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TROPOMI, a stepping stone for Global Troposphere Monitoring

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ABSTRACT

Accurate Earth Observation measurements can only be achieved by multi-spacecraft missions. One example is the Sentinels constellation where five satellites will cover the full spectrum of Earth Observation tasks: all-weather imagery (Sentinel 1), land observation (Sentinel 2), marine services (Sentinels 3), weather forecast (Sentinel 4), and atmospheric chemistry (Sentinel 5). The synergic operation of this constellation will constitute an important element of the European system “Global Monitoring for Environment and Security”.

A co-operation between ESA and NSO has been set to deploy a precursor of the Sentinel-5 mission. The satellite will embark TROPOMI an instrument designed to reach the goal of boosting performance two orders of magnitude with respect to missions in operation. The mission, with its dual role of technology demonstrator and operative element of the GMES, poses unprecedented challenges: a tight schedule to achieve in-orbit demonstration and a complex procurement to respect the industrial return of the participating nations.

TROPOMI uses groundbreaking technologies to bring spatial resolution, global coverage and measurement accuracy to unmatched levels. This paper presents an overview of the mission and describes the technologies developed to achieve the mission objectives. The innovations used in TROPOMI are at their early stage of development and may lead to revolutionary architectures.

INTRODUCTION

Observations from space of constituents gases of Earth atmosphere have over 30 years of history. These observations have been motivated by scientific research and by concerns of effects of human activities on the environment. They have greatly improved our understanding of processes governing stratospheric ozone depletion, climate change and transportation of pollutants. Long-term continuous measurements of atmospheric trace gas data have been limited to stratospheric ozone and a few related species, but reliable long-term space-based monitoring of atmospheric constituents with accuracy sufficient to serve atmospheric chemistry applications still need to be established. In spite of the long history on stratospheric measurements, retrieval of accurate information of the trace gases in the troposphere is still in its infancy.

Only a handful of missions are in operation and performing these measurements, as OMI, TOMS, GOME, and Sciamachy, that recently terminated its operation. The objective of the Sentinel 5 mission is to improve the current capabilities to measure concentration of trace gases, among which NO_2, SO_2, BrO, methane, formaldehyde. The measurements of Sentinel 5 with their improved horizontal and vertical resolution can be used in several fields, as enforcement of international agreements on air quality, to study chemical processes and heat exchanges in the lower atmosphere, and consequently improving the accuracy of numerical weather forecasts and climate models.

The measurement of the vertical distribution of trace gas from the satellites remote sensing is a complex process [1] and subject of current research activities. Correlating instrument engineering requirements, as the spectro-radiometric performance, to the quality of the final products, i.e. the vertical concentration of a specific trace gas is laborious calculation. An alternative approach to laborious and complex trade-offs and design optimization is manufacturing an instrument using state-of-art technology to better understand the achievable performance and cost drivers, and fine tune the design with the lessons learned. This approach is being followed with TROPOMI, a cost driven development that will provide a worth of experience and information for optimizing the design of Sentinel 5.

The Netherlands have a long standing experience in design, manufacturing and calibration of instruments for atmospheric measurements via GOME, SCIAMACHY, and OMI, and it has also direct scientific interest in exploiting the measurements with the work performed at institution as KNMI (Koninklijk Nederlands Meteorologisch Instituut) and SRON (Netherlands Institute for Space Research).

A project, dubbed TROPOMI, built on the experience on OMI was launched under Netherlands national funds, but it lacked the financial resources to be brought to completion and to be embarked on a satellite. The European Space Agency (ESA) saw an opportunity to use TROPOMI as a precursor of its Sentinel 5 mission and established a cooperation agreement with the Netherlands Space Office (NSO).

The project, that took the name of Sentinel 5P, where P stands for precursor , is now a joint project of the ESA and the NSO. In this joint project ESA is in charge of the procurement of the spacecraft and is financially supporting the procurement of some subsystems of the instrument, NSO is responsible for the development of the instrument and of it spectro-radiometric calibration. The way the project has been set-up, its outstanding technical challenges, its complex procurement scheme, and its tight schedule poses unprecedented challenges from both engineering and management point of view.

The experience built on this project, in phase C/D at the moment of writing, has already provided a few lessons that could be used in similar situations, namely when a complex procurement shall be handled in the shortest possible time. Furthermore, while the engineering team is still busy in solving technology challenges of the current design, a broader view should be gained by posing the following two questions:

1) how can the current technology development provide a strategic advantage to build the next generation instruments?

2) what are the technologies developments achieved on this project that will put this design into obsolescence?

Question 1) addresses, among others, the simple but recurring problem on transferring experience from one project to the next. If the results of a technology development are not framed in a proper way, the experience gained on one project may remain one-off and difficult to be exploited by another team, especially when the time span between two projects is of a few years.

Question 2) seems strange, as how can a technology development used to build an instrument put the same instrument design into obsolescence? An analogy comes from the microelectronic industry: computers using micro-chips are used to design the next generation of micro-chips, the computer using new micro-chips makes obsolete the computer used to design them. Something similar may occur also with optical payloads: technology developments to manufacture one optical component, as for example a low roughness high aspherical mirror, used only in just one or two elements of the system may put into obsolescence the entire design if, thanks to the development performed in the project, low roughness high aspherical mirrors can be reliably produced and at an affordable cost.

After a short overview of the Sentinel 5P missions and of its payload TROPOMI, this paper defines a structured approach to answer the above two questions.

The paper concludes with considerations on fast track small satellites used as a precursor mission of larger operative mission, an approach recently introduced at ESA. The paper presents a novel methodology to identify the optimum approach to jump starting a project that is very complex, with tight schedule, but still characterized by high technology innovation and with the dependability requirements of operational missions. The lessons learned on Sentinel 5 Precursor and on the development of TROPOMI are a very precious experience for ESA, as fast and cost effective missions will more and more constitute elements of future international in-orbit landscape.

THE SENTINEL 5P MISSION

The Sentinel 5P mission is a single stream satellite with TROPOMI mounted on a AstroBus platform (Figure 1) manufactured by Astrium UK, used for Spot-6. Modifications to the spacecraft to accommodate the

TROPOMI have been kept to a minimum to maximize the reuse of the existing design. Mission profile and spacecraft characteristics are reported in Table 1.

Figure 1 - Astrobus Platform

Table 1 - Mission Characteristics

Parameter	Values
Lifetime	7 years
Orbit	Sun-Synchronous @ 824 Km
Inclination	98.7 degrees
Mean LST	13:30 Ascending Node
Repeat Cycle	17 days
Spacecraft Platform	Astrobus L 250 (Astrium UK)
Spacecraft Launch Mass	900 Kg
Spacecraft Power	1500 W
Science Data Storage	230 Gbit
Science Data Link	310 Mbit/s OQPSK

The selection of the orbit and the large field of view of the instrument, namely 108 degrees, provides daily revisit. This ensure that seasonal cloud free measurements can be obtained in the tropical areas, where cloud coverage in rainy seasons makes measurements of the lower layers of the troposphere very difficult. Table 2 lists the level 2 data products of Sentinel 5. With the exception of the CO2, all products are targeted by Sentinel 5P.

Table 2 - Sentinel 5 Data Products

Level-2 data product	Wavelength range [nm]
Ozone vertical profile (O_3)	270 – 330
Sulphur dioxide (SO_2)	308 – 325
Albedo	310 – 775
Total ozone (O_3)	325 – 337
Aerosol	336 – 340
Formaldehyde (HCHO)	337 – 360
Bromine monoxide (BrO)	345 – 360
Rayleigh scattering (cloud), aerosol absorption	360 – 400
Aerosol	400 – 430
Nitrogen dioxide (NO_2)	405 – 500
Glyoxal (CHOCHO)	430 – 460
Aerosol	440 – 460
Cloud (O_2-O_2)	460 – 490
Water vapour and cloud	685 – 710
Cloud (O_2-A band)	750 – 775
Aerosol profile (O_2-A band)	750 – 775
Methane (CH_4) [& CO_2]	1590 – 1675
Aerosol profile	1940 – 2030
Carbon monoxide (CO) [& CH_4]	2305 – 2385

THE TROPOMI PAYLOAD

TROPOMI is a pushbroom imaging spectrometer with four spectrometers covering the spectral range from UV to short wave infrared (SWIR). The ground sampling distance and the spectral range are greatly enhanced with respect to its predecessors, as shown Figure 2 and Figure 3.

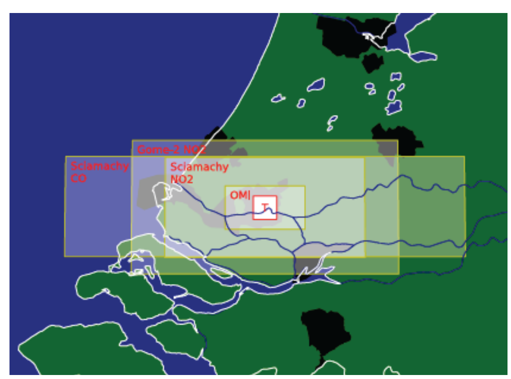

Figure 2 - Comparison of Ground Sampling Distances

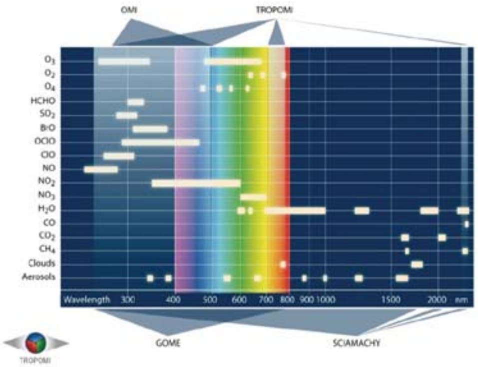

Figure 3 - Spectral Coverage

Figure 4 shows a functional diagram of the instrument. The instrument has a telescope and a calibration system common to all spectrometers. The UV, UVIS, and NIR spectrometers are assembled in a single mechanical part, nicknamed 'the motor block' as its many holes and cavities resembles a motor of a car engine (Figure 5). This solution, very laborious for what concerns design and manufacturing, has the advantage to greatly simplify the alignment of the many optical components and provides high thermal/mechanical stability to ensure the alignment of the spectral channels. The telescope is equipped with a polarization scrambler to minimize the sensitivity to the polarization state of the incoming light. The light from the telescope is separated in the flight direction by a slit which has a reflecting edge. The consequence is that the UV and SWIR bands will see a slightly shifted part of the Earth as compared to the UVIS and NIR channels (Figure 6).

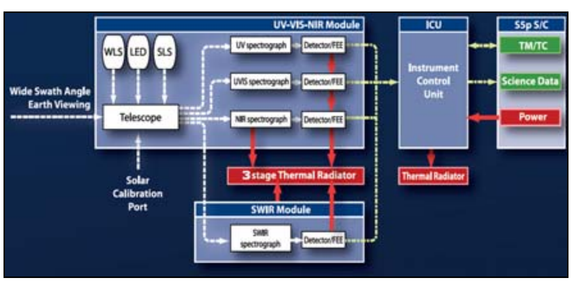

Figure 4 - TROPOMI functional diagram

The projection of the spectrometer slit on-ground has a curved shape, called spatial smile, caused by use of an off-axis telescope. The NIR and UVIS spectrometers use a common slit, while the SWIR and UV1 spectrometers are in-field separated of approximately 1 degree in the flight direction

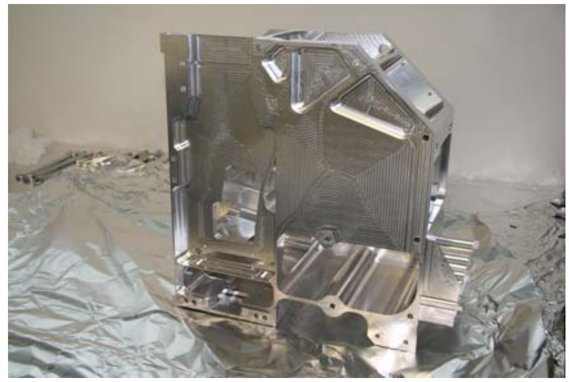

Figure 5 - UVN Mechanical Housing

The detectors will be cooled to ~210K to reduce the dark current contribution and they will be thermally isolated from the remainder of the detector modules, which are kept at room temperature.

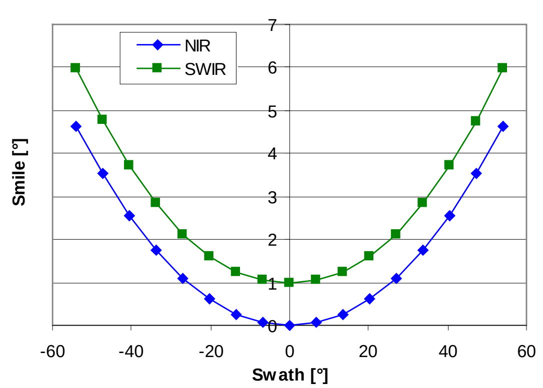

Figure 6 - On Ground Slits Projection

The SWIR spectrometer shares the telescope the UV, UVIS, and NIR spectrometers and receives the light via an optical relay. The SWIR optics will be cooled to ~200K to reduce thermal self-emission and the detector will be cooled to ~140K to suppress dark current. The SWIR spectrometer uses an immersed grating (Figure 7) to reduce the SWIR overall volume.

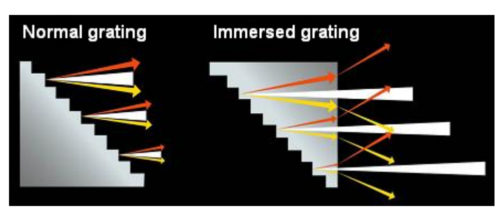

Figure 7 - Standard and Immerse Grating

The instrument control unit (ICU) provides power to the subsystems, receives tele-commands, send telemetries, and handle the processes to generate science data packets.

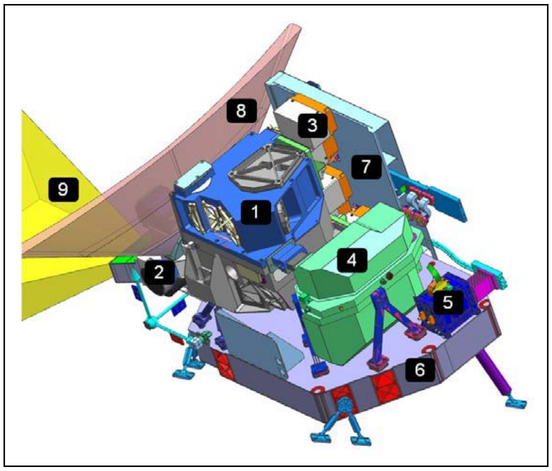

Figure 8 - TROPOMI Mounted on the TSS

The instrument is mounted on a telescope support structure which in turn is mounted on the spacecraft. A passive thermal radiator is used to remove heat from the system. Figure 8 shows TROPOMI located on the telescope support structure: (1) UV, UVIS and NIR Module, (2) Control Unit, (3) UVN Digital Electronics Module, (4) SWIR Module, (5) SWIR Front End Electronics, (6) Telescope Support Structure, (7) Thermal Bus Unit, (8) Nadir Field of View, (9) Field of View of the Sun Calibration Port.

The calibration unit includes the following elements:

- two sun diffusers: one for regular use, one for degradation monitoring;
- a white light source (WLS) used for measurements of photo response non-uniformity (PRNU), calibration, and on-ground health checks;
- a LED to monitor the short term variation in the output of the WLS;
- for the SWIR band, a set of 5 laser diodes are placed in the calibration unit, in order to be able to monitor the instrument spectral response function.

Each detector can be directly illuminated by two LEDs to check the detector response and its linearity.

TROPOMI has passed its CDR and the integration is well underway: the ICU and EGSE are integrated, the UVN detectors are completing the test, the SWIR detector has been delivered as well as the critical optical elements. The main focus, at this moment, is to ensure timely delivery of the SWIR module as foreseen later this year.

ESA / NSO JOINT PROJECT

The Netherlands have a long standing history in the area of atmospheric chemistry. Having been involved in the development of GOME , GOME-2 , Sciamachy and OMI , the NSO initiated the TROPOMI definition and enabling technology development in 2005. TROPOMI was set-out to gather unprecedented amounts of essential information about our planet's fragile atmosphere by combining OMI's high resolution and wide field of view with Schiamachy's large wavelength range.

In 2008 the GMES Atmosphere Service Implementation Group (GAS-IG) recommended a precursor mission ensuring the continuity between measurements performed by SCIAMACHY, on board of ENVISAT, and the Sentinel 5 mission to be launched on post-EPS, scheduled for launch on 2015. An agreement between NSO and ESA has been put in place to cooperate to implement the Sentinel 5 Precursor, that became a mission of the GMES Space Component.

NSO responsibility is the development, procurement, calibration, in-orbit commissioning of TROPOMI, and the generation of Level-1B data. ESA is responsible of the procurement of the satellite, the ground segment, the launch and in-orbit commissioning. The implementation of the Sentinel 5 Precursor mission is performed by a ESA/NSO Joint Project Team (JPT).

The procurement of TROPOMI is shared by NSO (~ 60%) and ESA (~ 40%), where NSO is supporting the procurement of the optomechanical assembly of the UVN, while ESA is providing financial support for the procurement of the SWIR Spectrometer, of the Digital Electronics Module and of the ICU. Dutch Space is the instrument responsible and was contracted by NSO and ESA in 2009 and December 2010 respectively.

The ground segment for Sentinel 5 Precursor consists of a Flight Operations Segment, Payload Data-processing Ground Segment and Mission Planning Facility. The Level 0-1b software is provided by KNMI to be installed in the Payload Data-processing Ground Segment. The Level 2 products are a joint procurement by ESA and NSO and is coordinated by KNMI. The Level 2 products are developed by KNMI, SRON, DLR and BIRA.

This short walk through the responsibilities and financing of both the flight hardware and the ground segment shows the tight interaction between ESA and

NSO and the cooperation necessary to ensure a smooth and successful project management.

TROPOMI TECHNOLOGY DEVELOPMENTS

One of the major innovations of TROPOMI is its wide field of view telescope. By using a manufacturing technology based on single point diamond turning, it has been possible to manufacture a fully reflective telescope with an across track field of view of 108 degrees and an unprecedented spatial resolution. The result is the outcome of several years of basic research on new materials, manufacturing processes and metrology done at TNO. Thanks to the results recently achieved, TNO is now capable of producing 'free form' optical mirrors, i.e. mirrors with non-rotational symmetric surface. Mirrors surface roughness, a concern only a few years ago, has been greatly improved thanks to the development at TNO of metrology and sub-aperture polishing techniques.

TROPOMI will be the first European optical payload using free form optics for the telescope. The mastering of the technology gained with the development done within the TROPOMI project and its preparatory phases gives a whole of new possibilities for innovative optical design that are still to be explored.

Concerning the detector, a trade-off between CCD and CMOS detectors was performed resulting in selecting CCD technology. CCD's, in spite of the CMOS rapid development, are still providing the best combination of UV sensitivity and charge handling. A ad-hoc development of the CMOS to meet the performance requirement was considered too risky.

The TROPOMI detectors are back-illuminated frame transfer CCD's, low dark current and a large format, i.e. 1024 x 1024 pixels of 26 µm. The detectors have been custom designed by E2V to reach a very high readout rate, a large full well and low readout noise. These contrasting requirements stem from the high signal-to-noises specified for low reference signals, namely an albedo of 2% and from the need to avoid saturation when performing measurements with a high albedo background.

The high charge handling is obtained by using multiple CCD output ports, high clocking speed, large pixel size, and register full well up to 2.5 Me-. The frame transfer clock lines are equipped with metal buttressing to minimize frame transfer smear. This reduces the line transfer times by about an order of magnitude. However, it was considered too risky to use more than 2 phase clocks for the transfer, which reduces the pixel full well by a factor 2, compared to conventional 4-phase image transfer. Altogether this results in good charge handling in combination with minimum smear.

The detectors have been developed and tested and, after optimizing the readout clocks, meet the ambitious performance. The flight detectors have been delivered to be integrated in the Detector Electronics Modules.

All detectors are optimized for the light that they will detect. The UVIS and NIR detectors have a graded anti-reflective coating, in order to reduce stray light and decrease interference effects in the silicon.

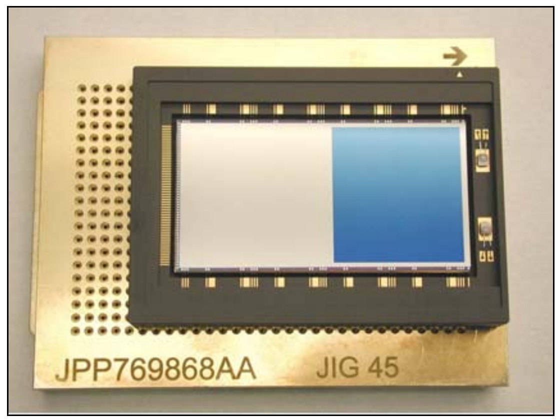

Figure 9 - EM of the TROPOMI CCD

Another important effort has been dedicated to the development of the SWIR band, with optics cooled at 200K to reduce thermal self-emission. Furthermore, the dispersing element of the SWIR is an immersed grating developed by SRON. The immersed grating, made of silicon, thanks to its high refraction index allows to reduce by a factor of 3 all three dimensions of the spectrometer. A design without immersed grating would be too large, but the drawback of using an immersed grating is the accurate temperature control needed. In fact, the silicon refraction index is function of temperature and a very accurate temperature stability is necessary to keep the spectral dispersion constant. Even a variation of temperature of a few tens of mK will cause an unacceptable spectral error.

The above paragraphs outline the major areas of new and original developments that will distinguish TROPOMI from all others spectrometers. Numerous design and development activities have been carried out to meet the challenging requirements from the measurement of atmospheric trace gases. The diffuser, the polarization scramblers, the SWIR detector, the thermal control system are just a few of a broad development effort. Entering in the details of each of them is beyond of the scope of this paper, but it is worth mentioning that the mix of complexity, time pressure and technology development makes TROPOMI a unique challenge. It gives the opportunity not only to boost technology, but also to experiment new and aggressive approaches to design, development and problem solving. The following paragraphs are an attempt done by the authors to put the daily job of the engineering and scientific work performed within the TROPOMI project in a frame that allows to formalize processes and include their lessons learned.

TECHNOLOGY PLATFORM

What is a Technology Platform? It is a term to indicate the underlying technologies, processes and methodologies used to ensure long term capabilities for research and product development. The term 'platform' is common in IT technology where is used to define the type of hardware on which software is developed and executed.

How can the concept of Technology Platform be applied to optical payload for remote sensing? The progress of optical payloads follow the evolution of:

- manufacturing technologies;
- optical design capabilities;
- optical metrology systems;
- final verification and calibration.

As new materials and manufacturing methodologies are available to build new optical components, as free form mirrors and lenses, the development of new metrology systems become necessary to test the item produced. Shortly after, new CAD tools are needed to design new optical system using the newly developed components. Once a new high performance optical instrument has been assembled, a new generation of instrumentation for optical test and calibration needs to be developed to check the final instrument performance.

The development of a Technology Platform consists in improving usability, reliability, and portability of each of these processes. It is not uncommon in space projects that ad-hoc processes have little or no chances to be reused in the next project. The step to improve the usability of a process developed ad-hoc for a project is often not taken. Reliability and portability of the process is seldom addressed, as it is out of the scope of a specific project.

The definition of a technology platform and the evaluation of the advantages it can bring to the next project is usually outside of the scope of a Project Manager, but it is the one and only possibility to build an unbeatable competitive advantage to be used by the next project.

Asking the question on how to improve usability, reliability, and portability of all the processes developed in manufacturing, design, and verification of a cutting edge instrument is the starting point to build a technology platform.

The question should come from outside the team, e.g. a Business Unit Manager and/or a Programme/Product Manager, depending on the organization of a company. The methodology on how to improve usability, reliability, and portability of all the processes needs to be discussed within the project team, possibly regularly and at each stage of the project. Obtaining a Technology Platform at the end of the project consists in finding the right balance between the effort it takes and the benefit it will produce, but it is also true that, if the problem is not properly approached, it may become necessary to 'reinvent the wheel next time'.

In the specific case of TROPOMI, TNO has performed a significant effort to make the manufacturing of free form mirrors a reproducible process. A large number of design of experiments have been conducted to fully understand the effects of the numerous parameters affecting the final quality of the mirror. Another example is the optical metrology developed for measuring the shape accuracy of aspherical lenses and mirrors, for which TNO has developed a sophisticated metrology tool named nanomefos.

Ad-hoc analysis tools also play an important role in the Technology Platform. In this area, the Dutch Space engineering team has developed TIDE, a modular and reconfigurable software tool to evaluate the accuracy of trace gas products from hyperspectral pushbroom instruments. TIDE started with quite a broad scope, from simulated atmospheric scenes, towards Level 2 trace gas products, but now tends to focus on instrument effects up to slant column trace gas products. The availability of sufficiently fine grid scenes and the use of a slant column retrieval allows to model all instrument effects without the need of a complex air mass corrections. TIDE is used in the everyday engineering practice but does not always include the complete chain.

These are just a few examples of elements composing a technology platform where a good level of usability, reliability and portability has been achieved. Remarkably, all these developments were done during the technology development of the preparatory phase of TROPOMI. The Phase C/D of a project with a tight budget and/or an aggressive schedule leaves little time and resources to deal with the problem of improving usability/reliability/portability of the new processes developed within the project. The organization or the company handling the project should not miss the opportunity to define, build and consolidate the technology platform, as it may be the only chance to do it. A reliable, well verified technology platform is of paramount importance to improve competitiveness. In a complex project like TROPOMI, where the elements composing the technology platform are scattered among research institutes, industry, and the scientific team, the concept of technology platform shall be introduced from the very beginning of the project. An effort shall be spent to define the technology platform in a well-structured way, as the stakeholders of a complex project may see their contribution as disclosing confidential information. Only approaching the problem with a broader perspective and possibly establishing long term cooperation agreements may generate the frame under which it is possible to establish a satisfactory technology platform.

Should we now start designing the next generation of TROPOMI using all the achievements of the technology developments, how TROPOMI will look like? The technology developments achieved in manufacturing free form mirrors and lenses and their metrology was used to produce only a few optical elements, due to the limited knowledge of the process. Now that TNO masters the process, it will be possible to use these two elements of the technology platform extensively throughout the optical system, and possibly leading to an instrument that could be significantly smaller and easier to build. The TROPOMI Scientific Team has very closely interacted with the Engineering Team and a number of analysis tools have been developed for the performance simulation, and more work will be performed during the calibration campaign. These models, validated by the result of the test campaign, will allow to reduce design margins, necessary when designing an innovative instrument. One of the perspective activities that are being explored by ESA is aimed at starting this process already now, while the full TROPOMI team is at work. The objective of this activity is to assess the technology platform, the level of usability, reliability and portability of its components and to lay down a leaner process for the next instrument.

JUMP STARTING A COMPLEX PROJECT

“The beginning is the most important part of the work - Plato”. This quote is true for any project to be started and large bibliography is available on the subject. What is not often clear from the very beginning is how to organize a project team to minimize the time it takes to bring the project to full speed right from the beginning and avoiding “stop and go” that often afflict the early stages of a large project. Without entering in generic considerations on processes to properly activate a project, it is interesting to go through some of the consideration presented in [2]. The authors suggest to make use of a plot they called NTCP (Novelty, Technology, Complexity, and Pace). Any project can be represented in this four axes plot. Projects with different mix of Novelty, Technology, Complexity, and Pace need different approaches and organization. Projects with high level of novelty need teams tightly working together, as for example the Lockheed “Skunk Works” [6]. A project with high technology contents requires design iterations, from the proof of concept to EQM. Where is TROPOMI standing in the NTCP plot? It scores high in all quadrants: contains novelties, as the cooled SWIR channel, and the free form telescope. The technology is also very high, as new high performance detectors have been developed, to mention just one of the technology challenges. Pace (meaning schedule) is very tight as well, as TROPOMI is a precursor and need to be flown asap, so the Sentinel 5 could benefit from the lessons learned on this project. Finally, the necessity of fulfilling ESA geo-return rules bring an added level of complexity as sub-contractors are selected on the basis of the financial resources made available by the participating Nations.

On TROPOMI it was very early understood that the effort in preparing interface control documents, necessary to handle the work of subcontractor needed a significant effort. Engineering teams have been collocated to resolve I/F problems as early as possible. In order to keep the high pace required by the project, ESA and NSO have formed a Joint Project Team to shorten the decision process time. The prompt reaction by the project managers in the various companies forming the consortium has minimized the time that could have been wasted in coping with the high level of complexity. Nevertheless, a thorough analysis of the NTCP diagram could have helped to task right from the start dedicated teams to attack the problems stemming from the high level of novelty, technology, and complexity, to reduce if not eliminate a few hiccups seen at the early stages of the project. Furthermore, the interaction among the stakeholders shall be adapted to cope with the pace of the project to avoid that the decision making process does not become a bottleneck for the flow of activities.

TROPOMI is being assembled and will soon enter the verification and calibration activities, certainly a very challenging part of the whole process, and more interestingly, the part of the project were all activities are on the critical path. While technologies issues are being resolved, and the complexity of handling the project will be reduced once the hardware will be assembled, the novelty and pace will remain high, as no other instruments of this level of accuracy have ever been calibrated. The project is getting organized to face the challenges of running a full calibration campaign within six months. The activity laying ahead will be source of new lessons to be passed to the next projects.

CONCLUSION AND ACKNOWLEDGMENTS

Differential optical absorption spectro-radiometry of Earth's atmosphere trace gases is the new frontier of remote sensing. To achieve the required instrument performance it is necessary to have very stable spectrometers with high spectral resolution and high SNR. TROPOMI is paving the way not only for future high end instruments that will be embarked on the next ESA Sentinel 5 mission, but it is also the opportunity to build a solid technology platform to be used as stepping stone future instruments. While high end applications as Sentinel 5 will further push the limit of the technology, a number of simpler and more affordable, but still meaningful, instruments could be designed using the technology platform developed for TROPOMI. The TROPOMI technology platform encompasses materials, manufacturing processes, metrology, calibration, and equally important, a tight cooperation between engineering and science teams. It is the intention not only of the authors, but of the whole community working on TROPOMI, engineers and scientists, to use TROPOMI technology platform as the stepping stone to explore new opportunities to develop a new class of affordable high performance spectro-radiometers.

The authors would like to thank the whole TROPOMI team, which list is too long to be reported here, working at Dutch Space, TNO, SSTL, KNMI and SRON for the fruitful exchange of ideas that made this work possible. Furthermore, the authors would like to acknowledge Mr. Kevin McMullan, Sentinel 5P Project Manager at ESA whose drive, dedication and enthusiasm are keeping the momentum necessary to move forward at a a project of this level complexity very fast pace.

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