ANITA2 Flight Model Development – A status report of the multicomponent ISS Air Analyser

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ANITA2 (Analysing Interferometer for Ambient Air) follows the European precursor mission ANITA1, which in 2007 and 2008 successfully operated on the ISS for 11 months. ANITA1 delivered information on the air conditions analysing in parallel 33 of the most important trace gases in the cabin atmosphere. The data have shown the benefits of in-situ measurements in a manned space cabin atmosphere. The advantages of the ANITA type instruments include high sensitivity, accuracy, precision and time resolution of the measurement data. The spectrometer relies on optical analyses with a Fourier Transform Infrared spectrometer. In 2016, OHB System and SINTEF were awarded by ESA the contract to develop the ANITA2 flight model, following some years of bread boarding of critical subsystems. The new system is characterised by a major reduction in mass, volume and power consumption, as well as improved characteristics in gas analysis sensitivity. The novel, sophisticated analysis S/W is further improved, employing statistical and non-linear calibration and analysis methods. As for ANITA1, the programme is planned to be a joint ESA/NASA project. It is also a stepping stone into the future, as a precursor system for manned exploration missions, e.g. to Mars and the Moon. The paper gives a progress report on the instrument development activities and will highlight status and achievements. The work described is performed under contract of the European Space Agency ESA.

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Nomenclature

ANITA	=	Analysing Interferometer for Ambient Air
BB	=	Breadboard
COTS	=	Commercial Off-The shelf-System
CUCL	=	Calibration Upper Concentration Limit
DFB	=	Distributed Feedback Laser
DLaTGS	=	Deuterated L-alanine-doped TriGlycine Sulfate (IR detector)
ESA	=	European Space Agency
EM	=	Engineering Model
FE	=	Flight Experiment
FM	=	Flight Model
FTIR	=	Fourier Transform InfraRed spectrometer/-metry
GUI	=	Graphical User Interface
HW	=	Hardware
IBB	=	Integrated Breadboard
IR	=	InfraRed
ISS	=	International Space Station
PDR	=	Preliminary Design Review
PFM	=	Proto-Flight Model
PLS	=	Partial Least Squares (multivariate statistical method)
SNR	=	Signal to Noise Ratio
SRR	=	System Requirements Review
SW	=	Software
TGM	=	Trace Gas Monitoring

I. Introduction

Starting in 1990, the European Space Agency ESA has selected the FTIR (Fourier Transform Infrared) technology for continuous monitoring of the crewed spacecraft air quality. Within different study and breadboard activities[1-9], supported by a very successful blind sample testing for NASA[1,3], it has been shown that the requirements on air monitoring with multi-gas detection are best fulfilled by an optical analysis method in combination with sophisticated analysis SW (Software).

The system's measurement principle is based on the detection of IR (infrared) absorption features stemming from the different gas molecules' vibrational and rotational modes. From the measured IR spectra the gas concentrations are derived via sophisticated analysis SW - applying optimised, non-linear simulations and data evaluation methods. The ANITA1 system's capability to measure with a time resolution of a few minutes allowed tracing the dynamics in the concentrations of multiple trace gases within the ISS cabin air for the first time.

The importance of a reliable and accurate online and in-situ measurement system such as ANITA has recently again been demonstrated, when a detector onboard the ISS indicated an ammonia leak, and the complete crew had to leave the US area of the ISS, even though it turned out to be a false alarm.

II. ANITA Overview

The ANITA2 development follows the successful ANITA1 precursor mission on the ISS in 2007/2008. Detailed information on the ANITA1 system and the principle of the operation can be found in the references[6,7]. This includes a list of the 33 gases measured. The system consisted of two specially designed mid-deck locker inserts (standard payload rack inserts) plus support HW. One mid-deck locker contained the FTIR measurement system, the other the electronics and the gas sampling unit. Figure 1 shows ANITA1, accommodated on the ISS. The measured optical spectra were automatically analysed by sophisticated analysis software to produce a detailed data set on the air quality inside the ISS every six minutes.

Following the successful flight of ANITA1, the ANITA2 programme was started after return of the flight hardware to ground. The work started with "lessons learned" regarding hardware and analysis software and went through two smaller bread boarding phases to develop and test improvements[10-12]. The ANITA2 Flight development programme was finally initiated in 2016[13].

Figure 1. NASA astronaut Clay Anderson operating ANITA1 on ISS. Photo: NASA

III. ANITA2 System Hardware Overview

ANITA (Analysing Interferometer for Ambient Air) is a FTIR (Fourier Transform Infrared) spectrometer that has the capability to monitor simultaneously a large number of gaseous compounds, with a high time resolution. The project ANITA2 is an ISS technology demonstrator for later exploration mission.

Targeted operational lifetime is 8,000 plus hours, gas sampling every 5 minutes, and calibrated to be able to measure over 30 gaseous compounds.

One critical element that may be the limiting factor for the operational lifetime of ANITA2 is the IR source. ANITA2 is designed in such a way that the IR source is accommodated in a position where a replacement will be possible in the future, paving the way for future long-term exploration, e.g. ANITA3.

ANITA2 will be operated as a single Middeck Locker insert accommodated in an EXPRESS Rack. This can be compared to ANITA1, which required two Middeck Lockers demonstrating major volume and mass savings. The accommodation of ANITA2 in an EXPRESS rack is depicted in Figure 2.

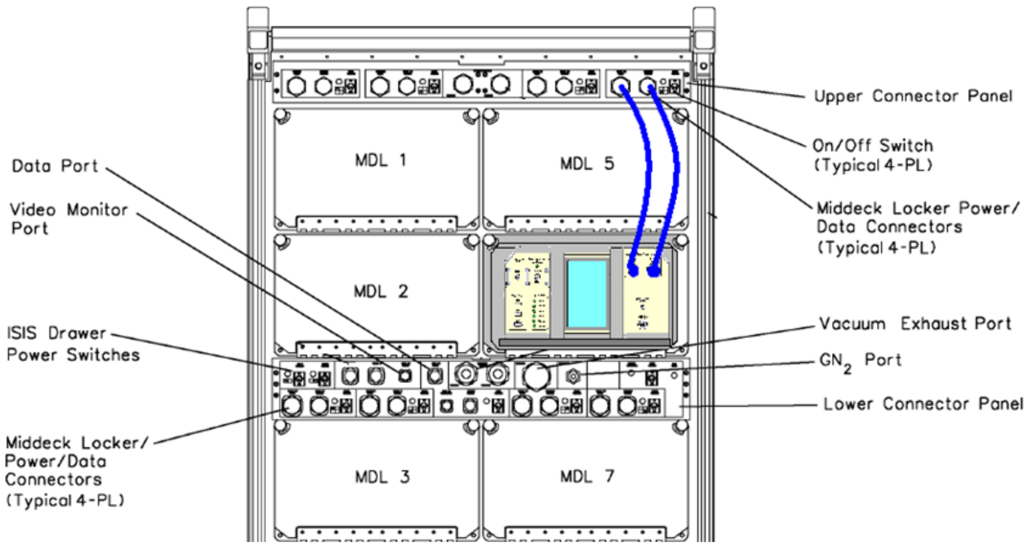


Figure 2. Accommodation of ANITA2 in a Middeck Locker Insert inside an EXPRESS Rack

The following Figure 3 shows the hardware, which is going to be developed and launched to the ISS. The ANITA2 Middeck Locker Insert is a new development, while the Sampling Hand Pump and Bags are recurring items from ANITA1 that will be used on demand to take air samples from arbitrary positions inside the ISS. The cables for power and data are not shown.

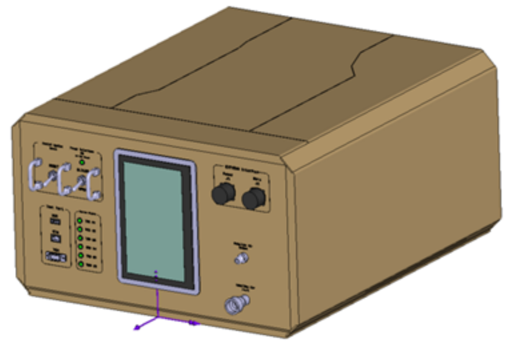
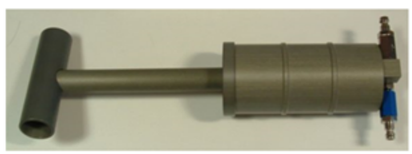
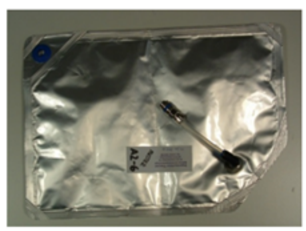
Engineering Name	Sketch	Status
ANITA2 Middeck Locker Insert		Under development, single Middeck Locker insert
Non-Local Sampling Hand Pump		Design is re-flight; will be manufactured according to ANITA1 drawing in Phase 2
Non-Local Sampling Bag		Design is re-flight; will be manufactured according to ANITA1 drawing in Phase 2

Figure 3. ANITA2 Hardware End Items (cables not shown)

The mechanical accommodation of ANITA2 in the Middeck Locker is shown in the following Figure 4. In principle the accommodation is divided into two compartments, closed and vented:

The “Closed Compartment”:

- This area contains the optical subsystem.
- It is backfilled filled with dry nitrogen (purity 99,999% or better).
- If required, by “late access” quick disconnects it is possible to replace or back-fill the nitrogen in this compartment.

The “Vented Compartment”:

- This area is actively cooled by the EXPRESS Rack provided avionics air.
- Air inlet and outlet are covered by debris grid.
- Most of the electronics are placed in this compartment.

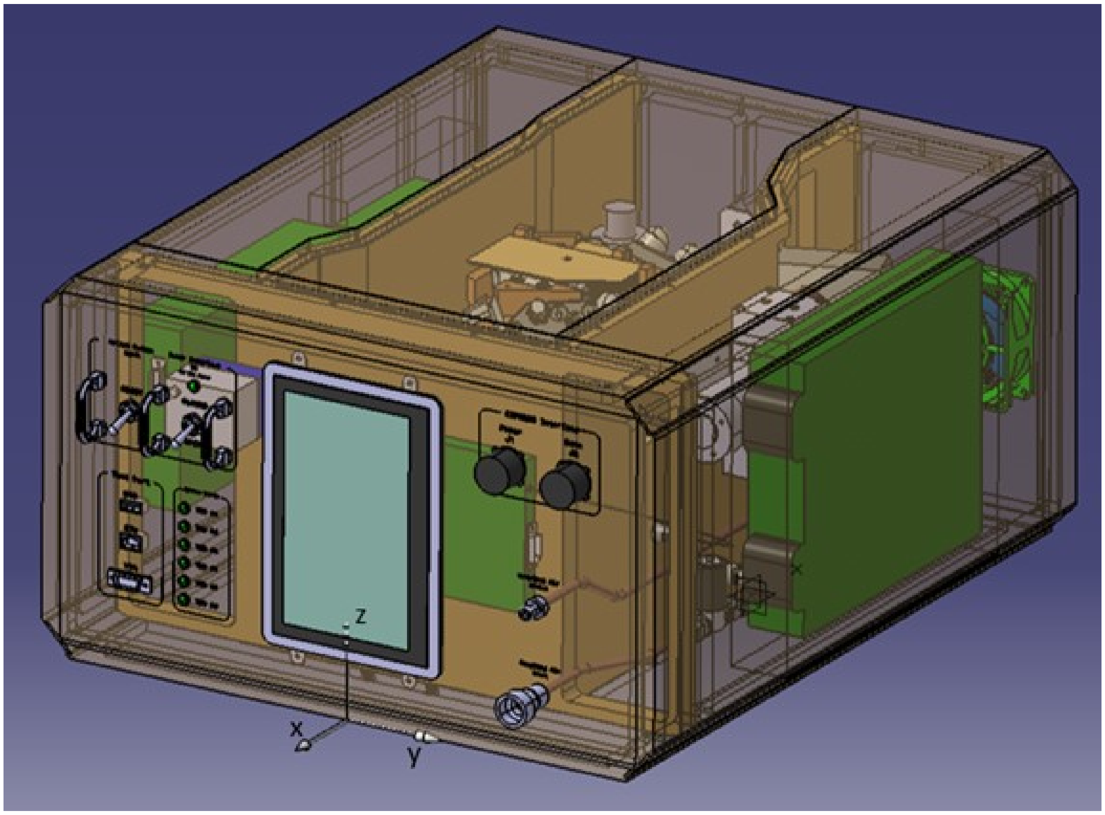


Figure 4. Mechanical Accommodation of ANITA2 indicating a closed (inside) and a vented compartment in a Middeck Locker (inside dimensions of a Middeck Locker: 17,337 width x 9,969 height x 20,320 depth, in inch)

It is noted that the Gas Cell is accommodated in the “Closed Compartment”. The Gas cell has the additional functionality to be the Optical Bench for all Spherical & Toroidal Mirrors and the COTS Spectrometer.

The following Figure 5 shows the complete optical assembly of ANITA2:

It consists of the following major elements:

- IR Source. It is a limited life item and as such placed in a position that a replacement for future applications can easily be realized.
- Interferometer. This FTIR spectrometer is a modified COTS item. The adaptation is in cooperation with the commercial supplier.
- Gas Cell. As noted above, it forms the Optical bench for the Interferometer and some of the mirrors.
- IR detector and
- Various additional optical elements.

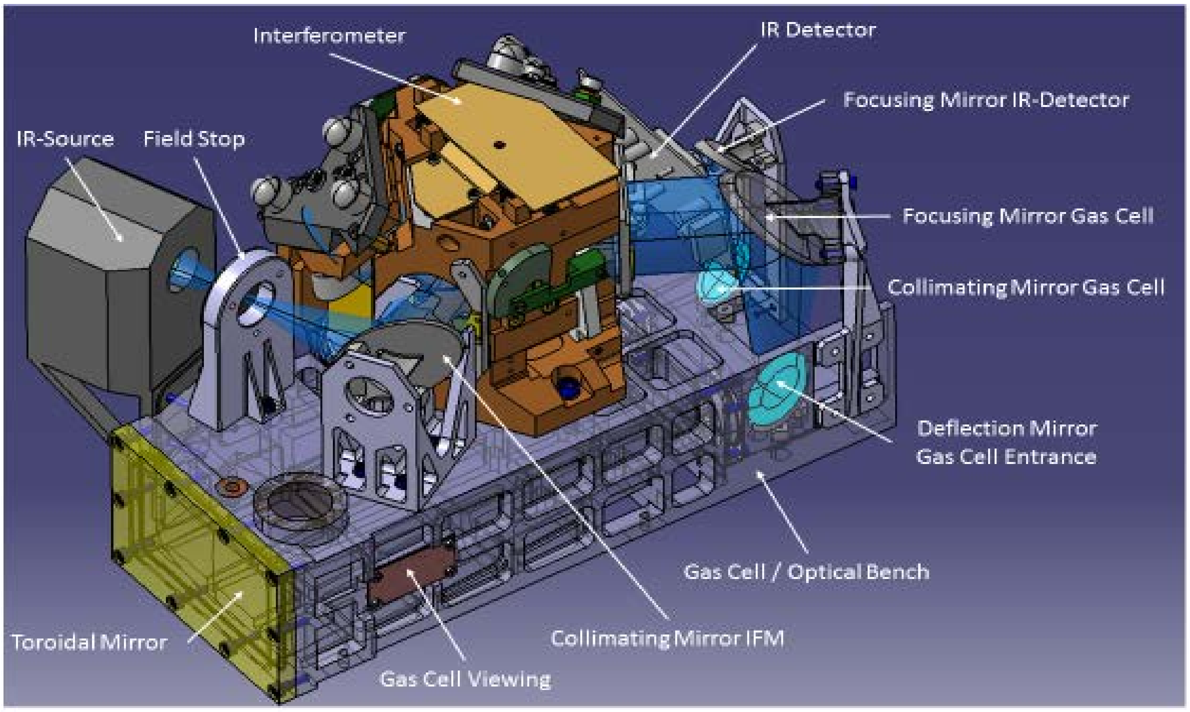


Figure 5. Mechanical Accommodation - Complete Optical Assembly

The following Figures 6 and 7 show the mechanical accommodation of the gas cell.

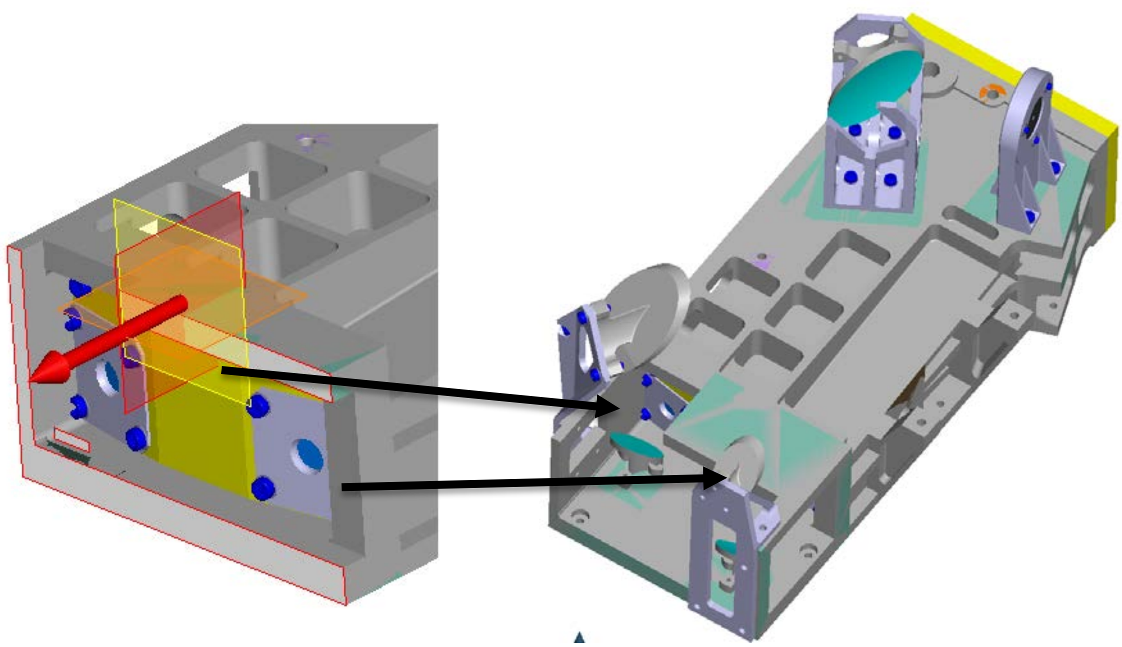


Figure 6. Mechanical Accommodation Gas Cell (1/2)

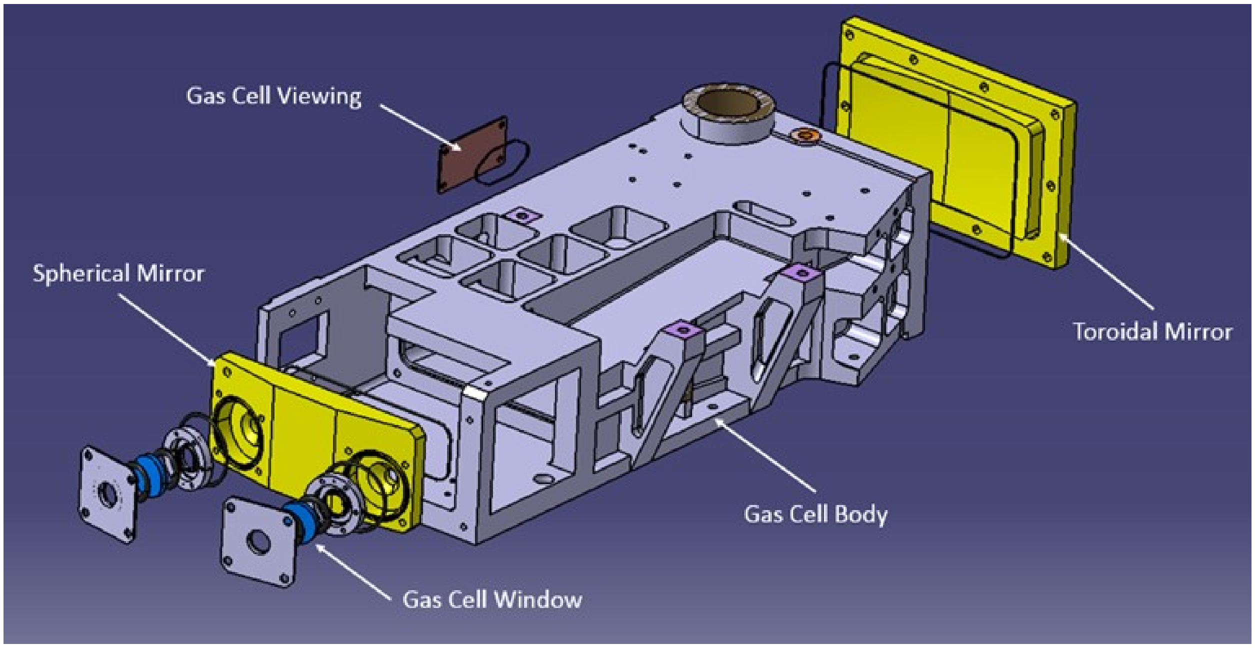


Figure 7. Mechanical Accommodation - Gas Cell (2/2)

The **electrical design concept** is depicted in Figure 8. The main components are:

- Interferometer Electronics, consisting of the Interferometer DSP (Digital Signal Processor), ADC (Analog-to-Digital Converter) and Control Unit
- Hard Drive
- Power supply and power distribution unit
- IR detector
- Laser Drive board
- Touch screen

The touch screen has not finally been selected yet.

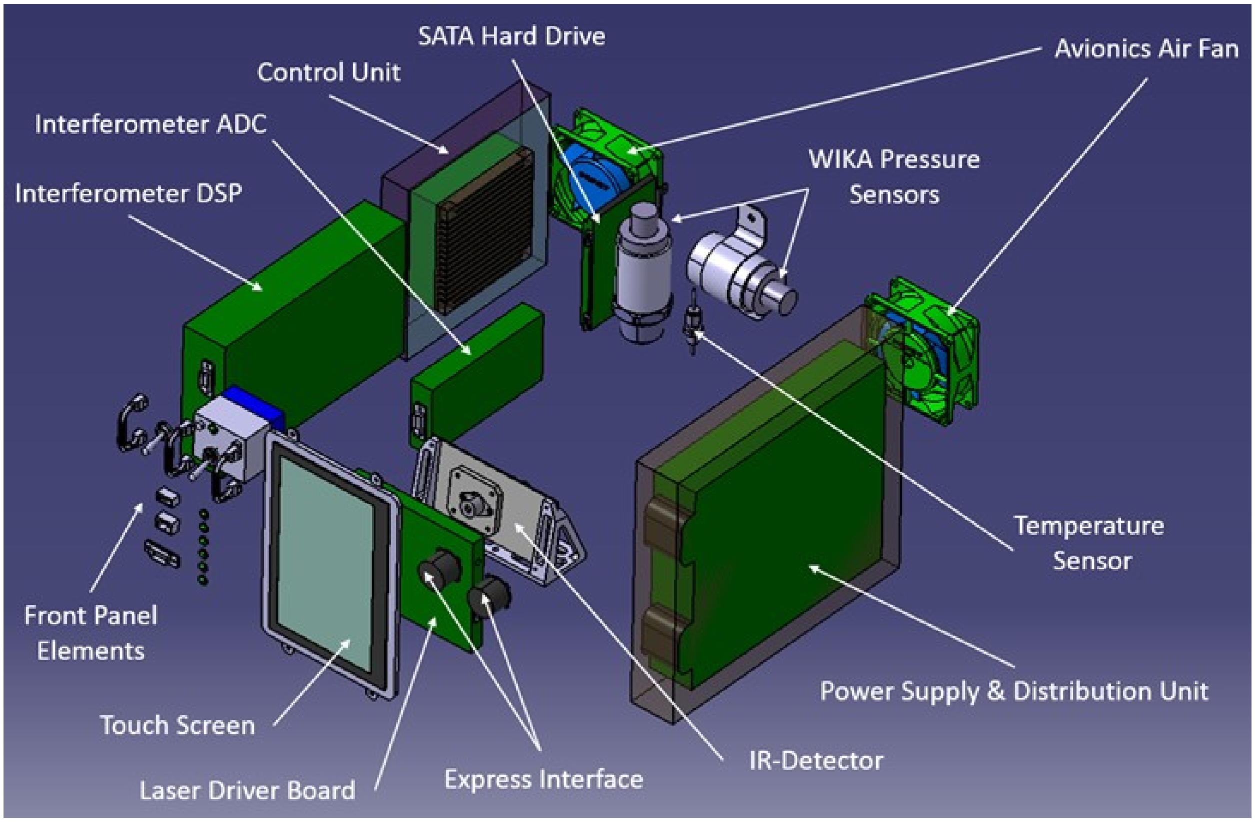


Figure 8. Electrical Parts Accommodation

IV. System Calibration and Data Analysis

A. Calibration

ANITA2 will be calibrated based on the same novel methods that were developed for ANITA1[5]. Initially one or more reference spectra for each target gas are measured on the target instrument, the ANITA2 PFM (Proto-Flight Model). Applying the reference spectra and test data from the instrument, the measurement process is simulated to produce three large sets of simulated spectra for different gas mixtures, spanning the defined gas scenario for the measurement task. The three sets of simulated gas spectra – denoted the *training set*, the *tuning set*, and the *test set* – are made stochastically independent in order to avoid modelling of noise or adapting to other arbitrary details. The training set is applied for multivariate statistical analyses of correlations in the data set between the gas concentrations and the spectral contents. The tuning set is used to select the useful correlations to make a calibration model for each target gas. The test set is applied to estimate the measurement quality for each target gas, including the expected detection limit. This *synthetic testing* is mainly used for optimising the calibration for each gas compound. The final estimates on the measurement quality, including the detection limits, will be made from testing on real multi-gas mixtures.

ANITA's gas calibration and analysis software has a unique ability to extract and exploit much of the information available in high-quality FTIR spectra. For ANITA1, the calibration simulations of the measurement process ensured that the extracted information was almost undisturbed by inter-gas spectral interference (the main problem), spectral baseline drift, and non-linear spectral response, and that spectral noise was handled in an optimal way. On the downside, small unexpected changes in spectral line shape in ANITA1 on the ISS proved to be sufficient to disturb ANITA1's gas estimation slightly[7]. The main changes occurred after cold starts of the system, and line shape variations could be grouped into two main line shape modes. Therefore, the disturbances on the gas estimations from spectral line variations could be greatly reduced through retrofitting two parallel calibrations adapted to these two line shape modes. However, in addition to applying two operative calibrations, this type of solution also requires an automated detection of the current line shape mode.

The line shape stability issue is being handled for ANITA2 through two parallel improvements. Firstly, attacking the source of the problem, the improved construction of the optical modulator will give even better line shape stability. Secondly, any remaining line shape variations that might occur on the ISS will have reduced impact through robustification of the calibration models[13]. Like most other types of robustness for the calibration models, this is implemented through including line shape instability in the simulations for the calibration.

B. Gas Scenario for the Calibration

ANITA2 is an ISS technology demonstrator for exploration. This means that the development shall pave the way for an ANITA3 to be maximally applicable and useful for long-term missions. However, the calibration of ANITA2 will also aim at making the system maximally useful on the ISS.

Any type of system calibration must be intended for a defined measurement scenario. For an air monitoring system like ANITA, a crucial point is the gas scenario, often referred to as the *gas list*, where each gas compound can be assumed to vary freely between zero and its CUCL (Calibration Upper Concentration Limit) – although neither water vapour nor carbon dioxide can drop really low in a closed crew environment.

The starting point for the definition of the gas scenario for ANITA2 on the ISS is:

1. ANITA1 pre-flight gas detection scenario and measurement results from the ISS air
2. NASA's newest listing of gases that are relevant for real-time monitoring in manned spaceflight
3. Other available information on historical, planned, or expected gas occurrences in the ISS air

NASA’s listing is intended to cover all desirable real-time air monitoring associated with manned spaceflight. No single monitoring system is expected or intended to cover the entire list. Also, not all compounds are necessarily relevant for the ISS cabin air. In particular, it would not be meaningful to calibrate ANITA2 for a gas that potentially is interesting for exploration missions but cannot occur in the ISS air.

There are two possible reasons to include a given gas compound in ANITA2’s gas scenario:

- Data on that compound can be useful for the end users, and the compound can possibly be detectable for ANITA2
- The compound may occur in a concentration that can give significant spectral absorption to disturb the estimation of other gases

Gases without optical absorption in the mid-IR range covered by ANITA2 – most notably nitrogen, oxygen, hydrogen, and noble gases – are not relevant for ANITA2. The same goes for gases that cannot possibly occur in the ISS air in concentrations detectable for ANITA2.

It is very important that the defined gas scenario for the calibration, i.e. the gas list with CUCL values, covers all the relevant measurement situations. On the other hand, the gas scenario should not include more gas compounds or higher CUCL values than necessary. This is the case because an extended gas scenario requires increased robustness in the calibration. Like other types of robustness, it must be implemented at the cost of reduced measurement quality in terms of reduced sensitivity in the gas estimations. – The method of calibration optimises the gas sensitivity at the required level of robustness.

The final updating of the pre-flight gas scenario for calibration of ANITA2 is planned to take place mid-2019, just before the detailed preparations are made for mixing of the gases for the calibration and test measurements.

C. Gas Analyses

The primary gas analyses will be performed automatically onboard the ISS. This will comprise the estimated gas concentration for each gas in the defined gas scenario, any special signal that a gas concentration is higher than desirable or acceptable, and primary outlier detection, i.e. detection that something is out of specification. Most interestingly, the system can discover if an unexpected gas occurs. In addition, it can detect if spectral artefacts or excessive spectral noise should be disturbing the gas estimations.

The estimated gas concentrations, any specific gas concentration signal, and any outlier signal will be generated onboard the ISS with ANITA2 working fully autonomously. However, since this is a technology demonstrator, this information will not be accessible to the ISS crew from the start. The currently defined ANITA2 programme ends after a one-month commissioning phase on the ISS. After successful commissioning, it may be decided to display the results to the ISS crew.

During ANITA2's commissioning phase, and possibly in a following operational phase, the primary gas estimates from the ISS will be treated further on ground. This will include different time-domain filtering for the different gases to increase the quality of the concentration estimates even further. It will also include average values over e.g. a day, a week, or a month to document average air quality and gas exposure levels relevant for human health and technical status on the ISS. Data tools for performing these processes on ground and reporting to the end users will be developed. The practical experience from applying these tools on ISS data will constitute part of the basis for including such features in the autonomous operation of a possible ANITA3 for exploration – and for other space missions or ground applications.

The autonomous outlier detection system on the ISS will detect any significant spectral feature that cannot be caused by any gas known to the system. This system can detect any unexpected gas, any spectral artefact, or excessive noise. In addition, an outlier signal should be given if any gas should be estimated to be far above its CUCL in the defined gas scenario or significantly negative. Significantly negative gas estimates can only be side effects from unexpected gases or instrument malfunction.

During ANITA2's commissioning phase, and in a following foreseen operational phase, any outlier signal from the ISS and its underlying spectral data will be treated further on ground. The first step will be to make a diagnosis to define the underlying problem. If there are indications of at least one unexpected gas, special analyses will try to detect which gas(es) and to confirm that the possible unexpected gas(es) can explain the problem. Data tools for supporting these processes on ground will be developed. The practical experience from applying these tools on ISS data will constitute part of the basis for including some of their features in the autonomous operation of a possible ANITA3. More complex analyses as well as actions to handle the situation will probably always be handled from ground.

D. Handling of Unexpected Results

One of ANITA's strong sides is the possibility to make new calibrations and apply them on ground or to install them on ISS from ground. This updating of the calibration is most important if a new, unexpected gas is detected in the ISS air, like it happened for ANITA1[7]. Initially, a workaround solution may be to block out the spectral interference from the new gas to construct a preliminary calibration[7]. This simply implies to rerun the calibration procedure, after manually removing or zeroing the spectral areas of significant unexpected gas interference, to produce the preliminary calibration to cover all the gases in the original scenario. This solution worked excellently for ANITA1, since the new gas sulphur hexafluoride only called for a quite small spectral area to be ignored. For a full upgrading of the ANITA2 calibration, the ANITA2 EM (Engineering Model) will be used as a GM (Ground Model, a twin on-ground ANITA2 system) to make reference measurements on the new gas. The GM will have the same construction as the PFM and be very similar, but of course not fully identical. The expected minor differences in their spectral characteristics can probably be made even smaller through special spectral transformations that were developed for ANITA1. With the reference spectrum for the new gas transformed to fit the PFM, a new calibration is constructed with the gas scenario extended by the new gas (or gases).

The possibility to post-fit new calibrations from ground, and for on-ground use only, can be exploited for all kinds of adaptations, optimisations, and workaround solutions to any unexpected problem.

V. Operational Scenario

The operational concept is summarised below:

- ANITA2 is intended to operate fully autonomously in local sampling mode after initially starting this mode.
- It is planned to perform every 12 hours a background measurement, which then will be used in all subsequent measurements for calculating the spectrum used in analysis.
- It is anticipated that a standard measurement will take 5 minutes (~2.5 minutes for gas exchange and acclimatization; the rest for measuring the interferogram).
- After each measurement, the interferogram will be transformed to a spectrum and passed to the analysis software by SINTEF, which will calculate the gas concentrations on-board ANITA2.

- Non-local sampling is performed on demand by a crew member with the hand pump and sampling bag; then the bag is connected to ANITA2 for analysis (crew procedure)
- ANITA2 will not require electrical or mechanical on-orbit maintenance.
- ANITA2 will consume nothing but power and produce no waste.
- ANITA2 will have a permanent calibration valid for the specified gas scenario.
- ANITA2 will have outlier detection to discover off-nominal operation, e.g. any unexpected gas outside the specified gas scenario.
- ANITA2's calibration can be updated from ground to adapt to an extended gas scenario, and various special calibrations can be built and applied on-ground optimised for the currently observed air compositions.

VI. Summary and Outlook

VII.

The successful operation of ANITA1 on the ISS has demonstrated the validity and performance of such an in-situ instrument in closed habitats such as the ISS. Recent incidents, e.g. regarding potential ammonia leakages in January 2015, even though false alarms, support the necessity of measuring the air composition including trace gases in-situ and with short response time.

Even with just the functionality of ANITA1, ANITA2 could be applied routinely, giving frequent readings of the trace gas contents of the ISS cabin air with a unique combination of accuracy, precision, sensitivity, and stability. Like for any well-designed measurement system, this would work perfectly well for any measurement task within the measurement scenario defined for the calibration. However, ANITA's novel method of calibration in addition allows several types of flexibility, including post-launch calibration updating and optimisations. It also is an excellent basis for many add-on features, including automatic outlier detection, warning and diagnoses, as well as different kinds of specialised calibrations for further optimised sensitivity, for special preparedness for emergency situations and for automatic handling of unexpected situations.

Examples on applications in addition to the ISS are indicated in the following Figure 9.

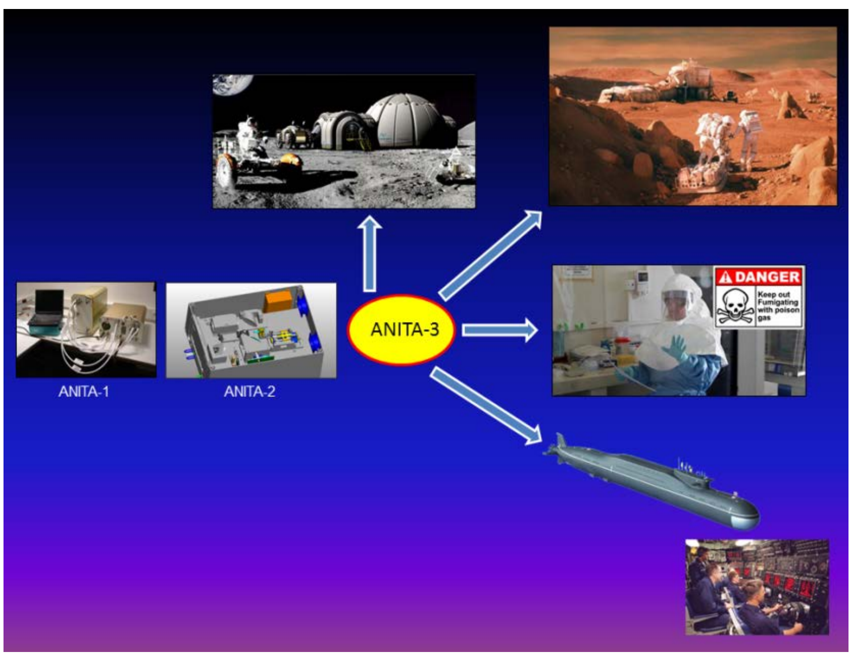


Figure 9. The ANITA Roadmap

At the time of writing this paper, 4 months after the project's kick-off, in February 2017 ANITA2 successfully achieved the System Requirements Review milestone. The next step is the design finalization, manufacturing and test of the Integrated Breadboard (IBB), which already will have a representative gas cell, interferometer and optical subsystem, and thus providing already an early indication of achievable technical and analytical capabilities for the Preliminary Design Review (PDR), After the PDR, the Engineering Model (EM) and later the Proto-Flight Model (PFM) will be built. The delivery of the Proto-Flight Model is scheduled for mid of 2020.

Acknowledgments

Thanks to all the NASA, ESA and DLR colleagues for the professional support and cooperation in the ANITA programme. The described work is being executed under ESA contract number 4000118166/16/NL/AT.

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