ANITA2 Trace Gas Analyser for the ISS - Flight Model Finalisation, Ground Test Results, and ANITA-X for future exploration missions

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The ANITA2 (Analysing Interferometer for Ambient Air) instrument is a trace gas analyser designed to operate on-board the ISS to monitor the cabin atmosphere. ANITA2 is capable of detecting more than 30 of the most important trace gases in parallel. The advantages of an ANITA type instruments include high sensitivity, accuracy, precision and time resolution of the measurement data, as well as no consumption except electrical power and no production of waste. This makes ANITA also a stepping-stone into the future, as a precursor system for crewed stations, bases, and exploration missions, including the (Deep-Space) Gateway and to/on the Moon and Mars. During the last year, the Flight Model of ANITA2 was successfully integrated and functionally tested. At the time of writing, ANITA2 will soon enter the phase of gas calibration measurements, followed by the building of a complete calibration and an extensive test campaign, applying multi-gas mixtures.

This paper presents the state of the FM as well as results of the very successful test campaign, including optical performance, vibration, audible noise, and EMC tests. In addition, an overview of ANITA-X for future exploration missions is presented. As of the current planning, ANITA2 will be ready for flight late in the summer 2021.

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Nomenclature

ANITA	=	Analysing Interferometer for Ambient Air
CDR	=	Critical Design Review
DLR	=	German Aerospace Center
ESA	=	European Space Agency
FM	=	Flight Model
EMC	=	Electromagnetic Compatibility
EXPRESS Rack	=	EXpedite the PRocessing of Experiments to Space Station Rack
FTIR	=	Fourier Transform InfraRed spectrometer/-metry
FWHM	=	Full Width at Half Maximum
NASA	=	National Aeronautics and Space Administration
IR	=	InfraRed
ISS	=	International Space Station
OBB	=	Optical Bread-Board
PDR	=	Preliminary Design Review
FM	=	Flight Model
SNR	=	Signal to Noise Ratio

I. Introduction

Already in 1990, the European Space Agency ESA started its technology selection process for monitoring of the air quality in crewed spacecraft. The preferred combination of technologies was FTIR (Fourier Transform Infrared) spectrometry combined with multivariate statistical calibration. Within different study and breadboard activities[1-3], supported by a very successful blind sample testing for NASA[4, 5], 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 software.

The measurement principle is based on the detection of infrared absorption features stemming from the different gas molecules' vibrational and rotational modes. From the measured IR spectra, the gas concentrations are derived by the analysis software - applying optimised, non-linear simulation and data evaluation methods. The ANITA1 system measured all the target gases in the ISS cabin air with a time resolution of six minutes. This allowed, for the first time in a space cabin, tracing of the dynamics in the concentrations of multiple trace gases, for a time span of 11 months in 2007 and 2008[6-8].

The importance of a reliable and accurate online and in-situ measurement system such as ANITA, has been demonstrated for example in 2015, when a detector on-board the ISS indicated an ammonia leak. Then, the complete crew had to leave the US area of the ISS, even though it turned out to be a false alarm[9].

Already at the beginning of operation on-board the ISS, ANITA1 showed one particular aspect of its high value through detecting an unexpected gas in the cabin air. ANITA1's automatic outlier detection and analysis enhanced and pinpointed an unknown and unexpected spectral feature, which could easily be identified on-ground to be caused by sulphur hexafluoride, SF6. Then, the method of calibration allowed the on-board calibration to be updated to include this gas. After the detection of the gas, it became clear that SF6 had been released by a medical experiment, but it had not been expected to persist in the ISS air. As SF6 was not expected to be present in the cabin air, it was never detected and identified by any other analysis method before, neither on-board nor on-ground. This shows the high suitability of the ANITA measurement principle also for future missions beyond low Earth orbit (LEO), where unexpected gases need to be detected and identified.

Missions beyond LEO also introduce new sets of requirements for ANITA. In particular, some long duration missions, like Gateway or Lunar Station, will include besides human accommodation most likely also periods of uncrewed operation, or solely robotic activities. These operations will call for new modes of operation and possibly a different system architecture of upcoming ANITA-X systems.

II. ANITA2 Overview

After the successful ANITA1 mission on-board the ISS in 2007/2008[6-8], the ANITA programme was continued through two breadboarding phases[10-13] to develop further improvements. In 2016, OHB and SINTEF were selected to develop an ANITA2 system to operate on-board the ISS for about one year as a technology demonstrator for exploration missions. As a demonstrator, ANITA2 will not be part of the official ISS air quality and safety system. However, the ANITA2 system will be calibrated and optimised to produce useful data on the ISS air composition. At the same time, this will ensure demonstration of system performance and operation relevant for exploration.

Key elements that qualify ANITA to be a good candidate for being a gas monitoring system on future human spaceflight missions are:

- Fully autonomous operation
- Measurement cycle of 6 minutes (of which ~4 minutes are used for measuring and the rest for gas sampling and acclimatisation)
- Automatic and on-line gas concentration estimation by software from SINTEF
- In-situ measurement minimizes changes in the gas concentrations (sorption effects) compared to taking samples and analysing on ground.
- Non-local sampling (e.g. from airlocks) is possible via air sample bags
- No maintenance and no consumables required
- High stability of optical system, so the calibration is permanent for the specified gas scenario
- Most gases can be measured, except diatomic homonuclear gases (N2, O2, ...) and noble gases, which do not absorb in the infrared spectrum
- The current gas scenario contains over 35 gases that are measured simultaneously. This includes various alcohols, aldehydes, ketones, aromatic compounds, acetates, halogenated compounds (including fluorinated gases for cooling and fire suppression), siloxanes, and some other gases such as ammonia, methane, CO, CO_2, and water vapour.
- Automatic outlier detection to discover off-nominal operation, e.g. the detection of an unexpected gas
- Update of calibration from ground is possible, e.g. to include new gases or to optimise for the observed gas scenario (performed for ANITA1)

The main improvements of ANITA2 compared to its precursor are increased spectral stability, further refined analysis software, and reduction in mass (58kg → 37 kg), volume (2 MDL inserts, external notebook & extension box → 1 MDL insert), power (173 → 80W)[14-19]. In addition, the interface complexity is reduced, as ANITA2 will need a single power cable only. Data connection is established via WIFI to give a high flexibility regarding positioning within the ISS. Being a completely self-standing single rack insert, which also includes a controlling PC with a touch panel, ANITA2 can be installed much easier and quicker than ANITA1. The high degree of autonomy makes the instrument suitable for operation at different positions on-board the ISS, outside the Express rack as well.

III. Operation Principle

The main operation principle is very briefly summarized here, as more details can be found elsewhere[14,18]. The infrared radiation emitted from a dedicated source is passed through an interferometer with adjustable path difference before interacting with the cabin air in a gas cell. The attenuated radiation is recorded by an infrared detector. The optical path difference is varied over time, and the detected intensity as function of the path difference is related to the spectrum via Fourier transform, which gives the name for this kind of spectroscopy.

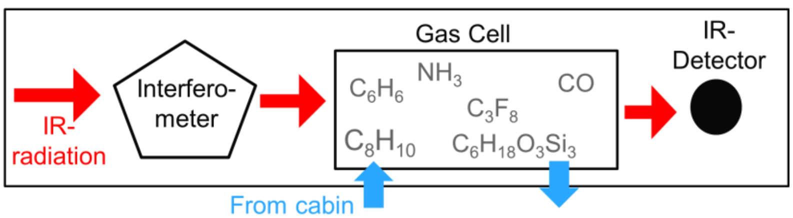

Figure 1: General schematics of ANITA2

Except for the IR source, all optical elements of ANITA2 are mounted directly onto the gas cell, which serves as an optical bench. This requires a complex geometry of the gas cell, however saving enough volume to accommodate the whole instrument in a single middeck locker. The front and rear of the gas cell are used as mirrors, where the reflecting surfaces are facing each other, as shown in Figure 2. The front mirror on the right accommodates two windows, through which the IR radiation can enter and exit the cell. The volume inside the gas cell, which will be filled by cabin air samples, has a length of about 25cm. Inside this volume the IR radiation can interact with the air molecules that selectively absorb molecule-specific wavelengths. The more molecules the radiation can interact with, the larger the absorption signatures. For this reason, the radiation is reflected 39 times inside the gas cell to achieve very good gas sensitivity with an optical interaction path of 10 meters.

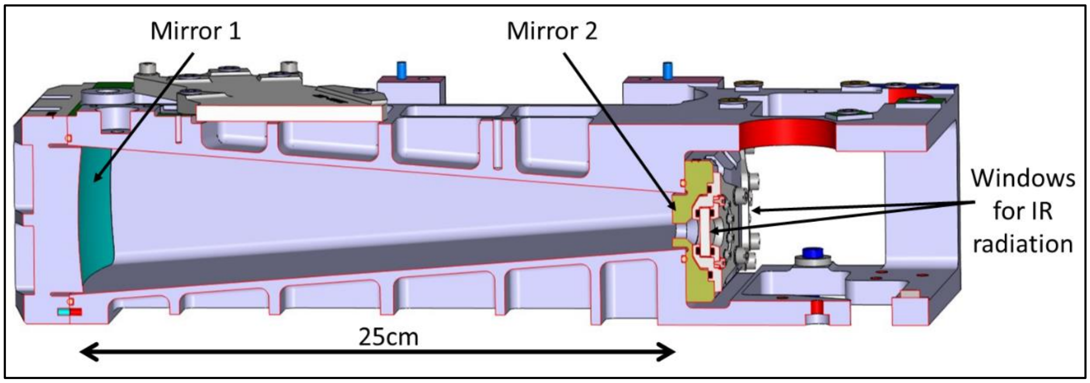

Figure 2: Cut-view of gas cell with internal mirrors.

The IR detector is a pyroelectric element, which has a lower sensitivity and a slower response than photon detectors. The slower response limits the speed by which the measurements can be recorded, but this gives no problem for trace gas analysis on-board the ISS. The main advantages of this detector are a close to perfectly linear response (good for gas estimation), and operation without cryogenic cooling (especially good on the ISS).

IV. Flight model assembly

In 2020, the Flight Model was assembled and optically aligned. First, the optomechanical elements, which is the gas cell, the mirrors and the interferometer were set up. The following steps were the integration of the electrical harness, the gas system, reference laser and the outer walls. Following this, several test campaigns were performed.

Despite some mechanical changes, the main design elements of the IR source remain unchanged from ANITA1: A silicon carbide element is heated by an electric current and serves as a blackbody radiation source. The thermal radiation will interact with the gas molecules in the air to be measured in the gas cell. The relatively low energy efficiency of this source is a trade-off to achieve the very broad bandwidth required (3 to 14µm).


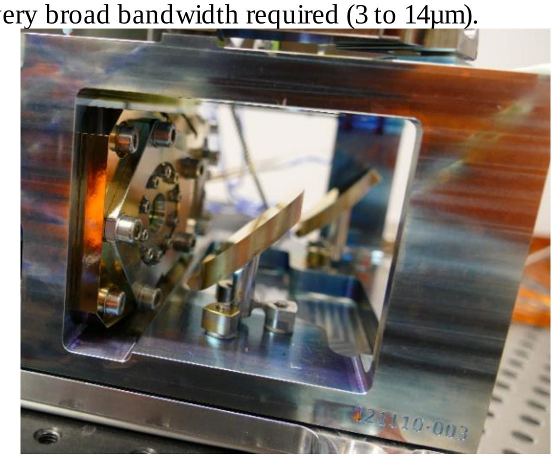
Figure 3: Left: IR-source: Heated u-shaped element and magnified mirror image can be seen. Right: Entrance and exit optics of gas cell including entrance window mounting.

In contrast to ANITA1, the interferometer consists of a pendulum design, featuring wear-, friction-, and lubricant-free movement. The interferometer assembly was designed by the company Bruker GmbH in Ettlingen, Germany and modifieds in cooperation with OHB to withstand the launch loads without impact on the alignment. The interferometer can be seen in Figure 4 as the central element on top of the gas cell. More information about the setup of the interferometer can be found in[14]. The gas cell has a proprietary coating to reduce adsorption of gases to the walls, which gives a blue shiny surface, as can be seen in Figure 4.

Figure 4 also shows the finally aligned optomechanical setup including cables and temperature sensors for the optical sub-system test campaign. The electronics board on the right is the preamplifier for the IR detector. The central element is the interferometer. In this configuration extensive tests were performed, to ensure that the optomechanical system works properly. These tests are important to be performed before the optical compartment walls are mounted, virtually excluding any later changes in alignment. The optical compartment forms an airtight container (N_2 leakage < 1.6 x 10^{-6} scc/sec at 100 kPa pressure difference) using Viton as sealing material, protecting the optical elements from degradation (dust, humidity, …).

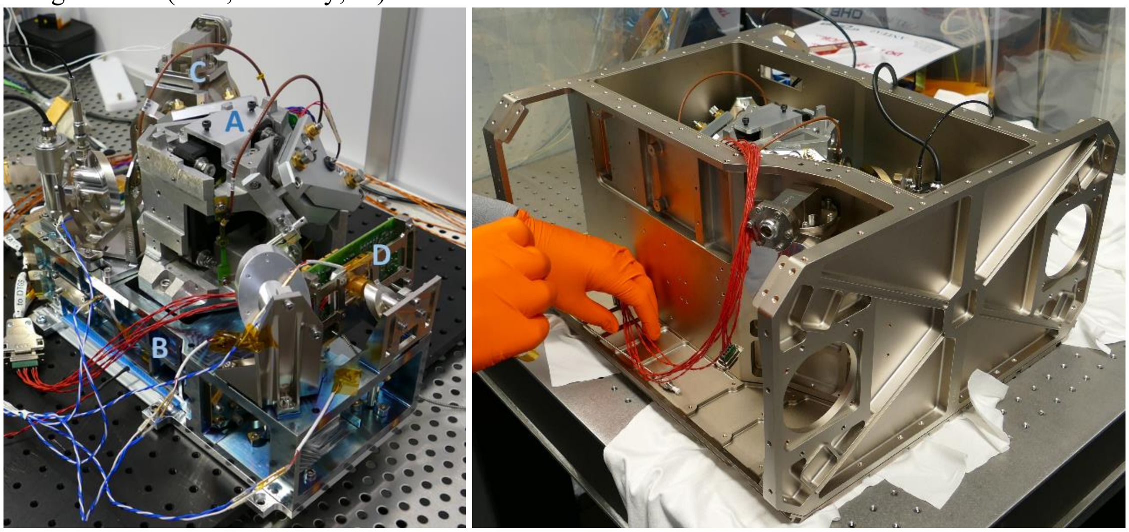

Figure 4: Left: Aligned FM optomechanical sub-assembly (A: Interferometer, B: Gas Cell, C: IR Source, D: IR Detector. Right: optical compartment walls mounted.

To minimise any offgassing, and to ensure a high performance over the lifetime of the instrument, this setup was baked-out at elevated temperatures and low pressure, as offgassing could potentially reduce the sensitivity of the instrument over time.

Figure 5 Left: ANITA2 harness integration. Right: Finally assembled ANITA2 inside a MDL.

The front panel of ANITA2 is divided into 3 accessible areas by the MDL front door. The touch display to control ANITA2 is mounted into the middle section of the MDL front door. In the left-hand section, several LEDs indicate the status of ANITA2.In the right-hand section, the power connector as well as the switches and the gas in- and outlets are located. The inlet is covered by a sintered brass filter to prevent dust entering the gas system. This filter can be removed to attach a gas bag for non-local sampling activities.

V. Flight model testing

A. Optical performance testing including thermal tests

The optical testing of the complete aligned FM instrument took place in normal laboratory environment and in a temperature chamber to assess the impact of variable temperatures.
ANITA2 applies active air cooling with the EXPRESS Rack cooling air ("avionics air") as a heat sink. However, the avionics air temperature can vary between 18.3°C and 29.4°C. This rather large temperature range leads to a similarly large possible temperature range for the ANITA2 instrument.
The investigated optical characteristics included spectral range and resolution, SNR, stability of spectra and line shapes, spectral artefacts, and the impact of variable orientation to assess potential changes due to gravity release in microgravity environment.
A spectrum measured by ANITA2 is shown in Figure 6. As the gas cell was filled with ambient air, significant water vapour and CO_2 signatures can be seen around 1600 and 2300 wavenumbers, respectively (and also around 3750 and 650 wavenumbers, respectively, outside the applied spectral range of about 700 to 3500 wavenumbers). The overall shape of the spectrum is mainly defined by a combination of the spectral emissivity of the IR source, the efficiency of the interferometer, and the coatings and the sensitivity of the detector. The relevant information lies in the spectral features ("lines" and "bands").

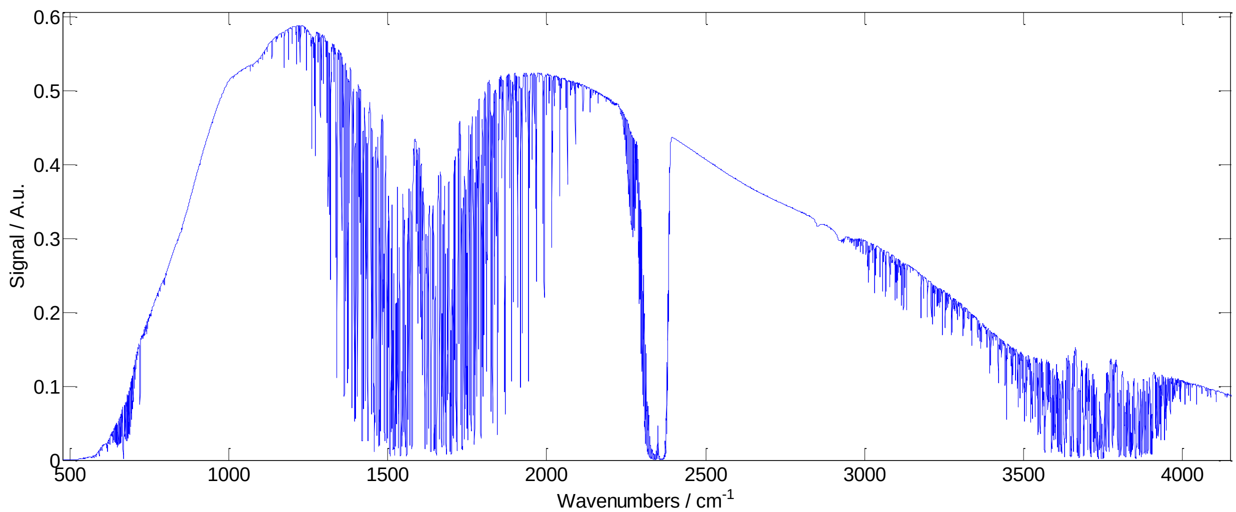

Figure 6: ANITA2 spectrum. The applicable spectral range spans from about 650 to 4400 cm^{-1}, which is 15.5 to 2.3µm.

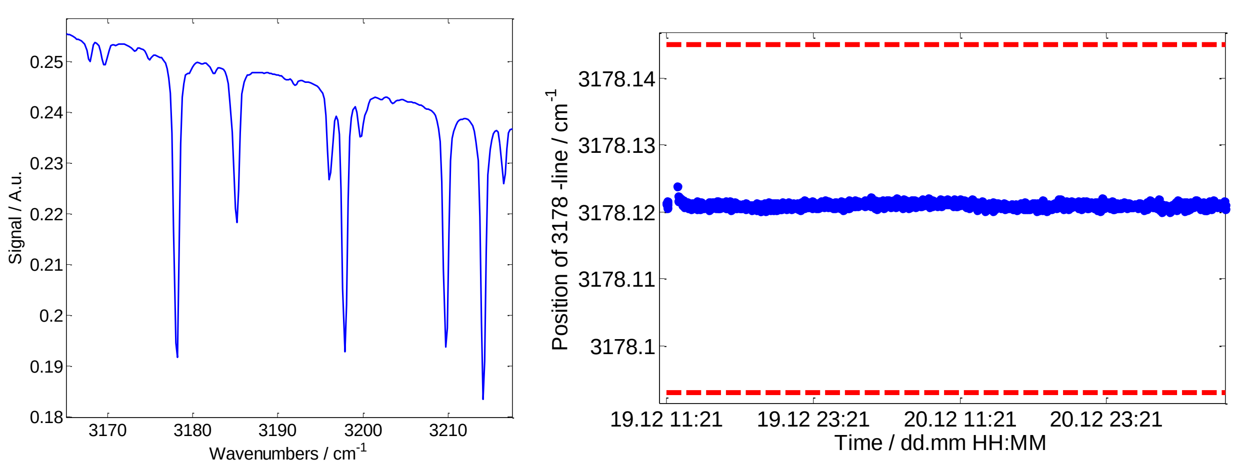

Figure 7: Left: Zoom into Figure 6 showing water vapour lines in more detail. Right: Position stability of one line over time. The red lines show the requirement.

The spectral resolution of the lines is important for measurement on small molecules, as these create narrow lines in the spectra. With a linewidth value (FWHM) of 0.66cm^{-1} e.g. for a water vapour line at 3178cm^{-1} (with triangular apodization in the Fourier transformation calculation), ANITA2 exhibits a very good value. In comparison, the ANITA1 instrument had a value of 1.1cm^{-1} for this water vapour line, which was significantly higher.
The asymmetry of the lines proved to be very low, showing a well-aligned instrument. Much more important than the actual shape of the lines are the stabilities of the shapes and positions. This stability was not equally high over time in ANITA1, so that special software countermeasures were made to maintain the full quality of the gas concentration estimations. For the stability, several line shape parameters were calculated for the complete test campaign and checked for stability.

Table V-1 Overview of Environmental Test Campaign of ANITA-2.

Test	Qualifying	Description	Parameters	Cycles (total time)
Thermal Non Operational	Transportation loads	ANITA-2 is switched off.	-21 to 51°C	1 (~36h)
Thermal Operational	ISS EXPRESS Rack thermal loads	ANITA-2 is recycling sample air and performing measurements every 5 minutes. 41°C is considering a conservative approach considering avionics air supply max. temperatrure, recirculation of warm exhaust air and model uncertainties.	13 to 41°C	3 (~48h)
Vibration	Launch loads	See Table V-2		
EMC	ISS EMC requiremet	Conducted and radiated tests are performed in several setups.	Tailored SSP 57000 rev. S	
Audible Noise	ISS audible noise requirements	ANITA-2 operating in different modes.	Tailored SSP 57000 rev. S	

The thermal tests performed (Table V-1) consisted of a non-operational test with temperature chamber temperatures from -21°C to 51°C and an operational test with temperatures between 13°C and 41°C. The latter temperature range is significantly higher than the air temperature range supplied by the rack (confer above), so the test performed is an extreme worst-case scenario. During the operational testing, continuous measurements were performed, so that changes in the spectra (SNR, Line shape) could be checked, and some results are shown in Figure 8 for two line shape parameters.

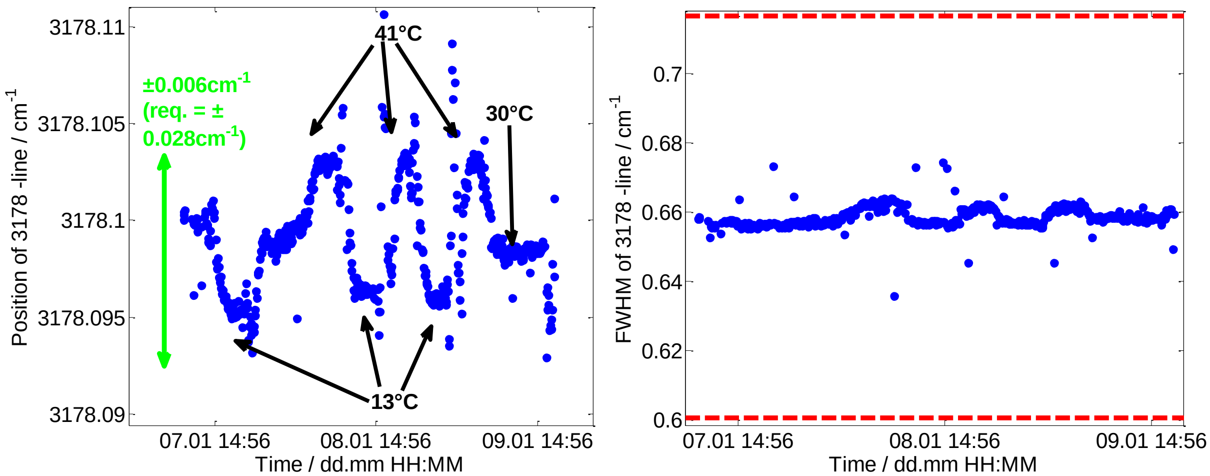

Figure 8: Line shape parameters at temperature testing. Left: Line Position. Right: Full with at half maximum. The red lines show the required stability, where for the line shape it is at ±0,028cm^{-1} and therefore outside the plot ranges.

A small temperature effect can be observed, mainly on the line position. Minor effects can be observed also on other parameters, e.g. the FWHM. Nevertheless, all variations are significantly lower than required for a stable gas measurement. E.g., the variation of line position is a factor of 5 smaller than the requirement, proving the good optical performance of ANITA2.
As all parameters were well within the requirements, the thermal testing was successful.

Another key number of the performance of the instrument is the SNR of the spectra. As there are different ways to define the SNR, the same method for its calculation was chosen as for ANITA1, to be able to compare the values. For this, 2 adjacent measurements with 1 minute measurement time are divided by each other. From this, so-called 100%-line the RMS-noise in the range from 2200 to 2220cm^{-1} is calculated after subtracting a linear fit. The "signal" is derived as the mean value in the respective range. The division of this "signal" by the RMS-noise is then taken as the SNR value. Here the FM gave an excellent average value of 5200, which is significantly higher than values of 3000 to 3600 reported from ANITA1. This change was mainly achieved by an optimized reflectivity of the mirrors inside the gas cell.

After the testing campaign, it can be stated that ANITA2 meets all requirements, so that high quality spectra are recorded, which is a prerequisite for good gas concentration estimation results.

As part of the tests, also a few single gases and gas mixtures were measured. Two examples of single gases diluted in N_2 can be seen in Figure 9.

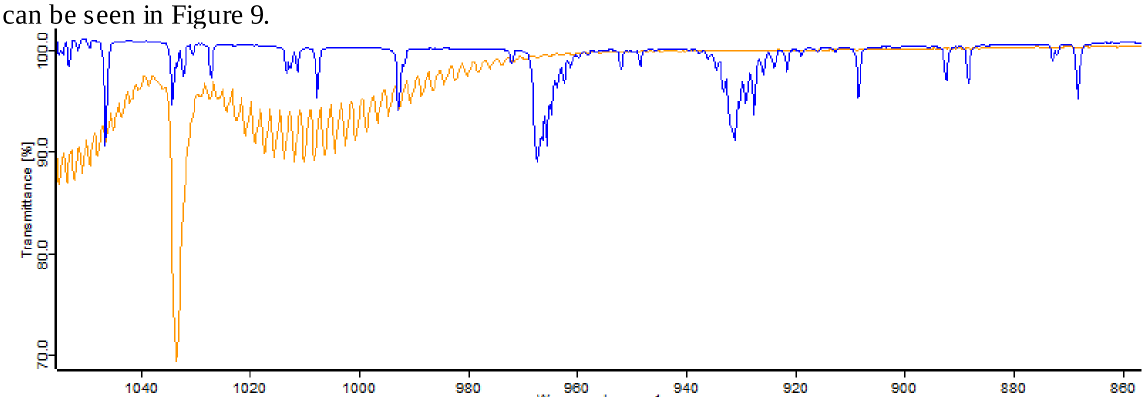

Figure 9: ANITA2 FM spectra from 20ppm methanol (orange) and 6ppm ammonia (blue) in N_2.

B. Vibration Testing

ANITA2 FM has been subject to vibration testing (Table V-1) to show that the optical performance will not be affected by the vibration environment during launch. After each No impact of the vibration environment onto the optics could be observed afterwards, demonstrating the robustness of the system.

Table V-2 Vibration test campaign. Performed in ANITA-2 in launch configuration, packed in foam and cargo transport bag. This sequence is performed once per axis.

Test	Description	Pass / Fail	Loads
Sine Sweep	Sine sweep to find eigenfreuquencies	Application of spec. loads.	0.5g 5-2000Hz
Random Vibration	Envelope of possible launch vehicles.	Application of spec. loads.	6.5grms
Sine Sweep	Sine sweep to find eigenfreuquencies	Frequency shift < 10% compared to before random vibration	0.5g 5-2000Hz
Functional check	Functional Check to verify operation of each subsystem	Unchanged functional and optical (line shape and position) paramters	N/A

C. Audible noise and EMC (electromagnetic compatibility) testing

The audible noise testing was performed in an external test house, where the noise emitted by ANITA2 at different operational conditions was recorded. This is required to ensure that the audible noise environment on board the ISS is not creating an additional source of stress to the astronauts. Therefore, noise limits are very stringent. ANITA2 showed compliance to these requirements using an operation (pump down) concept, which enables ANITA2 to sample new gas every 6 minutes.

Similar to the audible noise testing, the EMC testing was performed to show that on one hand ANITA2 is not susceptible to any electromagnetic (neither conducted nor radiated) perturbation, and on the other hand is not emitting any perturbations which could affect other systems on board. Also here no issues were found, and ANITA2 should be acceptable for the use on board the ISS:

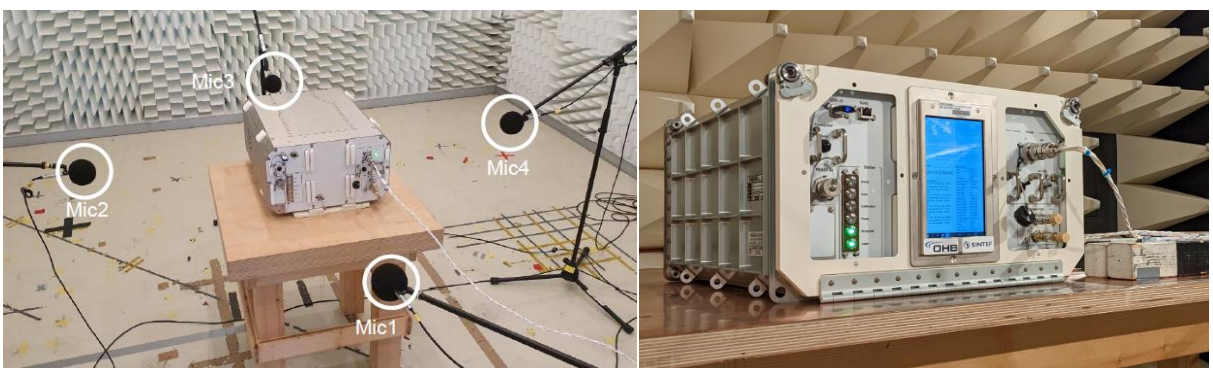

Figure 10: Left: Setup for audible Noise Testing; Right: ANITA2 at EMC test

VI. Next steps

After all testing, the ANITA2 FM will be shipped to SINTEF to perform the gas calibration campaign. This is planned to take about 3 months, so that ANITA2 will be ready for launch in the summer of 2021. The calibration campaign starts with measurements on all gases to be included in the calibration. Then, a system calibration will be constructed, applying simulations, spectral pre-processing, and multivariate analyses[5,7,18]. Finally, the gas measurement performance will be tested through measurements on 30 multi-gas mixtures.

In parallel, the ANITA2 Ground Model will be finalized and tested. Besides being a reference model on ground, the GM can be used to extend the gas list, in case another unexpected gas will be detected by the FM onboard the ISS, like it happened during the ANITA1 mission.

VII. ANITA-X concepts

ANITA2 as a technology demonstrator shall pave the way for more ANITA versions, which could be part of future infrastructure for manned and periodically manned spacecraft. Different missions could call for different varieties of the design.

In a first step, ANITA2 could be modified to become an integral part of the ISS air quality and safety system. The required changes would mostly affect the electronics and software, while the structure and general concept of ANITA2 could remain relatively unchanged.

The advantages of ANITA become even more relevant when looking to long duration missions. ANITA is well suited to be further developed for Gateway, a Moon base, or even Mars. The main differences for these scenarios compared to a mission on-board the ISS would be: I) A strong increase in travel time from Earth. II) A significant increase in cost per mass. III) Increased radiation doses. IV) For some missions, manned, unmanned, as well as a robotic stages of the mission.

ANITA 2 is maintenance free during its mission. Nevertheless, it is allready designed for easy replicability of all possible life limited items having future long duration missions already in mind. Possible items with limited lifetime are (I) the interferometer, (II) the air sampling pump, and (III) the IR source. (I) The interferometer and its bearings are built wear-free, and the enclosed and protected design of the optics prohibits dust and aerosols entering from outside. Therefore, the interferometer can be continuously operational over several years. (II) For the pump, the roughly 100k 2-minute cycles of pump operation required per year are not a major limitation leading also to an expected lifetime in the order greater than 2 years continouse operation. For ANITA-X the pump will be made easily accessible, so that even a robot could perform a possible replacement. (III) The remaining possible life-limiting item is the IR source. OHB is currently operating several IR sources for more than 24 months continuously[18], proofing that with the right operation concept, also this item needs very limited maintenance. This long-time testing also enabled OHB to predict a possible failing IR source well before its actual failure, making it possible to schedule a replacement from observations, preventing any unexpected downtime of the system. Also, the IR source is designed to be replaceable without any special training (no optical adjustment needed).

Another advantage of ANITA is that the calibration is permanent for the specified gas scenario. Therefore, no recalibration is needed throughout its lifetime, unless any new gas should occur unexpectedly. And even then, such a new gas can be automatically detected, allowing the ground support to produce an updated calibration and have it uploaded to ANITA in space (as demonstrated during the ANITA1 operation). This makes ANITA well suited to ensure excellent atmosphere monitoring, even during long absence of astronauts and prior to their arrival.

Since a possible robotic operation of future exploration stations or a time of hibernation is to be expected, it might be possible that the operational air pressure and temperature on-board could vary significantly during the uncrewed periods. The nature of the ANITA measuring principle allows for a calibration according to these changed atmospheric conditions and could simply be set within the ANITA software.

The most challenging aspect will be the increased radiation during exploration missions. Whereas the control unit can be easily replaced with a commercially available radiation-hardened computer, and most of the specially designed electronics for ANITA2 can be modified to withstand these radiation doses, this is not true for the modified COTS interferometer electronics board. The current approach of robustifying an existing COTS interferometer, including its control electronics, will not withstand the radiation doses outside of the geomagnetic field. This is mostly due to the fact that a modification of COTS electronics can be done only to a certain extent. Therefore, OHB and Bruker are pursuing further modifications of the interferometer used for ANITA2, such as the development of control electronics that meet the high requirements for an exploration mission.

The possibly changing ambient requirements throughout the mission duration also requires a change in thermal design. Whereas ANITA2 is air-cooled, this approach might not be suitable for a long duration mission anymore. This is due to the fact that the optical bench needs to be kept at a relatively constant temperature for good optical performance. Using an air-cooled system, a change in air pressure would directly affect the cooling performance of the system. Therefore, ANITA-X would make use of either a cold plate or a water cooling system, depending on which is available from the local infrastructure.

The discussed system changes would prohibit a significant further shrinking of the system in the next step. However, a further reduction in mass would be possible.

VIII. Summary and outlook

After the start of the current ANITA2 project in September 2016, the instrument was designed, and the critical optomechanical elements were built in a flight-like design. An extensive test campaign with this Optical Breadboard was performed, showing a high performance in spectral quality. The process of production, integration and testing of the Flight Model was completed early in 2021.

The successful nearly one-year flight test of ANITA1 on the ISS demonstrated the validity, performance and useful complementarity of this in-situ instrument in closed habitats such as the ISS. ANITA should become a mandatory measurement device for crewed space cabins, owing to its capabilities such as nearly real-time detection of incidents, in-situ measurement of air composition including trace gas dynamics and slow changes in gas concentrations. In addition, ANITA has no consumption except for power, and it produces no waste.

Even with just the functionality of ANITA 1, 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 will work perfectly well for any measurement task within the measurement scenario defined for the calibration. In addition, ANITA's novel method of calibration allows several types of flexibility, including post-launch calibration updating and optimisations. It is also 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.

With the described achievements, the ANITA2 project successfully passed the PDR in 2018, and the CDR in 2019. The ANITA2 technology demonstrator Flight Model assembly was finished 2020, and passed all optical and environmental tests, so that it will be ready for launch to the ISS in the summer of 2021.

The envisioned next generation systems, ANITA-X, are excellent candidates to be integrated in future manned space mission scenarios, including the NASA (Deep Space) Gateway and Moon or Mars bases.

Acknowledgments

Thanks to all the NASA, ESA and DLR colleagues, for their 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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