotic Network (AERONET).



Figure 0.24: Sun-lunar photometer at INOE, Magurele.

Multiwavelength Raman lidar

Multiwavelength depolarization Raman Lidar (RALI) is an instrument capable to detect the Raman backscattering radiation from atmospheric water vapour, nitrogen, and Mie / Rayleigh backscattering radiation from atmospheric molecules and aerosol particles, providing data products related to optical, microphysical and geometrical properties. The system is part of the European Aerosol Research Lidar Network (EARLINET) as an advanced Lidar station. The output parameters are the backscatter coefficient, the extinction coefficient, water vapour mixing ratio (for 407 nm), particle depolarization ratio (for 532 nm). Advanced products have been dedicated to aerosol typing, microphysical inversion and aerosol mass concentration retrievals.



Figure 0.25: The multi-wavelength Raman lidar at INOE site from Magurele.

The main data products provided by the multi-wavelength Raman lidar are the extinction profiles and the AOD for three wavelengths: 355, 532, 1064nm. For daytime measurements, the extinction profile is retrieved from the backscatter by using an assumed lidar ratio (LR) based on the aerosol type estimation within the profile. For nighttime measurements, the extinction profile for 532 and 355nm is retrieved directly from the Raman channels.

BIRA CAPS (Environnement S.A., AS32M)

The Cavity Attenuated Phase Shift (CAPS) nitrogen dioxide (NO_2) AS32M monitor from Environment S.A. (http://www.environnement-sa.com/products-page/en/air-quality-monitoring-en/as32m-analyzer-no2-nitrogen-dioxide-monitor/) measures the NO_2 volume mixing ratio using its broadband absorption in the blue and the CAPS principle (Kebabian, 2005). Below a schematic of the CAPS set-up and its measurement principle. In practice, the square wave modulated light from a blue LED passes through an absorption cell (cavity) and is detected as a distorted wave form, which is characterized by a phase shift with respect to the initial modulation. The amount of that phase shift is a function of fixed instrument properties—cell length, mirror reflectivity, and modulation frequency—and of the presence of a scattering targets or absorbers (air, particles, trace gases, etc.) within the cavity.

The AS32M is enclosed within a standard 19 inch rack-mounted instrumentation box, weighs 12.5 kilograms, and uses 225 Watts of electrical power including the vacuum pump (1 L/min). During airborne operations, the data were recorded at a high frequency (1 point/sec) on a USB key plugged in the back of the instrument rack.



Figure 0.26: The Environment S.A. AS 32M CAPS NO_2 analyser.

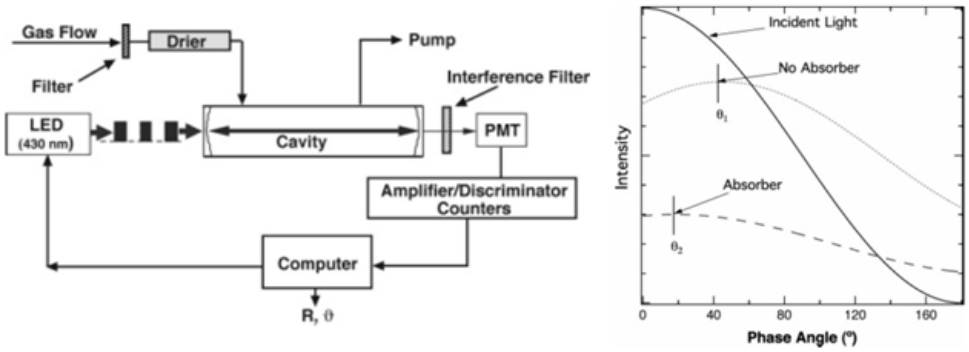


Figure 0.27: Left: Schematic of the CAPS analyser. Right: Illustration of the phase shift due to the absorber (from Kebabian, 2005).

Mobile lab

Mobile laboratory who can accomodate various instruments for measurements: in situ gas analysers, weather station and UV depolarisation lidar. UV depolarisation lidar detects Mie/Rayleigh backscattering from atmospheric molecules and aerosol particles. Uses a 355 nm laser, with a power of 60 mJ with two detection chanels: parallel and cross. Dynamic range can be up to 20 km, depending by weather condition. Processed parameters are backscatered coefficient and extinction profile for an assumed lidar ratio.

In-situ ambient monitors measure gas concentrations using well-known reference detection methods such as the cross-flow modulated semi decompression chemo-luminescence method (for NO_x monitor), UV fluorescence (SO_2 monitor), non-dispersion cross modulation infrared analysis method (CO monitor), ultraviolet absorption method (O_3 monitor), cross-flow modulated selective combustion type method combined with a hydrogen ion detection method (THC monitor) and gas filter correlation spectroscopy (CO_2). The instruments are housed on a mobile laboratory designed for field campaigns.



Figure 0.28: Mobile laboratory with UV depolarisation lidar next to it.

ANNEX B: COCCON questionnaires

This questionnaire is intended for outlining possible contributions from the COCCON community in support of the S-5p validation campaign implementation plan (project in response to ESA SoW SoW-ESA-EOPG-CSCOP-SOW-22_S5P_MPC_CCN3). The activities are planned for 2019.

PI, Co-Is, Affiliation, email contact	Omaira García (ogarciar@aemet.es), Emilio Cuevas, Eliezer Sepúlveda Izaña Atmospheric Research Centre (IARC), Meteorological State Agency of Spain (AEMET)
Collaborators, Affiliation	F. Hase (KIT)
Contribution reference	IARC-AEMET
Crossreferences	
Description of suggested activity	1) Validation of the space-based XCO2 and XCH4 observations under different surface albedo conditions placing one EM27/SUN at: a) Santa Cruz de Tenerife station (28ºN, 16ºW, 52 m a.s.l., Tenerife, Spain), urban environment and low ground albedo (ocean). These measurements will be performed in temporal coincidence with the high-resolution IFS located at the Izaña Atmospheric Observatory (IZO, 28ºN, 16ºW, 2370 m a.s.l.). These observations will enable us to characterize the total column of CO2 and CH4 from sea level in the surrounding of Tenerife and estimate the partial columns missed by the Izaña high-resolution IFS. b) El Arenosillo" Atmospheric Sounding Station (37ºN, 6.7ºW, Huelva, Spain), background station and low ground albedo (forest). c) Plataforma Solar de Almería (PSA, 37ºN, 2ºW), located in the Tabernas desert with high ground albedo (desert).

	2) Performing CO2 and CH4 measurements in the urban environment of Madrid (Spain).
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	All the suggested activities will be performed with one spectrometer provided by AEMET. The duration of the activities will be: 1)-a) Four months (one month per season) 1)-b) Two weeks 1)-c) Two weeks 2) Two-Four weeks
Available measurements of relevant auxiliary and met variables	1)-a) Meteorological records, air quality data (e.g. CO records), aerosol information in total column and vertical distribution (AERONET and MPLNet), solar radiation data. 1)-b) Meteorological records, ozone total column amounts and UV solar radiation data provided by Brewer spectrometers, aerosol information in total column (AERONET). 1)-c) Meteorological records, solar radiation data. 2) Meteorological records, aerosol information in total column (AERONET), solar radiation data and Brewer observations.
Associated activities of relevance	1)-a) The Santa Cruz of Tenerife station is located horizontally only about 10 km far away from the high-mountain Izaña Atmospheric Observatory (IZO, 2.4 km a.s.l.). IZO is a GAW/WMO station with continuous in situ greenhouse gas measurements (CO2, CH4, N2O) and other trace gases (CO, O3, H2O e HDO) and is a high-resolution NDACC&TCCON station. The Izaña measurements are complemented by Brewer observations, in situ aerosols, aerosol in total column, solar radiation data, and meteorological records. 1)-b) The EM27/SUN measurements will be performed in the framework of the 14th RBCC (Regional Brewer Calibration Centre, poner web) Intercomparison campaign.
Preferred time period for activity in 2019	February-November
Funding issues, risks	1)-a) This activity will be funded by the IARC-AEMET. 1)-b) This activity will be funded by the IARC-AEMET. 1)-c) This activity needs to be supported by

	external fundings. 2) This activity is proposed subject to the availability of national (AEMET) fundings.
General remarks, requests + suggestions to be forwarded to ESA via the CIP	A recommendation of the proposed activity by ESA to AEMET stating the usefulness of the proposed activities would be appreciated. The activity 1)-c) is need to be supported by external fundings.

PI, Co-Is, Affiliation, email contact	Caroline Bès (caroline.bes@cnes.fr, CNES, France) Yao Té and Pascal Jeseck (yao-veng.te@upmc.fr, mailto:pascal.jeseck@upmc.fr , LERMA, France)
Collaborators, Affiliation	Cyril Crevoisier, LMD, France
Contribution reference	MAGIC
Crossreferences	CROSSTRACK
Description of suggested activity	The CNES EM27/SUN spectrometer will be used for measuring the XCH4, XCO and XCO2 distribution from a site TBD
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	One spectrometer will be available all the year 2019.
Available measurements of relevant auxiliary and met variables	TBD (Precise mobile pressure sensor and GPS will be purchased before the campaign)
Associated activities of relevance	The MAGIC campaign, as described by Cyril on his email of the 18th of July, focused on GHG will be run in 2019.
Preferred time period for activity in 2019	
Funding issues, risks	
General remarks, requests + suggestions to be forwarded to ESA via the CIP	A collaboration with the MAGIC campaign would be fruitful for every participant. Contacts : Cyril and Caroline

PI, Co-Is, Affiliation, email contact	Dragos Ene (dragos.ene@inoe.ro), Alexandru Dandocsi (alexandru.dandocsi@inoe.ro), INOE 2000
Collaborators, Affiliation	F. Hase, KIT
Contribution reference	-
Crossreferences	-
Description of suggested activity	- daily measurements (weather permits) from the location in Magurele; - several days measurements at location of importance in Romania (near mud volcanoes, landfills, oil refineries etc.)
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	1 spectrometer property of ESA in the context of RAMOS project.
Available measurements of relevant auxiliary and met variables	sun/lunar photometer (AOD), Raman lidar (AOD), weather station, in situ gas analyzers (CH_4, NO_2, SO_2, O_3, *X*CO)
Associated activities of relevance	-
Preferred time period for activity in 2019	May - August
Funding issues, risks	overlapping with other activities
General remarks, requests + suggestions to be forwarded to ESA via the CIP	-

PI, Co-Is, Affiliation, email contact	Frank Hase, KIT frank.hase@kit.edu
Collaborators, Affiliation	Matthias Frey, KIT NN, KIT (PhD student starting in Sept 2018)
Contribution reference	CROSSTRACK
Crossreferences	MAGIC
Description of suggested activity	Measurements in central Europe throughout the year for achieving an improved across-track coverage (together with other activities in western and Eastern Europe), provision of up to three spectrometers for support of other COCCON S-5p validation activities.
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	1-4
Available measurements of relevant auxiliary and met variables	As a basis site in central Europe, measurements will be performed north from Karlsruhe, in the vicinity of the ICOS tall tower (200 m), which also provides a full suite of meteorological data.
Associated activities of relevance	-
Preferred time period for activity in 2019	Jan - Dec
Funding issues, risks	Low risk, spectrometers and personnel available
General remarks, requests + suggestions to be forwarded to ESA via the CIP	-

PI, Co-Is, Affiliation, email contact	Matthias Frey (m.frey@kit.edu), KIT Thomas Blumenstock, KIT Frank Hase, KIT
Collaborators, Affiliation	Jan Cermak, KIT Frank Göttsche, KIT
Contribution reference	BRIGHT
Crossreferences	-
Description of suggested activity	Operation of a COCCON spectrometer at the research and training site Gobabeb in Namibia. The location is a very dry, high ground albedo site
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	One spectrometer, operation throughout the year planned (customs regulations might require withdrawal of spectrometer by December 2019)
Available measurements of relevant auxiliary and met variables	Radiometer measurements of surface temperature, meteorological measurements (pressure, temperature), DOAS spectrometer
Associated activities of relevance	--
Preferred time period for activity in 2019	Jan - Dec
Funding issues, risks	The spectrometer is for check and upgrade (implementation CO channel) at KIT, main risk is damage or loss during shipment to Namibia, or occurrence of a measurement gap if the spectrometer fails on site and repair in Germany is required.
General remarks, requests + suggestions to be forwarded to ESA via the CIP	We have successfully operated this spectrometer in Namibia in earlier years.

PI, Co-Is, Affiliation, email contact	M.Grutter, (grutter@unam.mx) CCA/UNAM Mexico Michel Ramonet (michel.ramonet@lsce.ipsl.fr), LSCE, Gif-sur-Yvette, France
Collaborators, Affiliation	Morgan Lopez, LSCE W.Stremme CCA/UNAM
Contribution reference	Mexico-City
Crossreferences	-
Description of suggested activity	a pair of calibrated and comparable EM27-sun instruments located up and downwind of a large source area in Mexico City (e.g. industrial complex and the power plant in the north of Mexico City), to evaluate the source strength between both instruments
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	1 instrument to be purchased by CCA as part of a French/Mexican research proposal; one CCA instrument already available
Available measurements of relevant auxiliary and met variables	High precision surface measurements of CO2, CH4, CO, and meteorological parameters.
Associated activities of relevance	Long term measurements of greenhouse gases in Mexico-City
Preferred time period for activity in 2019	To be discussed
Funding issues, risks	ANR/CONACYT are funding a 3 years project dedicated to CO2 measurements in Mexico-City
General remarks, requests + suggestions to be forwarded to ESA via the CIP	-

PI, Co-Is, Affiliation, email contact	Michel Ramonet (michel.ramonet@lsce.ipsl.fr), Morgan Lopez (morgan.lopez@lsce.ipsl.fr) LSCE, Gif-sur-Yvette, France
Collaborators, Affiliation	F. Hase, KIT Y.Té, LERMA
Contribution reference	Tropics
Crossreferences	-
Description of suggested activity	Deployment of two EM27/SUN spectrometers for XCH4, XCO2, XCO measurements in Western Africa, associated to the LAMTO (Ivory Coast) and AM5 (Morocco) surface measurement sites.
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	1 instrument provided by LSCE, 1 provided by KIT (?) for measurements during a period of 2 to 3 months
Available measurements of relevant auxiliary and met variables	High precision surface measurements of CO2, CH4, CO, and meteorological parameters.
Associated activities of relevance	Long term measurements of greenhouse gases in Western Africa as part of ICOS-France network
Preferred time period for activity in 2019	June – August: in Morocoo this correspond to the period of dust coming from Africa. Nov - Feb: In Lamto for the observation of the biomass burning plumes
Funding issues, risks	The human ressources to operate the instruments are available at both sites, and national funding to cover the travel/shipment of the instruments will be available.
General remarks, requests + suggestions to be forwarded to ESA via the CIP	-

PI, Co-Is, Affiliation, email contact	Dave Pollard (dave.pollard@niwa.co.nz), John Robinson, NIWA, Lauder, NZ.
Collaborators, Affiliation	Frank Hase, KIT
Contribution reference	ANT-Pollard
Crossreferences	-
Description of suggested activity	We propose to install an EM27/SUN at NZ's Arrival Heights laboratory on Ross Island (77.82S, 166.65E) for the Austral summer periods of 2019
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	An application for funds to purchase an EM27/SUN is being made to NIWA. A letter of support from ESA and other project partners would add considerable weight to this application.
Available measurements of relevant auxiliary and met variables	Full met data. NDACC-IRWG site. In-situ O_3. Flask samples.
Associated activities of relevance	US NSF Antarctic program conduct regular (twice daily) radiosonde profiles.
Preferred time period for activity in 2019	Austral summer, January-April and October-December
Funding issues, risks	High risk that EM27/SUN purchase will not be funded. Moderate risk of delays in travel/deployment to/from Antarctica due to weather or operational priorities.
General remarks, requests + suggestions to be forwarded to ESA via the CIP	A Letter of support for the purchase of an EM27/SUN addressed to Sam Dean, Chief Scientist – Climate, Atmosphere and Hazards. Would strengthen the bid for funding of this purchase.

PI, Co-Is, Affiliation, email contact	PI: Jia Chen, CO-I: Florian Dietrich Technical University of Munich Jia.chen@tum.de
Collaborators, Affiliation	Dr. Frank Hase, KIT Prof. André Butz, Heidelberg University
Contribution reference	-
Crossreferences	-
Description of suggested activity	5-6 EM27/SUNs and their automated protection systems will be deployed for assessing greenhouse gas emissions in German cities, e.g. Hamburg. We will place 4-5 spectrometers on the city edges to capture the inflow/outflow column amounts at arbitrary wind conditions and one spectrometer in the city center, which serves as a downwind station of half a city. The obtained differential column measurements will be incorporated with an inversion system to quantify the emissions, to detect emission anomalies and unknown emitters.
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	5-6 spectrometers will be available for the city campaign (2 will be provided by TUM, ? by DLR, ? by KIT). The campaign duration is about 3 weeks.
Available measurements of relevant auxiliary and met variables	We will launch radiosondes, perform surface wind measurements. High precision pressure sensors and GPS will be deployed on each site.
Associated activities of relevance	Mobile measurements using Picarro instruments will be performed.
Preferred time period for activity in 2019	July – Sept.
Funding issues, risks	-
General remarks, requests + suggestions to be forwarded to ESA via the CIP	-

PI, Co-Is, Affiliation, email contact	Michel Grutter, UNAM, grutter@unam.mx Wolfgang Stremme, UNAM, stremme@atmosfera.unam.mx
Collaborators, Affiliation	F. Hase, KIT Th. Blumenstock, KIT
Contribution reference	PhD thesis, Jorge Baylón
Crossreferences	-
Description of suggested activity	Measurements in Mexico City
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	One operational of EM27/SUN since March 2016 installed at the UNAM campus in Mexico City. 2nd channel installed in Aug 2017. Another EM27/SUN will be available startin 2019.
Available measurements of relevant auxiliary and met variables	- Column measurements in the MIR region (Vertex80) at the UNAM station in Mexico City - NDACC instrument (HR120/5) outside the city (Altzomoni) - CO2, CH4, CO, and H2O in situ measurements, as well as other ambient and meteorological parameters available from the RUOA network (station UNAM www.ruoa.unam.mx)
Associated activities of relevance	- Campaign-based measurements of volcanic gases - Ongoing ANR-Conacyt project in collaboration with LSCE (France)
Preferred time period for activity in 2019	May – August (except July)
Funding issues, risks	Long periods for acquisition / delivery of spare parts and service.
General remarks, requests + suggestions to be forwarded to ESA via the CIP	NDACC-IRWG & TCCON Annual Meeting in 2018 will be in Mexico

PI, Co-Is, Affiliation, email contact	André Butz (andre.butz@iup.uni-heidelberg.de), Institute of Environmental Physics (IUP), Heidelberg University, Germany
Collaborators, Affiliation	F. Hase, KIT J. Chen, TUM A. Fix, DLR A. Roiger, DLR
Contribution reference	Mobile-Butz
Crossreferences	-
Description of suggested activity	An EM27/SUN spectrometer is adapted for mobile stop-and-go operations on a car or a small truck. For localized emission sources such as power plants, coal mine ventilation shafts and volcanoes, the stop-and-go mode enables recording plume cross sections by driving transects underneath the plume. Mobile deployments further enables approaching several locations per day in order to cross-reference several stationary EM27/SUNs or to determine concentration gradients by pairing with a stationary EM27/SUN. We suggest to either deploy the mobile spectrometer next to a localized source or to coordinate its deployment with other stationary spectrometers.
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	Between May 22 and Jun. 17, 2018, the mobile spectrometer will be deployed in an ad-hoc network configuration with 4 stationary EM27/SUN (KIT, TUM, INOE) in the Upper Silesian Coal Basin in southern Poland. Activities for 2019 are currently in the planning phase.
Available measurements of relevant auxiliary and met variables	Mobile pressure sensor and GPS at operation of spectrometer.
Associated activities of relevance	The campaign in the Upper Silesian Coal Basin in May/June 2018 will be coordinated with the aircraft campaign COMET 1.0. Several research aircraft with in-situ and remote sensing instrumentation for CH4 (and CO2 and other gases) will operate in coordination with the ground-based spectrometers
Preferred time period for activity in 2019	May – August
Funding issues, risks	The campaign in May/June 2018 is funded by the Federal Ministry of Education and Research (BMBF) through the project AIRSPACE.

	Activities in 2019 are subject to the availability of national (DLR, DFG, BMBF) funding. Operational risks are low: Mobile deployments have successfully been performed during three field campaign and led to two peer-reviewed publications (Klappenbach et al., 2015, Butz et al., 2017).
General remarks, requests + suggestions to be forwarded to ESA via the CIP	ESA and/or DLR should fund this activity.

PI, Co-Is, Affiliation, email contact	William R. Simpson (wrsimpson@alaska.edu), Niki Jacobs, University of Alaska, Fairbanks, AK, USA
Collaborators, Affiliation	M. Dubey, LANL F. Hase, KIT
Contribution reference	ARCTIC-Simpson
Crossreferences	-
Description of suggested activity	A pair of EM27/SUN spectrometers will be used for probing the XCH4 and XCO distribution in the boreal Arctic on scales of several 10 to several 100 km. One spectrometer will be operated permanently at the Fairbanks campus, the other will be moved at selected observation sites and perform simultaneous measurements.
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	Two spectrometers (one provided by LANL, one provided by KIT) will be available during a selected campaign period of up to two months in 2018 and about depending on LANL spectrometer availability up to one month in 2019.
Available measurements of relevant auxiliary and met variables	High quality reference ground pressure sensor and Aeronet measuremenents (AOD) at Bonanza Creek. Mobile pressure sensor and GPS at operation site of mobile spectrometer.
Associated activities of relevance	A collaborator at UAF, Eugenie Euskirchen operates eddy-covariance flux towers in the Bonanza Creek Long Term Ecological Research (LTER) station measuring CO_2 and CH_4 fluxes. The NASA ABoVE project also operates in the area and can provide detailed regional ecosystem mapping. NOAA performs regular flask-based aircraft profiling in the vicinity (https://www.esrl.noaa.gov/gmd/dv/site/site.php?code=PFA).
Preferred time period for activity in 2019	May - August
Funding issues, risks	This activity is proposed subject to the availability of national (NASA) funding. Otherwise, the risk of the proposed activity seems low: (1) the investigators are already familiar with the operation of the spectrometers and data analysis (2) the campaign is performed in US territory
General remarks, requests + suggestions to be forwarded to ESA via the CIP	A recommendation of the proposed activity by ESA to NASA stating the usefulness of the proposed activity would be appreciated.

PI, Co-Is, Affiliation, email contact	Hartmut Boesch, email: hb100@le.ac.uk, University of Leicester, UK Neil Humpage , University of Leicester, UK
Collaborators, Affiliation	Jia Chen, TU Munich, Germany
Contribution reference	NERC MOYA
Crossreferences	-
Description of suggested activity	A EM27Sun will be installed in Jinja, Uganda to observe methane and CO in regions of tropical wetlands (and fire).
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	1 spectrometer is available and is planned to be deployed for the duration for 12months
Available measurements of relevant auxiliary and met variables	Mobile weather station (T, p, H2O). Potentially aerosol information from portable microtops.
Associated activities of relevance	A series of measurements are carried in Uganda from the NERC MOYA project include flux measurements and aircraft (FAAM) deployment
Preferred time period for activity in 2019	The activity is planned from later summer 2018 to late summer 2019
Funding issues, risks	The activity is funded
General remarks, requests + suggestions to be forwarded to ESA via the CIP	

PI, Co-Is, Affiliation, email contact	N. Jones, D. Griffith, S. Wilson, University of Wollongong
Collaborators, Affiliation	F. Hase, KIT
Contribution reference	SOUTHFIRE
Crossreferences	-
Description of suggested activity	Observation of bushfire plumes, enhanced CO and spectrally resolved optical thickness of biomass burning plumes
Availability of EM27/SUN spectrometer(s) (number of devices, duration)	One UoW instrument, one additional instrument provided by KIT
Available measurements of relevant auxiliary and met variables	MAXDOAS HCHO observations of the plume
Associated activities of relevance	--
Preferred time period for activity in 2019	October-December 2019
Funding issues, risks	Availability of national funding would allow upscaling of the proposed activity (e.g. extend observation period). Note that occurrence and extent of bushfires is variable from year-to-year.
General remarks, requests + suggestions to be forwarded to ESA via the CIP	