Air quality monitoring for the International Space Station applicable to aircraft cabins and cockpits

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New multigas measurement technology has been developed as part of and in parallel with a series of projects for the European Space Agency (ESA). Based on well-established Fourier transform infrared (FTIR) spectroscopy and novel calibration and analysis methods, ESA's Analysing Interferometer for Ambient Air (ANITA) system has successfully demonstrated continuous air quality monitoring on the International Space Station (ISS). ANITA performed automatic multigas measurements in quasireal time with high sensitivity, specificity, stability and reliability. The novel analysis techniques are well suited also for general workplace air monitoring, industrial processes and other multicomponent measurement tasks.

Keywords: calibration, infrared spectroscopy, measurement simulation, multigas measurement

1. INTRODUCTION

Ensuring human health and safety is a prime concern in spacecraft as well as in other human-occupied enclosed spaces, including aircraft cabins and cockpits. The air quality is of particular importance. Much as in other closed or semi-closed habitats, sources of air contaminants in spacecraft include off-gassing (from structural materials, electronic equipment etc.), system failures (leaks, overheating, trace gas control system breakthrough etc.), and the crew itself (metabolic products). It is for this reason that ESA has a long-term research and development programme in which SINTEF is developing advanced air quality monitoring technology (calibration and analysis) in co-operation with Kayser–Threde GmbH, Germany (hardware and system). The key technologies employed are FTIR spectroscopy, simulations of the measurement process, and partial least squares (PLS) analysis, a family of multivariate statistical methods applied for calibration. The software includes novel compensation methods for hardware insufficiencies.

ANITA was launched on Space Shuttle STS-118 in August 2007. After installation and start-up in the US laboratory *Destiny* on the ISS in September (Fig. 1), the system successfully monitored the trace gases as well as the background gases water vapour, carbon dioxide and methane in the ISS cabin air until August 2008. ANITA provided considerable new information on the trace gas dynamics in the ISS air; most of the gases had never before been measured with high time resolution. Some gases had never been measured in the ISS air at all. A further improved system, ANITA2, is currently under development, aiming for permanent operation on the ISS. ANITA3 is also a future possibility for space exploration missions.

2. APPROACH TO AIR QUALITY MONITORING

Proper air quality monitoring requires parallel measurements on multiple trace gases in the presence of background gases at higher concentrations, where water vapour and carbon dioxide are most often the most disturbing ones. Any applied measurement technique must handle the basic and normally very difficult problem of avoiding significant cross-sensitivity between the different gas compounds; that is, the estimated concentration of any given gas should not depend on the concentration of any other gas. Many techniques are, in addition, vulnerable to chemical poisoning of the sensor, changing or even destroying it. Other normal drawbacks or inconveniences include the need for system servicing, refilling of consumables, and necessary recalibration. For many types of system, it is also very demanding to implement autonomous system operation, including fully automatic read-out and data evaluation. Another challenge is to obtain a sufficiently short response time. And, few systems have stability and reproducibility good enough to allow detection and analyses of small or slow developments, like increasing leakages or overheating, and the effects of corrective actions.

Optical systems in general make it possible to perform fast and fully automatic measurements, consuming nothing but electric power and producing no waste. Extensive built-in compensations may allow excellent stability and reproducibility as well as the possibility of a calibration stable over extended intervals (years). Optical systems can be very robust towards chemical poisoning, and even towards significant radiation loss owing to possible contamination of exposed optical surfaces. Such optical contamination—by aerosols (including mist/fog), dust, soot or ashes—can be effectively reduced through filtering of sampled air or clean-air flushing of front-end optics.

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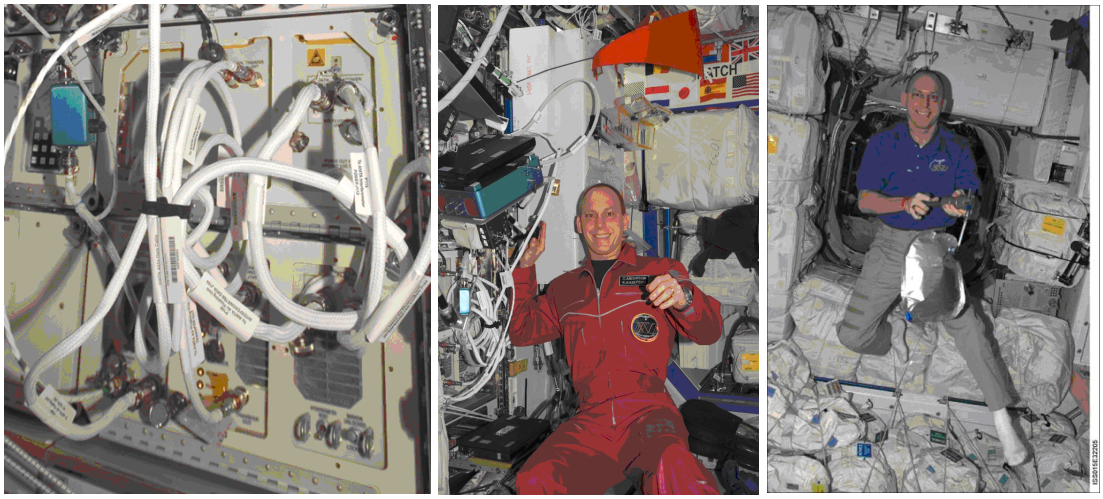

Figure 1. Photographs from the ISS. To the left, a close-up of ANITA in two standard rack inserts, including a rebuilt commercial FTIR instrument. In the middle, ANITA's special flight engineer Clayton Anderson with ANITA close to his right lower arm. To the right, Clay taking a remote air sample with a hand pump (courtesy of NASA).

Many gases with narrow spectral absorption lines, which in practice means gases with very small molecules, can be measured very well individually with laser systems, typically applying one laser for each gas. The key is to find a narrow absorption line for each gas that may not be disturbed by any other gas occurring in the sample. In many cases this is possible in practice, since each narrow absorption line only occupies a very short interval in the IR spectrum.

For multigas measurement, also including larger molecules, it is necessary to survey much broader parts of the optical spectrum. FTIR instruments can collect spectral data with high resolution over a wide spectral range simultaneously, and this very efficient collection of information is combined with excellent spectral stability. FTIR method can resolve details of the characteristic spectra for individual gas compounds (cf. Fig. 2), potentially making gas measurements specific, sensitive and accurate. Also, most gas compounds of interest have unique spectral signatures in the mid-IR region normally covered in FTIR. The few exceptions include gas molecules consisting of two equal atoms (e.g., nitrogen, oxygen, hydrogen) and noble gases (e.g., helium, neon).

However, since the individual gas spectra have highly overlapping spectral features (Fig. 2), measurement of many gases in mixtures with widely variable concentrations is extremely demanding. The complexity of optical multigas measurement required development of novel software for calibration and gas analysis. This software was developed at SINTEF as part of, and in parallel with, the ESA programme [1].

3. ANITA SYSTEM DEVELOPMENT AND TESTING

The measurement task in the ISS air is very demanding. There are more than 30 gas compounds to be monitored. Any combination of the compounds may be present, and each compound may be present in a wide range of concentrations. Many of the compounds may give high optical absorption, distorting or even fully removing potential spectral information, while low or very low detection limits are required even for low-absorbing compounds (typically low ppm [parts per million] or ppb [parts per billion[1]] concentrations).

ESA's research and development programme started with technology selection. FTIR absorption spectrometry was selected as the basic technique, since it had the best potential to fulfil the requirements of simultaneous multicompound detection and continuous air quality analyses.

The initial system development went through two main breadboard phases. Commercial laboratory FTIR instruments were deployed with optimized settings and moderate adaptations. The calibration and analysis software was developed and implemented with augmented abilities and functionality. An important step in proof of the concept was the very successful competitive blind sample testing for the National Aeronautics and Space Administration (NASA) in 2000 [2], in which the ANITA precursor emerged as a clear winner.

The ANITA system for the ISS required that the commercial FTIR instrument be rebuilt to reduce mass and volume and allow operation in microgravity. It is equipped with an automatic sampling system and has a

[1] In this paper, ppb means parts per 10^9 (US convention).

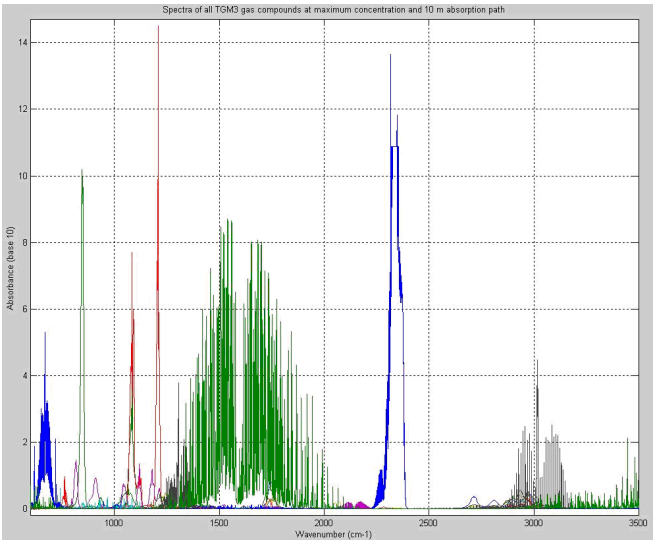

Figure 2A. Infrared spectra for all 30 gases (only 6 different trace colours [colour online]) at maximum concentration in the calibration of the ANITA precursor TGM3 (ESA's Trace Gas Monitoring Phase 3). The optical absorbance is shown as a function of wavenumber (unit cm^{-1}, i.e. the inverse wavelength measured as the number of wavelengths per cm). ANITA covers the spectral range 700–3400 cm^{-1} (3–14 μm). The large multiline absorption bands belong to water vapour (green), carbon dioxide (blue) and methane (black), incidentally demonstrating why these gases are major greenhouse gases. The other strong absorbers are halogenated hydrocarbons like Freons. They exhibit more localized absorption (but are still potent greenhouse gases). The high spectral information content is striking.

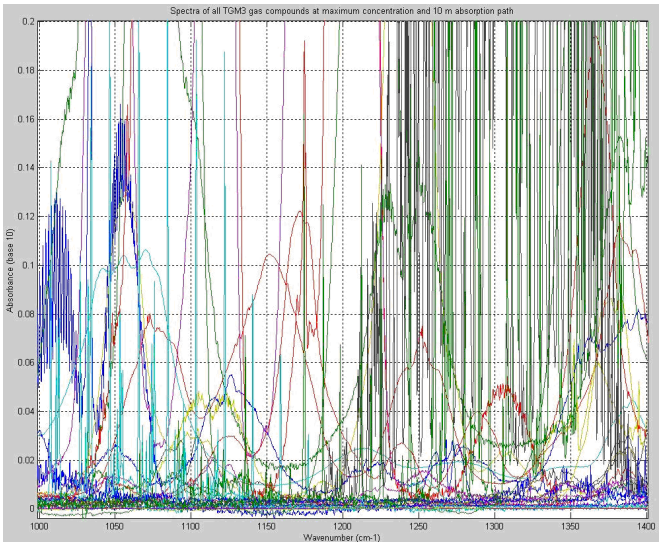

Figure 2B. Expanded view of an important part of the graph in Fig. 2A. The problem of spectral interference seems to be overwhelming, on top of the fact that significant parts of this spectral region cannot be used for gas estimation owing to high absorption from some gases (absorbance > 1 in Fig. 2A). Despite these obstacles, ANITA's combination of good FTIR spectra, proper instrument simulations and advanced statistical analyses enabled the construction of a reliable and sensitive calibration for multigas measurement, making use of numerous spectral data points for gas estimation. Referring to this graph, ANITA can measure gases with a peak absorption amounting to just a very small fraction of the lowest vertical scale division (colour online).

pump downstream from the gas cell. This pump also allows background measurements with very low gas cell pressure. Neither pure nitrogen (in principle available onboard the ISS at no extra cost, since it is needed to replace air lost through leakages and the use of airlocks) nor space vacuum (seemingly abundant in space) could be used for background measurements for reasons of safety, logistics and flexibility in the positioning of ANITA.

The ANITA FTIR instrument comprises a Globar IR source (silicon carbide black body), a helium–neon reference laser, a White gas cell with a 10 m measurement path, a DTGS (deuterated triglycine sulfate) detector (pyroelectric, uncooled), resolution 0.7 cm^{-1} (0.5 cm^{-1} before apodization), applied spectral area 700–3400 cm^{-1} (3–14 μm), and a measurement time of 2 min.

The calibration procedure consists of five main steps:

1. Measurement of one or more reference spectra for each gas compound at accurately known concentration(s) in nitrogen.
2. Realistic simulations of the measurement process, applying the reference spectra and known instrument parameters and behaviour to produce numerous synthetic measurement spectra for calibration.
3. Preprocessing of the synthetic spectra to sort the available spectral information to aid the following statistical analyses.
4. To undertake multivariate linear statistical analyses to produce one optimal linear calibration model for each compound.
5. To establish a table for nonlinear correction for those compounds that give nonlinear spectral response owing to narrow spectral lines that are not fully resolved by the instrument.

The principle of the statistical analyses is "learning by example" (i.e., measurement spectra representing known gas concentrations). Since the measurement spectra have been synthesized through simulations, such a procedure is often denoted a synthetic calibration. In principle, the basis for this learning could be real measurements on accurately produced gas mixtures. However, since hundreds of such mixtures would be required, this would be extremely time-consuming and expensive. Also, even if the gas mixing procedure is excellent, giving believed true gas concentrations very close to reality, the set of gas mixtures would contain noise in the sense of different errors in the believed true gas concentrations. This noise is avoided in the more consistent synthetic data set applied in the synthetic

calibration, and any number of synthetic spectra can be readily produced.

The resulting calibration includes the following attributes:

- Solves the major problems of multigas spectroscopy, viz.
  -Optical spectral interference between gases
  -Spectral baseline drift
  -Optical saturation effects (overhigh spectral absorption)
  -Nonlinear spectral response
- Handles noise optimally, utilizing information from numerous spectral data points.
- The runtime operation is simple, fast, and fully automatic. All complexity is handled in the calibration process.
- The calibration is permanent, unless conditions change beyond the specifications (gas scenario or instrument hardware).
- Easy adaptation by recalibration, even without physical access to the system—also allowing adapted post-event analyses.
- The method may be readily applied to any well-designed FTIR instrument, and adapted to other uses.

In a monitoring task, it is generally advisable to store the measurement spectra. This allows deeper post-event analyses, especially if a problem or interesting event has occurred, or whenever more detailed information is sought. The flexible method of calibration then allows two types of adapted post-event analyses: (1) If an extraordinary gas release has possibly happened (e.g., engine oil breakthrough, fire, overheating, leak event), additional gases may need to be included in the calibration. With an extended calibration, complete, time-resolved post-event air analyses can be undertaken with the originally measured spectra; no physical access to the monitoring system is needed; (2) For closer scrutiny of the air contents in any period of time, a special calibration can be constructed for a gas scenario that just covers the observed variations of the actually occurring gases. The standard calibration must necessarily cover the worst cases of expected air content. Removing nonoccurring gases and reducing the variation span of the remaining gases to the observed levels make an easier gas scenario. Calibration models optimized for the observed gas scenario allow gas measurements with better precision and detection limits, since the calibration models do not need so much built-in robustness with respect to the worst cases.

An automatic air quality monitor like ANITA can give warnings or alarms at predefined levels of gas exposure.

In addition to estimating gases, ANITA's analyses comprise an automatic outlier detection function. Based on all estimated gas concentrations, the properly scaled reference spectra are subtracted from each measured spectrum. The remaining spectral details represent noise and unexplained spectral features. Based on several criteria, the system may give outlier warnings, pinpointing problematic spectral areas and suspicious spectral features. Outlier warnings may be triggered by unexpected gas compounds ("outlier gases") or possible instrument malfunction.

4. PRE-FLIGHT TESTING OF ANITA

The pre-flight testing of ANITA's multigas measurements had three main steps:

1. Synthetic testing: Running of ANITA's calibration on numerous simulated measurement spectra.
2. Gas testing: Running of ANITA's calibration on 30 accurately known multigas mixtures, using a 1 minute measurement time [3].
3. End-to-end testing, from air sampling to automatic air analysis.

The synthetic testing confirms the correct construction of the calibration models, with proper responses to phenomena like spectral interference, measurement noise and spectral baseline drift.

Following the extensive synthetic testing, the much more time-consuming and expensive gas testing could be limited to 30 multigas mixtures. For a gas scenario of 32 gases, including strong spectral influence from the background gases water, carbon dioxide and methane, ANITA exhibited estimated detection limits for the 29 trace gases ranging from 0.003 ppmV to 1.0 ppmV (parts per million referred to volume or number of molecules). Details about ANITA's gas scenario and detection limits can be found in Table 1.

5. ANITA ON THE ISS

After installation on the ISS, ANITA mostly operated fully autonomously, taking air samples locally and making automatic air analyses every 6 minutes [4, 5]. In addition, whenever desired, remote air samples could be taken by a hand pump in a sample bag (Fig. 1, right) and fed to ANITA for automatic analyses. During certain intervals, mostly owing to computer problems not directly related to ANITA, it was not in operation (shown as red interpolation lines in Figs 3 and 4).

Right from the first measurement on the ISS, ANITA gave outlier warnings [5]. Thanks to the automatic enhancement of unexplained spectral features, one feature could easily be identified as a probable unexpected gas, and it was soon further identified as sulfur

Table 1. ANITA's gas scenario and estimated detection limits for a 1 minute measurement time according to the gas testing. The detection limits for the background gases are not important and were not tested for.

	Compound name	Type[a]	CUCL[b] (ppmV)	Estimated[c] detection limit (ppmV)
1	methanol (methyl alcohol)	alcohol	70	0.10
2	ethanol (ethyl alcohol)	alcohol	30	0.3
3	2-propanol (isopropanol, isopropyl alcohol)	alcohol	30	0.5
4	1-butanol (n-butyl alcohol)	alcohol	50	1.0
5	formaldehyde (methanal) (CH_2O)	aldehyde	5	0.10
6	acetaldehyde (ethanal) (CH_3CHO)	aldehyde	30	0.4
7	propionaldehyde (propanal, propyl aldehyde) (CH_3CH_2CHO)	aldehyde	50	0.4
8	butyraldehyde (butanal) ($CH_3(CH_2)_2CHO$)	aldehyde	40	0.3
9	toluene (methyl benzene)	aromatic	6	0.9
10	*meta*-xylene (*meta*-dimethyl benzene)	aromatic	15	0.4
11	*ortho*-xylene (*ortho*-dimethyl benzene)	aromatic	6	0.4
12	*para*-xylene (*para*-dimethyl benzene)	aromatic	20	0.2
13	ethyl benzene	aromatic	20	0.9
14	ethyl acetate ($CH_3COOC_2H_5$)	ester	5	0.3
15	n-butyl acetate ($CH_3COO(CH_2)_3CH_3$, $C_6H_{12}O_2$)	ester	4	0.2
16	dichloromethane (methylene chloride)	halogenated	12	0.3
17	Freon 11 (CCl_3F)	halogenated	2	0.013
18	Freon 12 (CCl_2F_2)	halogenated	1	0.04
19	Halon 1301 (trifluorobromomethane) (CF_3Br)	halogenated	1.25	0.05
20	Freon 113 (CCl_2FCClF_2, $C_2Cl_3F_3$)	halogenated	3	0.05
21	perfluoropropane (octafluoropropane) (C_3F_8)	halogenated	100	0.03
22	hexane (n-)	hyd.	12	0.3
23	acetone (2-propanone, dimethyl ketone) (CH_3COCH_3)	ketone	10	0.4
24	2-butanone (methyl ethyl ketone) ($CH_3COCH_2CH_3$)	ketone	30	0.3
25	hexamethyl cyclo-trisiloxane ($[(CH_3)_2SiO]_3$ in Si-O ring)	siloxane	2	0.003
26	octamethyl cyclo-tetrasiloxane ($[(CH_3)_2SiO]_4$ in Si-O ring)	siloxane	1.2	0.003
27	decamethyl cyclo-pentasiloxane ($[(CH_3)_2SiO]_5$ in Si-O ring)	siloxane	1	0.012
28	ammonia	misc.	4	0.06
29	carbon monoxide	misc.	10	0.05
30	methane	background	500	-
31	carbon dioxide	background	10000	-
32	water	background	25028	-

[a] aromatic = aromatic hydrocarbon; halogenated = halogenated hydrocarbon; hyd. = hydrocarbon; misc. = miscellaneous; background = background gas (always present). [b] CUCL: calibration upper concentration limit (variation span from 0 to CUCL). [c] ISO 95% confidence.

hexafluoride, SF_6.[2] Since this gas only has a rather narrow absorption band in the covered spectral region, it was a good preliminary solution to make a new calibration (on the spot in the control centre) with this band excluded. This gave a new, applicable preliminary calibration for all the expected gases without much interference from the new gas. Initially, the SF_6 could only be roughly estimated by manual analysis of its very characteristic spectral feature. Later, when a proper reference spectrum for SF_6 could be measured on the ANITA ground model, a full calibration for 33 gases was produced, uplinked to the ISS and installed in ANITA without astronaut involvement.

ANITA provided considerable new information on trace gas dynamics in the ISS air, since most of the gases had never before been measured with high time resolution. Some gases had never been measured in the ISS air at all. A good example is perfluoropropane (PFP), which earlier had only been estimated without any measurement. PFP is used in cooling systems on the ISS and in ISS Soyuz spacecraft. Two example curves are shown in Fig. 3 [5, 6].

[2] The sulfur hexafluoride on the ISS originated as a tracer gas in a medical experiment, and it survived all air cleaning actions.

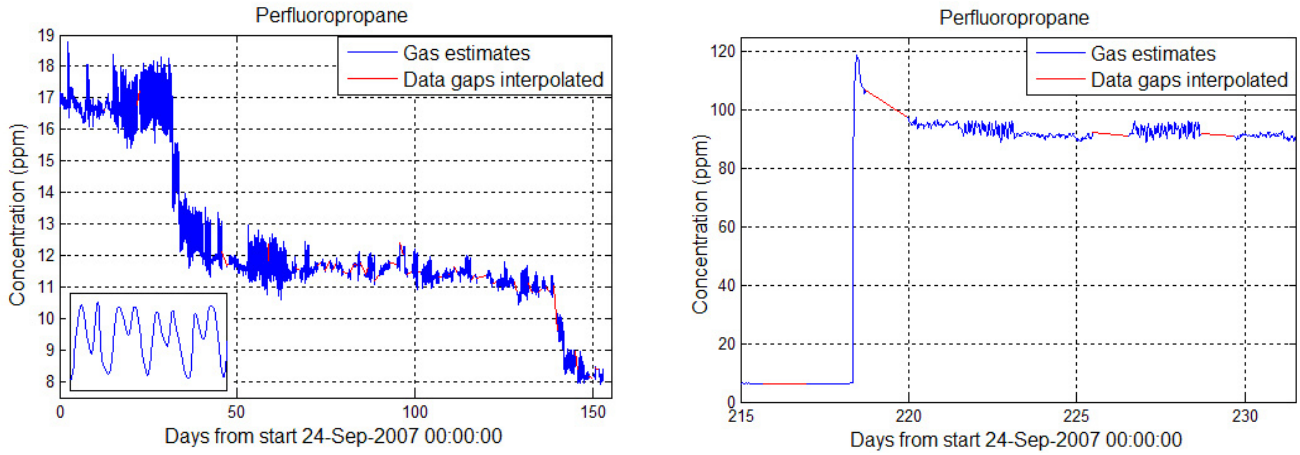

Figure 3. ANITA measurements on PFP (perfluoropropane) in the ISS air (colour online). The left-hand graph shows the first five months of operation. The bands of large variations may look like noise, but are regular oscillations with a full period of 4 hours 49 minutes, and they occur when the US CDRA (Carbon Dioxide Removal Assembly) is running. The oscillations reveal that PFP is temporarily adsorbed and then released back into the ISS air by dual action sorbent beds with somewhat different capacities. A step down in concentration occurs each time ISS exchanges air with PFP-free spacecraft (two Shuttle visits and subsequent opening of new air-filled ISS modules). These PFP steps actually allow calculation of the relative air volumes of the spacecraft and modules. The only increase in PFP occurs from day 19, due to a visit from a PFP-containing ISS Soyuz. The right-hand graph shows 17 days around a PFP leak event 29 April 2008. ANITA could quickly detect and quantify the PFP release and monitor the effects of the clean-up actions. ANITA showed these actions to be ineffective, hence they were abandoned, saving electric power and equipment wear.

Examples for two other gases, carbon monoxide and methane, are shown in Fig. 4 [5, 6]. In a clean and well functioning closed human environment, both gases are mainly produced by humans themselves.

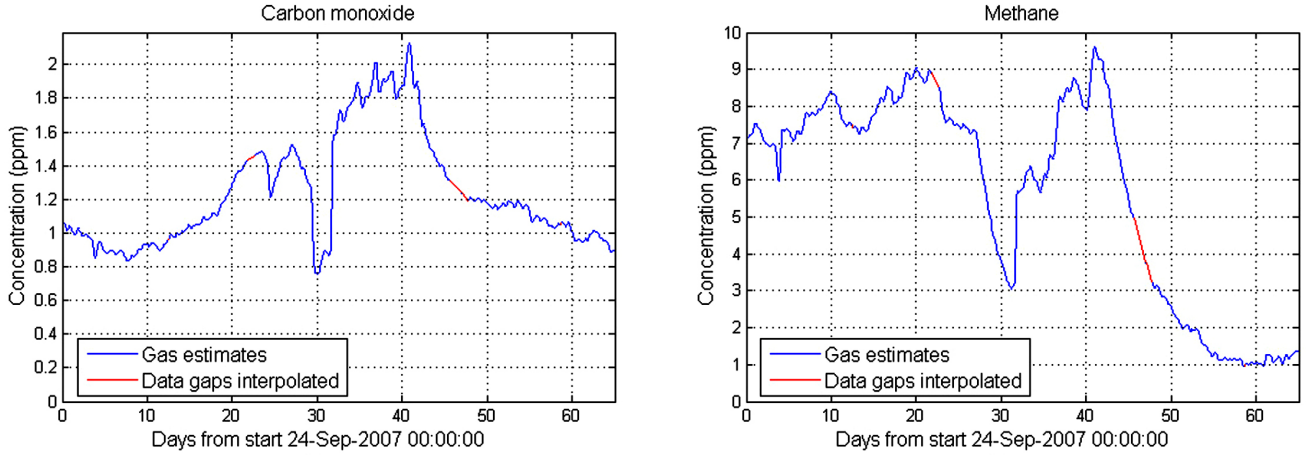

Figure 4. Graphs from ANITA's measurements on carbon monoxide and methane in the ISS air, covering the first two months of operation (colour online). For both gases, the sharpest rise in concentration starts at the same point of time after 31.5 days, when the hatch was opened to a visiting Space Shuttle. After the Shuttle left, the concentrations of both gases were gradually reduced again. This behaviour for these human-produced gases reflects the fact that the Shuttle has a larger crew and a smaller ECLSS (Environmental Control and Life Support System) than the ISS.

Carbon monoxide is a gas of crucial interest for human health. Even when it is clearly below the SMAC (space maximum allowable concentration) value in the ISS air, it is important to keep the concentration low. ANITA's quasireal-time monitoring and time-resolved concentration profiling allows tight control of the situation as well as an overview of any events. Of particular interest is early warning in case of equipment overheating or smouldering fires.

Methane is a completely harmless gas at ppm levels. However, it may be of interest as an indicator of the removal of organic molecules from the ISS cabin air. ANITA's detailed time-resolved measurements on the ISS represented a new source of information.

6. APPLICATION TO AIRCRAFT CABINS AND COCKPITS

An FTIR instrument for use in an aircraft during flight requires special housing and mounting in order to isolate the instrument from vibrations, and a robust construction to minimize the effects of the vibrations that nevertheless reach the instrument.

Virtually all gases that it is reasonable to consider in the context of air pollution can be monitored by an FTIR-based system resembling ANITA. The question is only whether the sensitivity (detection limits) for the gases allow monitoring down to the necessary concentration levels. Currently, there are no specific chemical exposure limits with which airlines must demonstrate compliance *during operation*. There are relevant aircraft design standards, such as the requirement that manufacturers demonstrate that the aircraft systems are designed to provide "enough fresh air to enable crew members to perform their duties without undue discomfort or fatigue" (airworthiness certification standard CS 25.831(a)), and the air must be "free from harmful or hazardous concentrations of gases or vapours" including not more than 5000 ppm carbon dioxide (CO_2) and 50 ppm carbon monoxide (CS 25.831(b)), but these are not operating standards.

The SAE document Aerospace Recommended Practice 4418A [7] is entitled "Procedure for Sampling and Measurement of Engine and APU (Auxiliary Power Unit) Generated Contaminants in Bleed Air Supplies from Aircraft Engines". Of particular interest in that document is a list of marker compounds. Regarding testing of aircraft engine bleed air, it is assumed that if the levels of these marker compounds are within the specifications, then the levels of all other potential engine-generated contaminants will also be within acceptable levels. The document also states that "Acceptable engine-generated contaminant limits are inherently lower than allowable cabin contaminant levels, to ensure that contaminant levels are maintained below maximum allowable levels during aircraft operation."

The list of marker gas compounds with associated exposure limits from ref. 7 are shown in Table 2. It should be noted that these concentration limits are not generally accepted as appropriate limits for a healthy atmosphere in an aircraft. The values are contested on several aspects of their derivation, including old source standards, nonconformity with existing ground-based standards, effects of the lower air pressure in aircraft, single gases *vs* gas mixtures, and passengers (nonworkers) *vs* crew (workers). Nonetheless, this gas list with concentration limits is a relevant starting point for considering techniques for air quality monitoring.

In Table 2, the listed gas concentration limits are compared to sensitivity data for ANITA. Out of the eight listed compounds, we have ANITA or pre-ANITA test data for six compounds in complex (i.e., difficult) gas scenarios. From library spectra of the two remaining gases, acrolein and benzene, we have made comparisions with other gases and estimated expected detection limits for equally complex gas scenarios. Such estimations are always somewhat uncertain, since the detailed positions of features in the gas spectra may have considerable influence on the detection limits, possibly leading to better or poorer detection limits than the typical values that can be estimated through simple spectral observations. However, major spectral interference problems can usually be accounted for. For example, it is obvious that the detection limit for benzene would be much better at low concentrations of carbon dioxide, since benzene could then be measured via a much stronger absorption feature, which is overshadowed by high levels of carbon dioxide. ANITA's expected detection limit for benzene in Table 2 has been estimated on the basis of a rather weak absorption feature, which is unaffected by carbon dioxide (making the benzene measurements fully undisturbed by that gas).

Table 2. Gaseous marker compounds to be sampled and analysed for the bleed air quality test, according to ARP4418A [7]. The first two columns have been taken from Table 1 in ARP4418A: the list of compounds and their concentration limits (maximum recommended allowable engine-generated concentrations above ambient levels at time of test). ANITA's detection limits—tested as well as expected—refer to complex (i.e., difficult) gas scenarios. All stated detection limits except for MEK are from ANITA's gas test results (Table 1). Only acrolein is expected to be difficult to measure at and below the stated limit with a system like ANITA.

Compound	Limit[a] (ppmV)	ANITA det. limit (ppmV)	Comments on measurement with ANITA
Acetaldehyde	10	0.4	
Acrolein	0.2	Not tested	Expected detection limit about 0.4 ppmV
Benzene	1.0	Not tested	Expected det. lim. about 0.3 ppmV with high CO_2 interference
Carbon dioxide	2000	OK	ANITA covered from low conc. to 10000 ppmV on the ISS
Carbon monoxide	12	0.05	
Formaldehyde	0.8	0.1	
Methyl ethyl ketone	200	1	Result from a pre-ANITA system. Not in ANITA's gas scenario.
Toluene	40	0.9	

[a] Maximum allowable concentration, referred back to prEN4618 2004 (*Aerospace Series Aircraft Internal Air Quality Standards, Criteria and Determination Methods*).

The data in Table 2 show that if a system just like ANITA is applied to aircraft engine bleed air quality testing, all marker gases except acrolein can be monitored at and below the stated maximum recommended allowable engine-generated concentrations. ANITA's detection limit for acrolein is uncertain, but quite probably about twice the recommended concentration limit. For most of these marker gases, ANITA's detection limits are far below the recommended concentration limits. This means that ANITA could give detailed information on normal air quality, early warning if any marker compound starts to rise above its normal concentration level, and an alarm about any unhealthy air content. Also, whenever new health considerations and/or improved aircraft technology lead to stricter concentration limits, ANITA could still cover much of the need for air quality measurement.

Carbon monoxide is of particular interest, being a primary candidate for a possible single marker gas. Like in space, this gas is excellent for early warning against many problems, including equipment overheating and smouldering fires. Normally—but not always—this gas is also produced as part of any aircraft engine bleed air contamination from seal breakthrough ("fume event"). The exception occurs if the temperature were too low to give pyrolysis of the leaked engine oil.

The listed concentration limit for carbon monoxide in Table 2 is 240 times ANITA's detection limit. This allows ANITA to produce detailed information about the status of this gas. In addition, it is possible to make a considerably faster measurement cycle with reduced but still useful sensitivity and accuracy. This could reduce the response time from a couple of minutes to a fraction of a minute.

Carbon dioxide, on the other hand, is normally far from critical in itself in terms of human health. E.g. on the ISS, the SMAC (space maximum allowable concentration) is 10 000 ppm, and ANITA periodically measured up to 7000 ppm without anybody having a problem. However, if an ordinary room occupied by people approaches this level of CO_2, the air will be very unpleasant owing to other gases originating from the people. Therefore, the level of CO_2 is a convenient indicator for the efficiency of the ventilation and the resulting air quality regarding gases originating from people. Contrary to this normal situation, selective contaminant removal in the air revitalization systems on the ISS decouples the general air quality from CO_2 concentration.

In addition to normally being an indicator of ventilation efficiency, the concentration of CO_2 can be helpful for sorting out the possible reason for an increase in the concentration of other gases in aircraft. This includes on-ground and in-flight intake of polluted external air, where the CO_2 content can be clearly higher than the global background of 400 ppm in clean air.

With an automatic air quality analyser like ANITA, automatic warnings and alarms can be programmed to be fired based on the levels of individual gases as well as combinations of gases. The criteria for warnings or alarms can include medical as well as technical diagnostic aspects and possibly contain explicit advice on the probable cause of a problem. These criteria will of course depend on whether the air sampling is from the cabin/cockpit or from an upstream point in the ventilation system. Possible use for on-ground engine testing would require different criteria as well as background measurements on the inlet air to reveal the specific contribution from the engine.

FTIR systems in normal set-ups measure almost only the gas phase. For measurement of nongaseous materials in the air, like liquid aerosols (including mist/fog), dust, soot and ashes, additional instrument(s) would be needed. However, aerosol droplets are always liable to exchange material with the gas phase—often at or near equilibrium. An inlet air filter to protect the FTIR gas cell optics will stop aerosol droplets in the first place, but give gradual droplet evaporation. This leads to a slower, delayed response, which could potentially give a correct measure of total droplet exposure during a pollution event.

In addition to the immediate operational use, accumulated data from automatic air quality monitoring in aircraft can be further advantageously exploited. Typical levels and variations of trace gases in the aircraft cabin and cockpit air can be established. Data on aircraft engine performance regarding bleed air quality will become available from real operations, not just under standard on-ground testing régimes using steady-state engine operation, when e.g. oil leaks into the bleed air (potential "fume events") have their lowest probability. Any occurring oil leak event can be documented and related to the aircraft operation. Possibly, specific combinations of flight parameters like power setting changes and aircraft speed can be identified as particularly risky for generating temporary oil leaks. Engine performance can be tracked over time after maintenance and through engine ageing, with potential for adjustment of maintenance intervals or even condition-based maintenance.

With ANITA-type technology, any special event occurring can be further scrutinized through post-event analyses of the stored IR spectra, as described above in §3.

7. CONCLUSION

ANITA has proven its applicability and usefulness as an air quality monitor through operation on the ISS in 2007–2008, when it was flown in an ESA-NASA co-operation.

Development of a further improved system (ANITA2) is ongoing, aiming for permanent operation on the ISS, and possibly an ANITA3 for space exploration missions. The novel analysis techniques are also well suited for general workplace air monitoring, industrial processes and other multicomponent measurement tasks.

For application in aircraft cabins and cockpits, an FTIR-based air monitoring system of ANITA's type can measure most gases of interest, including all the compounds listed in SAE Aerospace Recommended Practice 4418A as marker compounds for aircraft engine bleed air quality testing [7]. The question is only whether the sensitivity (detection limits) for the gases allow monitoring down to the necessary concentration levels. All the listed marker compounds except acrolein can be measured at and below the upper concentration limits for engine bleed air prescribed in ARP4418A.

With an automatic air quality analyser like ANITA, the current values for key gases could be displayed on the flight deck, and automatic warnings and alarms could be fired based on the levels of individual gases as well as combinations of gases. The gas exposure history will be stored, and any occurring special event may be further and subsequently scrutinized to obtain more gas details through post-event analyses of stored IR spectra.

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