

# Instrumentation on commercial aircraft for monitoring the atmospheric composition on a global scale: the IAGOS system, technical overview of ozone and carbon monoxide measurements

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## ABSTRACT

This article presents the In-service Aircraft of a Global Observing System (IAGOS) developed for operations on commercial long-range Airbus aircraft (A330/A340) for monitoring the atmospheric composition. IAGOS is the continuation of the former Measurement of Ozone and water vapour on Airbus In-service airCRAFT (MOZAIC) programme (1994–2014) with five aircraft operated by European airlines over 20 yr. MOZAIC has provided unique scientific database used worldwide by the scientific community. In continuation of MOZAIC, IAGOS aims to equip a fleet up to 20 aircraft around the world and for operations over decades. IAGOS started in July 2011 with the first instruments installed aboard a Lufthansa A340-300, and a total of six aircraft are already in operation. We present the technical aircraft system concept, with basic instruments for O<sub>3</sub>, CO, water vapour and clouds; and optional instruments for measuring either NO<sub>y</sub>, NO<sub>x</sub>, aerosols or CO<sub>2</sub>/CH<sub>4</sub>. In this article, we focus on the O<sub>3</sub> and CO instrumentation while other measurements are or will be described in specific papers. O<sub>3</sub> and CO are measured by optimised but well-known methods such as UV absorption and IR correlation, respectively. We describe the data processing/validation and the data quality control for O<sub>3</sub> and CO. Using the first two overlapping years of MOZAIC/IAGOS, we conclude that IAGOS can be considered as the continuation of MOZAIC with the same data quality of O<sub>3</sub> and CO measurements.

**Keywords:** IAGOS, commercial aircraft, ozone, carbon monoxide, instrumentation

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## 1. Introduction

Global climate change represents the most serious environmental issue facing mankind today, with implications for the global political stability and the global economy. Reliable predictions of the future climate using models are

central and fundamental requirements for determining future mitigation strategies. The use of commercial aircraft allows the collection of highly relevant observations on a scale and in numbers impossible to achieve using research aircraft, and where other measurement methods (e.g. satellites) have technical limitations. Commercial aircraft are considered an ideal platform to record vertical profiles from 0 to 12 km in the troposphere over regions never or poorly sampled by other programmes (e.g. surface

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or radio soundings network). They also allow to extensively sample the region of the atmosphere between 9 and 12 km corresponding to the critical upper troposphere–lower stratosphere (UTLS) region at mid-latitudes, where most of the long-range aircraft are flying, at high horizontal and vertical resolution.

Few projects have used commercial aircraft, there were historical programmes such as the Global Atmospheric Sampling Program in the 1970s (GASP; Falconer and Pratt, 1979), the Measurements of Nitrogen Oxides and Ozone Along Air Routes programme (NOXAR; Brunner et al., 2001) in the 1990s, and still until now, the Comprehensive Observation Network for Trace gases by Airliner project (CONTRAIL; Machida et al., 2008) that is operated since 1993 with carbon dioxide ( $\text{CO}_2$ ), carbon monoxide (CO) and other trace gas measurements on several Boeing aircraft from Japan Airlines. In this context, the In-service Aircraft of a Global Observing System (IAGOS; [www.iagos.org](http://www.iagos.org)) is a new research infrastructure conducting long-term in situ observations, on a global scale and from aircraft of international airlines, of gas atmospheric composition such as ozone ( $\text{O}_3$ ), CO,  $\text{CO}_2$ , nitrogen oxides ( $\text{NO}_y$  and  $\text{NO}_x$ ), water vapour and methane ( $\text{CH}_4$ ), with additional aerosols and cloud particle measurements (Petzold et al., 2015). The IAGOS consortium combines research institutes, universities, national weather services, airline operators and aviation industry. Participating airlines from different continents ensure a global coverage of the network. Scientifically and technologically, IAGOS builds on the experience gained within the former research projects MOZAIC (Measurement of Ozone and water vapour on Airbus In-service airCRAFT;

Marenco et al., 1998 and [www.iagos.fr/mozaic](http://www.iagos.fr/mozaic)) and CARIBIC (Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container; Brenninkmeijer et al., 2007 and [www.caribic-atmospheric.com](http://www.caribic-atmospheric.com)).

Briefly, MOZAIC was initiated in 1993 by European scientists, aircraft manufacturers and airlines to better understand the natural chemical atmospheric composition variability ( $\text{O}_3$  and water vapour as key species for climate and air quality issues) and how it is changing under the influence of human activities, with a particular interest in the aircraft impacts. MOZAIC consisted in automatic and regular measurements, by five long-range passenger airliners, of  $\text{O}_3$  and water vapour since 1994 and CO (as one of the main  $\text{O}_3$  precursors and pollution tracer) since end of 2001. Additional  $\text{NO}_y$  measurements (nitrogen reservoir to further understand the  $\text{O}_3$  budget) was made on one aircraft for 5 yr (2001–2005). A large database of measurements (38 494 flights over 1994–2014, see map in Fig. 1) allows studies of chemical and physical processes in the atmosphere (Nédélec et al., 2005), validations of global chemistry transport models (Stohl et al., 2003) and satellite retrievals along with studies on climatologies and trends (Thouret et al., 1998b).

About 10 yr ago, back in 2004–2005, the historical MOZAIC consortium has started the transition from a ‘three successive phases’ research programme into a research infrastructure preparatory phase with objectives of (1) making a long-term deployment on a 20 aircraft fleet (>20 yr) and (2) making near real-time transmission of data. Therefore, new developments for  $\text{O}_3$  and CO core measurements have then started to propose a combined

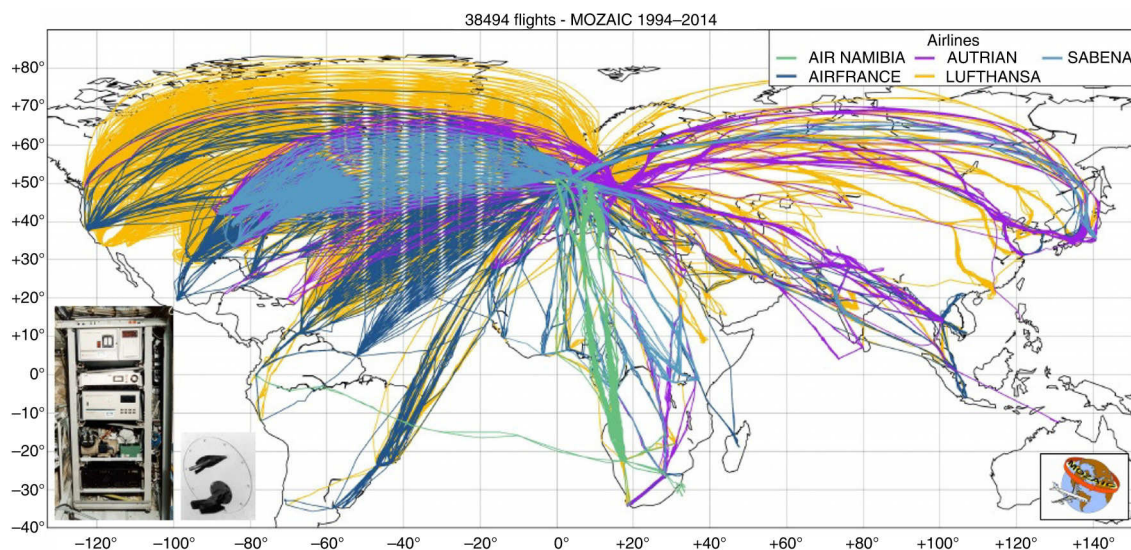


Fig. 1. Map showing the spatial coverage of 38494 MOZAIC flights between 1994 and 2014. Airline names are shown on the top right corner, and the MOZAIC system and Inlet are seen on the bottom left corner.

instrument smaller and lighter to allow more room for additional optional packages (measuring greenhouse gases, nitrogen oxides and aerosols). In the frame of MOZAIC, two different analysers were used to measure  $O_3$  and CO. Design and performances of the  $O_3$  instrument (UV analyser) are described in Thouret et al. (1998a). Design and performances of the CO instrument (IR analyser) are described in Nédélec et al. (2003). Routine IAGOS measurements started in mid-2011 with the first A340 from Lufthansa equipped with the first set of newly developed high-tech instruments for atmospheric gas measurements ( $O_3$ , CO, water vapour) and cloud particles. Five other aircraft have been equipped so far, operated by Air France, China Airlines, Cathay Pacific, Iberia and Lufthansa (two aircraft).

The objective of this article is to present the methodology and performances of this new  $O_3$ –CO instrumentation within the so-called Package1. The other associated instruments such as the water vapour sensor and the cloud droplet detector are described elsewhere (Helten et al., 1998; Beswick et al., 2014; Neis et al., 2014). IAGOS aims to achieve a level of data quality that other measurement methods are unable to attain deploying all over the world identical systems with regular quality assessment procedures, including calibration against reference instruments based on Global Atmospheric Watch (GAW) standard procedures. Therefore, we aim to demonstrate that the longest time series of  $O_3$  (and CO) recorded since 1994 (and 2001) can be considered as uninterrupted using equivalent devices with the same maintenance/calibration procedures and under the responsibility of the same group. Indeed, this makes MOZAIC–IAGOS a unique in situ data set for  $O_3$  trend assessments over already two decades.

## 2. The IAGOS technical concept

With 20 yr of successful operation, the MOZAIC project clearly proved the pertinence of using commercial aircraft for global atmospheric composition monitoring on a routine basis. Therefore, European partners involved such as the Centre National de la Recherche Scientifique (CNRS, France) and Forschungszentrum Jülich (FZJ, Germany) with additional funds from the Sixth Research Framework Programme (FP6) agreed in 2003 to set up the ‘In-service Aircraft for a Global Observing System – Design Study’ (IAGOS-DS) as a development project for new improved and optimised airborne system packages. Finally, the IAGOS technical concept design was achieved in 2009.

The knowledge gained through MOZAIC initiated the designs of a new European Aviation Safety Agency (EASA) certified instrumentation that has to be specifically mounted on in-service aircraft as new aircraft time-optimised production processes make installations almost impossible within a final assembly line. The choice was made to continue with

Airbus A340 and A330 as aircraft carrier for the IAGOS system for several reasons. First, their potential for installing scientific equipment were very well known by the European research team since they served the MOZAIC project for two decades. Secondly, their number representation is large among airlines. Indeed, although Airbus A340, characterised by their outstanding long-range distance capabilities, are no longer commercialised by Airbus since 2010, more than 300 aircraft are still flying worldwide. Moreover, about 1500 Airbus A330 that fulfil the ETOPS (Extended-range Twin-engine Operational Performance Standards) certification have been ordered. And finally, Airbus initiated in 2015 the design of a new A330 generation (A330neo). The latter ensures that the A330 will remain in operation over the next 20 or 30 yr and will be suitable to carry the IAGOS instruments for long-term operation.

### 2.1. IAGOS aircraft instruments

To install and to maintain a scientific instrumentation aboard, commercial aircraft on a long-term basis present challenging issues to solve. First, all the systems involved must fulfil the aeronautic certification rules for aircraft safety. Second, all system operations must be fully automatic with minimal maintenance. Third, the measuring instruments must continuously provide high data quality during operation periods of several months.

Also, the choice of the measured parameters is a compromise between scientific interest, technical possibilities and aircraft operation constraints. Therefore, it was decided to split the overall instrumentation into two packages according to each individual device complexity and operational lifetimes. These packages are briefly described below.

The Package1, developed by CNRS, is the IAGOS central system. It can last 6 months in operation before replacement and it includes the  $O_3$  instrument, the carbon monoxide (CO) instrument, the data acquisition system and the interface that collects aircraft parameters such as position, speed and ambient meteorological data (see Table 1). Associated components to Package1 are the MOZAIC water vapour sensor from FZJ (Helten et al., 1998; Neis et al., 2014) and the University of Manchester Backscatter Cloud Particle probe (BCP; Beswick et al., 2014). After landing, all data are transmitted to the IAGOS receiver station (see Section 3.5). More details on Package1 are provided in Section 3.

The Package2 are optional instruments that can be installed in addition to Package1. The IAGOS project counts four different Package2 types so far. The Package 2 concept focuses on instruments for measuring specific species and properties such as nitrogen-containing compounds ( $NO_x$ ,  $NO_y$ ), greenhouses gases ( $CO_2$ ,  $CH_4$ ) or aerosol particle properties. Details on instruments and

Table 1. Parameters provided by the A340/A330 aircraft system

Names	Units	Precision
Baro altitude <sup>a</sup>	m	0.3
Radio altitude <sup>b</sup>	m	0.1
gps altitude	m	0.1
Latitude/longitude	deg.	0.01
Air pressure	hPa	10
Total air temperature <sup>c</sup>	°C	0.25
Static air temperature <sup>d</sup>	°C	0.25
Aircraft ground speed	m s <sup>-1</sup>	0.1
Aircraft air speed	m s <sup>-1</sup>	0.01
Wind speed <sup>e</sup>	m s <sup>-1</sup>	0.01
Wind direction	(°)	0.01
Meridional wind speed	m s <sup>-1</sup>	0.01
Zonal wind speed	m s <sup>-1</sup>	0.01

<sup>a</sup>The baro altitude is the geopotential height computed from the aircraft static pressure measurements using the International Civil Aviation Organization (ICAO, [www.icao.int](http://www.icao.int)) standard atmospheric profile.

<sup>b</sup>Radio altitude is the altitude above surface, valid only below 2500 m.

<sup>c</sup>Total air temperature (also named stagnation temperature) is measured by a temperature probe mounted in Rosemount housing on the surface of the aircraft.

<sup>d</sup>The Static air temperature is calculated by aircraft computer, using the Mach number and the total air temperature.

<sup>e</sup>Wind speed and direction are calculated by the aircraft Air Data Computer.

possible configurations are given by Petzold et al. (2015). All these instruments are very complex to operate routinely, and their needs of gas calibrations shorten their lifetime before replacement compared with the Package1.

## 2.2. IAGOS system design/architecture

The experience gained during MOZAIC demonstrates that scientific instrumentation can be installed, certified and operated in the avionics compartment of an Airbus aircraft. The system is located on the left side below the cockpit (see Fig. 2), which presents several advantages. First, the space is reserved by Airbus for an optional Ground Refresh Unit (GRU) that is generally not installed by airlines. Second, there is an inlet plate structural provision for the GRU on the fuselage. The latter allowed to install (and later remove) the IAGOS inlets without altering the aircraft structure. This is the major issue for airlines to accept the system aboard. Third, the position is close to the electrical systems, and navigation parameter systems are included. And finally, it is close to the aircraft nose, which presents a thin aerodynamic boundary layer and therefore minimising inlet sizes.

Detailed design and EASA certification of the IAGOS system installation was done by the aeronautic company

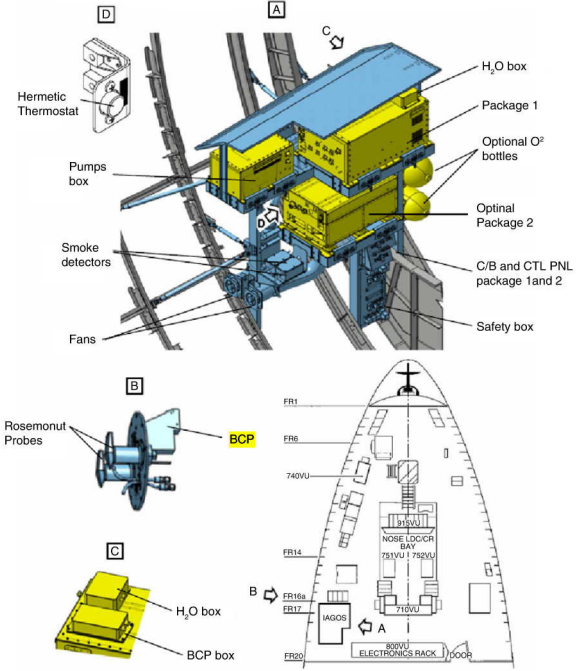


Fig. 2. Scheme of the IAGOS system mounted on an Airbus aircraft (Package1 + Optional Package2).

Sabena Technics Bordeaux, which has all capabilities to make modifications of Airbus aircraft (both A340 and A330). The IAGOS rack is installed in the GRU reserved area either space free or with the device priority removed before installation (it happened only for one China Airlines A340 so far). As Package2 options are designed for reactive gases and particles, it is always located in the rack lower part to shorten tubing lengths from the inlet plate. Package2 compressed gas cylinders, such as O<sub>2</sub> for the nitrogen oxides measurements or calibration gases for the greenhouse gases measurements, are fixed on the rack right side. The Package1 and its connected pump box for air pressurisation are located on the upper shelf. Great efforts were made to obtain a minimal instrumental total payload. The Package1 basic installation weighs about 100 kg and optional Package2 weighs about 60 kg including gas cylinders.

A specific inlet plate (see Fig. 3) was designed and certified to be installed on the fuselage. It contains the following elements: a twining Rosemount temperature sensor and humidity sensor (H<sub>2</sub>O) (Helten et al., 1998), a forward Pitot Teflon-coated tube (1/4 inch and 6.35 mm) as air inlet for the Package1, a BCP optical block window for cloud detections (Beswick et al., 2014), a second Rosemount sensor for the Package2 options, a backward Pitot tube for Package2 air exhaust and a discharge indicator for the Package2 gas supply bottles.



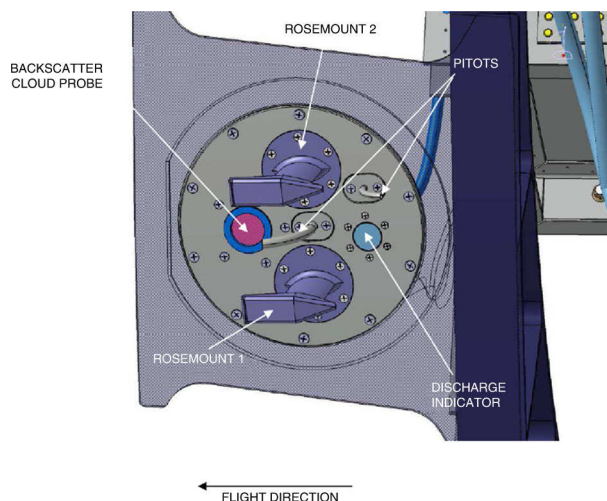


Fig. 3. Scheme of the IAGOS inlet plate fixed to aircraft fuselage.

The IAGOS system starts as soon as the aircraft is powered with no action requested from the airline crew. Power and maintenance panel (comprising circuit breakers), indicators and push-buttons guarantee the system to be safely power supplied and give controls for testing and maintenance operations. A safety box (comprising a set of relays) controls the functioning of each system part that depends on aircraft state configurations (e.g. weight on wheel, engine running, cargo door opened and locked, landing gear up, etc.). The whole IAGOS system is protected from overheating using a thermostat (Fig. 2, D) that stops the system if the avionics compartment temperature is over 45 °C. Cooling fans extract air from Package1, Package2 and the pumps box. IAGOS-specific smoke detectors monitor any smoke or fumes. A dedicated push-button is located on the aircraft cockpit overhead panel and allows powering off the entire system at any time.

### 2.3. System installation on aircraft

The IAGOS system installation is performed on in-service aircraft during layovers (at least 3 weeks) scheduled for inspections or modifications (e.g. cabin seats, passenger entertainment systems, etc.). Two weeks are needed to

mount the whole system with another week dedicated to the functional tests and the certification by the airworthiness authorities. Indeed, even if the equipment have qualified according to aeronautic rules, all aircraft systems have to be checked to make sure that they are not affected by adverse electromagnetic impacts caused by the IAGOS instruments. After completion and approval, the EASA provides a Supplemental Type Certificate (STC) only valid for each individual aircraft. For non-European aircraft, the EASA STC has also to be approved by the local airworthiness authorities before aircraft release into service. At the date of March 2015, six Airbus A340 or A330 have been equipped with the IAGOS system (see Table 2).

Aircraft are then operated by airlines similar to IAGOS non-equipped aircraft without any additional restrictions. Only superficial check-up are periodically requested for aircraft airworthiness such as inlet plate visual inspection or relay functional tests. Instrument replacements (Package1, pump box, H<sub>2</sub>O and BCP) are performed by airlines maintenance staff during scheduled layovers approximately every 6 months or before in case of functional failures detected after reception data analysis.

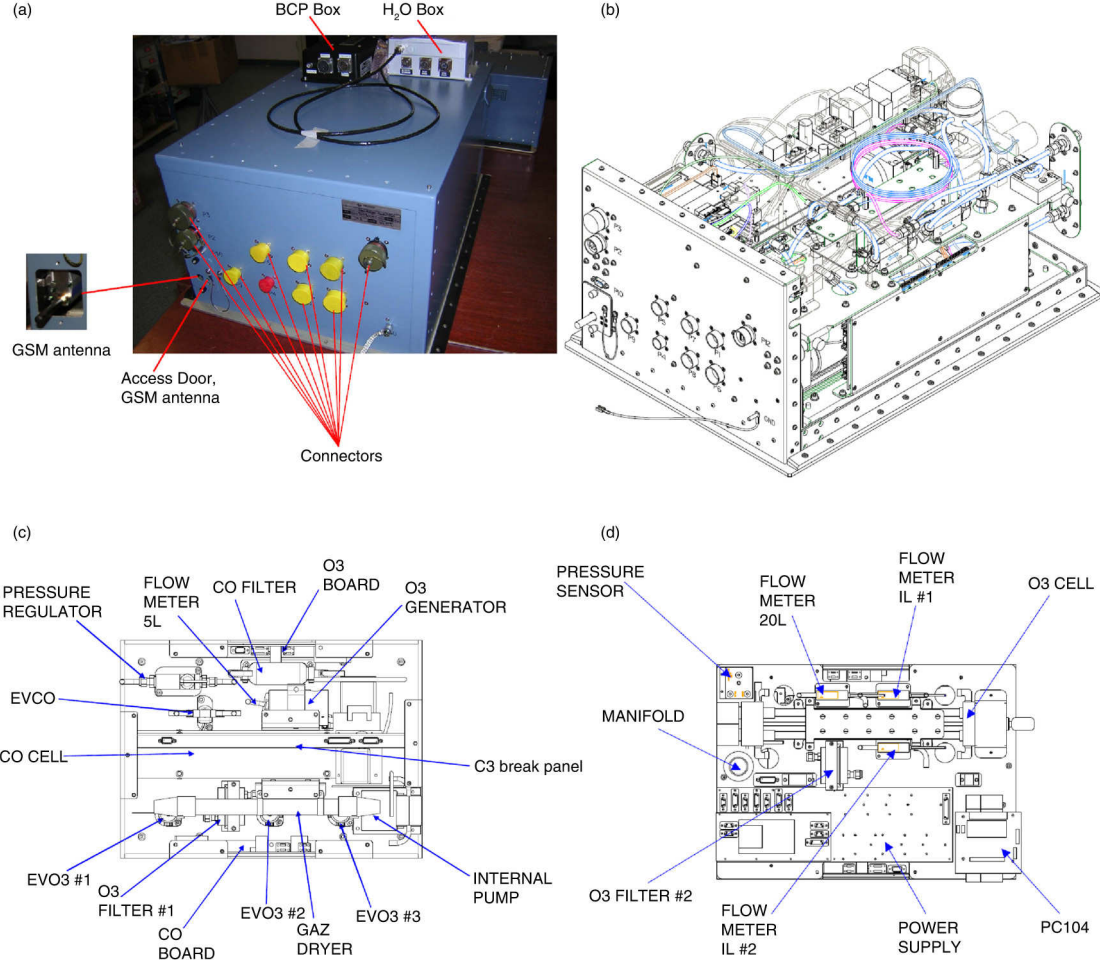
### 3. IAGOS central instrument ‘Package1’

The Package1 was developed by CNRS and was based upon the MOZAIC experience for O<sub>3</sub> and CO routine measurements aboard commercial Airbus aircraft. The objective was to use the same proven technology but optimised in terms of performance, capability, weight, volume and aeronautic standard compliance. Several prototypes have been built and tested both in laboratory and on research aircraft between 2002 and 2007. One of these prototypes is still routinely operated by the French Airborne Environment Research Service ([www.safire.fr](http://www.safire.fr)) on aircraft Falcon20 and ATR42 since 2010.

The detailed Package1 conception, its pump box, its realisation and its qualification for flight acceptance have been subcontracted to an engineering industrial company in Toulouse (LGM Ingenierie). The instruments (Package1, pump box and associated devices H<sub>2</sub>O and BCP) have been qualified to aeronautic certification procedure DO-160

Table 2. Aircraft currently equipped with the IAGOS instruments

Airline	Type	Tail sign	Installed in:	Date
Lufthansa	A340	D-AIGT	Hamburg/Frankfurt	July 2011
China Airlines	A340	B-18806	Taipei	June 2012
Air France	A340	F-GLZU	Paris	June 2013
Cathay Pacific	A330	B-HLR	Xiamen	July 2013
Iberia	A340	EC-GUQ	Tel-Aviv/Madrid	February 2014
Lufthansa	A330	D-AIKO	Malta	March 2015



**Fig. 4.** Package1 picture and schemes. Without H<sub>2</sub>O and BCP boxes, Package1 weighs 35 kg and the dimensions are 630 × 450 × 314 mm. The main elements are listed and described in Table 3. (a) Photo of Package1. BCP box and H<sub>2</sub>O box are fixed on top. The GSM antenna for data transmissions is seen on the connectors face bottom left side. (b) Scheme of Package1 inside. (c) Scheme of the upper shelf viewed from the top. (d) Scheme of the lower shelf viewed from the top.

(tests for vibrations, electromagnetic interferences (EMI), power supply protections, lightning, overheating, etc.). A Package1 description is provided below.

### 3.1. General Package1 layouts

Package1 elements are mounted on two shelves stacked on top of each other and fixed with vertical panels (see Fig. 4b). The block shelves are mounted on shock absorbers inside the cabinet, which is maintained with quick change locks in the IAGOS rack shelf. The external EMI-filtered board connectors (see Fig. 4a) are mounted inside the rear panel. The different main elements are listed and briefly described in Table 3. They can also be seen in Fig. 4c and d.

The Package1 flow diagram is presented in Fig. 5. The pump box (see Section 3.2) pressurises air from outside the aircraft to

in-cabin pressure level at the manifold. The excess air also exhausts at in-cabin pressure and is monitored by a flowmeter at 20 L min<sup>-1</sup> to ensure that the internal pump provides a sufficient flow to the instruments. For weight and volume optimisation, only one internal pump is used for both O<sub>3</sub> and CO measurements at 4 L min<sup>-1</sup> for normal functioning. The latter is not Teflon coated but is located downstream the O<sub>3</sub> air flow path to prevent O<sub>3</sub> destruction. Using adjusted length of 1/8 inch Teflon tubes, a part of the air flow (2 L min<sup>-1</sup>) goes first in the O<sub>3</sub> path and then recombine at 4 L min<sup>-1</sup> into the CO path where it is pressurised to 2 bar. After the pressure regulator, air is sent to the Nafion gas drier as purge gas and is exhausted to the aircraft cabin. For O<sub>3</sub> calibration verifications, the EVO3 #3 is commuted to pass the air flow through the O<sub>3</sub> generator prior to the O<sub>3</sub> measurement path. This step is done to make routinely an O<sub>3</sub> internal calibration check-up.

Table 3. List and description of Package1 subassemblies

Main element	Function and description
Upper shelf	
O <sub>3</sub> device	O <sub>3</sub> absorption cells, UV source, UV detectors (Thermo Scientific for Model 49)
O <sub>3</sub> filter	O <sub>3</sub> filter (MnO <sub>2</sub> ) for O <sub>3</sub> zeroing (Thermo Scientific, PN 14697)
Power supply board	Several protected voltages to the different elements (LGM Ingénierie)
Data acquisition system	4 PC104 cards; Diamond Systems: Athena CPU, Serial ports(Relays Ballard Technology: PM429 for Arinc-429)
PC104	
Flowmeters	CDK FSM series
Manifold	Teflon bottle connected with Teflon tubing (Bioblock 15032)
Pressure sensor	Pressure monitoring of the O <sub>3</sub> cells (Thermo Scientific PN 9877)
Flow controls	Teflon 1/8 inch tubes with length adjusted to provide 2 L min <sup>-1</sup> for O <sub>3</sub> path and 4 L min <sup>-1</sup> for CO path (see blue and pink spiral tubing in Fig. 4b)
Lower shelf	
CO device	CO absorption cell, IR source, IR detector with its thermal regulation card, CO cell motor (Thermo Scientific for Model 48 Trace Level)
Internal pump	KNF and NPK09
O <sub>3</sub> processing board	Control and signal acquisition/processing for O <sub>3</sub> device (LGM Ingénierie)
CO processing board	Control and signal acquisition/processing for CO device (LGM Ingénierie)
O <sub>3</sub> generator	Used for internal O <sub>3</sub> calibration check (Thermo Scientific, FC001)
Air drier	Nafion multitube for drying the air prior to the CO cell (Permapure PD100T-12)
Gas pressure regulator	Pressure regulation (2 bar) in the CO cell (Bronkhorst P702C-GAC-22-V-005A)
O <sub>3</sub> filter	To remove atmospheric O <sub>3</sub> before CO measurements (Thermo Scientific, PN 14697)
CO filter	Sofnocat catalyst from Molecular Products Ltd. filled in Swagelock 304L-HDF4-75-PD (75 cm <sup>3</sup> )
Electrovalves	Three Teflon valves for O <sub>3</sub> (Teqcom), one stainless steel valve for CO (Thermo Scientific, 738)
GSM modem	Worldwide data transmission, four bands Wavecom, Package1 GSM Modem FastRack (evolution planned for 2015 with 3G Modem)

### 3.2. The IAGOS pump box

The Airbus aircraft maximum altitude during a flight is 41 000 feet (12.5 km) where the ambient pressure is 178 hPa. Therefore, to make the measurements, the ambient air has to be driven inside the aircraft and pressurised at

in-cabin standard pressure (about 740 hPa) in high altitude. It is done thanks to the pump box (see Fig. 6) in a similar way as in the previous MOZAIC systems (Thouret et al., 1998a).

The pump box contains two pumps either two Thomas 118ZC20/24 or two Thomas 415ZC36/24. These models

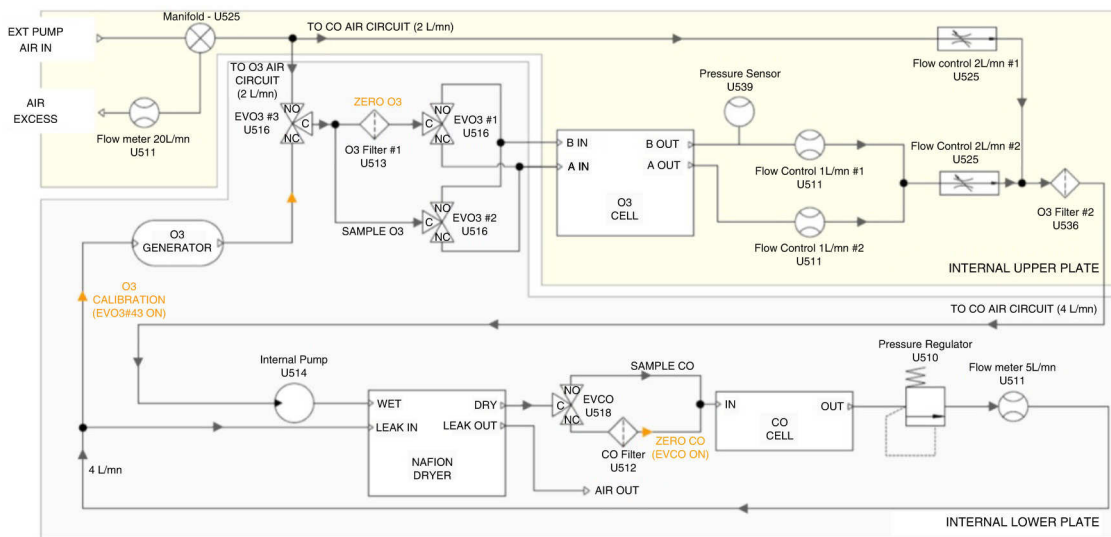


Fig. 5. Packagel air flow diagram within the upper and lower plates.

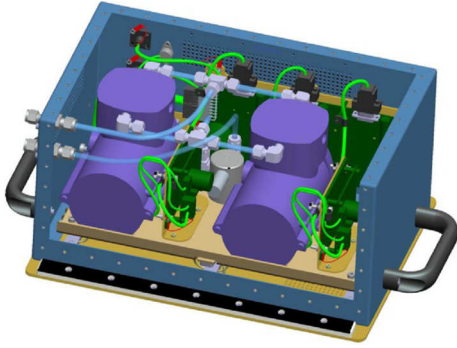


Fig. 6. IAGOS pump box – the box contains two pumps in parallel (see text), the electronic control cards and a Teflon solenoid valve. All tubing are Teflon-coated with a 1/4 inch diameter.

deliver an air flow of  $30 \text{ L min}^{-1}$  at 1013 hPa and  $5 \text{ L min}^{-1}$  at 180 hPa. It is sufficient to provide the Package1 with  $4 \text{ L min}^{-1}$  at maximum altitude. All pump internal parts in contact with sampled air are Teflon coated to avoid  $\text{O}_3$  destruction. As in the MOZAIC system, laboratory tests showed no  $\text{O}_3$  losses within the pumps (Thouret et al., 1998a).

Since one pump is enough to make the measurements, the system daily alternates between the two devices to extend their lifetimes. The pump is started when the aircraft moves position and a Teflon body solenoid valve is commuted to sample cabin air with a particulate filter to prevent polluted airport air to contaminate the inlet lines and the instruments. The valve is commuted to external air during take-off as soon as the aircraft speed is above  $25 \text{ m s}^{-1}$ .

The pump box is connected to the inlet pitot tube (see inlet plate in Fig. 3) and to the Package1 via two stainless steel Teflon-coated hoses (Rotarex Sagana, Serie FX01, internal diameter 6 mm) with a length of, respectively, 1500 and 500 mm. Both hoses are replaced every 2 yr to verify that there is no  $\text{O}_3$  losses due to hose contamination.

### 3.3. $\text{O}_3$ measurements

The IAGOS  $\text{O}_3$  instrument (Table 3) is a standard Model 49 bloc (Thermo Scientific). The latter was also used in the MOZAIC systems (Nédélec et al., 2003), and its main components such as measuring cells, UV source and UV detectors have showed a very good robustness and precision with a 6–12 months lifetime.

The measured  $\text{O}_3$  air flow scheme is presented in Fig. 5. To prevent  $\text{O}_3$  destruction all tubing up to the  $\text{O}_3$  cells are made with Teflon. Air is at cabin pressure and instrument components are located upstream of the internal pump.  $\text{O}_3$  measurements are performed by UV absorption at 254 nm.

Two cells are used, one for ambient air containing  $\text{O}_3$  and the another one with zero  $\text{O}_3$  air (removed by a  $\text{MnO}_2$  filter). The cells are switched every 4 s: 3 s for the air flush and 1 s for the measurements. The pressure is measured in the  $\text{O}_3$  cells to automatically correct the measurements for cabin pressure variations.

The compact  $\text{O}_3$  processing board developed for the Package1 provides concentrations every 4 s using the Beer–Lambert law:

$$\frac{I}{I_0} = e^{-KLC} \quad (1)$$

$K$  is the molecular absorption coefficient ( $308 \text{ cm}^{-1}$  at  $0^\circ\text{C}$  and 1 bar),  $L$  is the cell length (38 cm),  $C$  is the  $\text{O}_3$  concentration in ppmv,  $I$  is the UV radiation measured in air containing  $\text{O}_3$  and  $I_0$  is the UV radiation in air with no  $\text{O}_3$ . As the Airbus A330/A340 aircraft maximum cruise speed is nearly  $250 \text{ ms}^{-1}$ , the Package1  $\text{O}_3$  analyser samples at a horizontal resolution of about 1 km during cruise and a vertical resolution of about 50 m during ascents and descents.  $\text{O}_3$  measurement's total uncertainty is  $\pm 2 \text{ ppbv} \pm 2\%$ . As the same technology used in the MOZAIC systems is used, it combines the Thermo Model 49 uncertainty ( $\pm 2 \text{ ppbv} \pm 1\%$ ) and the Calibration Thermo Model 49PS uncertainty ( $\pm 1\%$ ).

Before and after each Package1 operation period (nominally 6 months), a  $\text{O}_3$  laboratory flight calibration is performed by the CNRS. Package1 is  $\text{O}_3$  calibrated by comparison with a Thermo Scientific Model 49PS reference instrument and for several concentration levels to also check the instrument linearity within 1%. These levels are: 0, 50, 100, 200, 300, 500 and 800 ppbv. The reference instrument is sent twice a year to the French Laboratoire National d'Essais (LNE) for comparison with a National Institute of Standards and Technology (NIST) instrument. The  $\text{O}_3$  cell pressure sensor is also controlled via a reference device.

The Package1 is equipped with an internal  $\text{O}_3$  generator for instrument calibration verifications, which produces concentration levels of 0, 100 and 500 ppbv. This is done on ground and during cruise every 2 h. As the precision of this in-flight calibration (15–20%) is much lower than that of the laboratory calibration precision (2%), it is mainly used as a diagnostic of possible calibration instrument drifts.

### 3.4. $\text{CO}$ measurements

The CO instrument (Table 3) is a standard Model 48 Trace Level (Thermo Scientific) bloc similar to the one found in the MOZAIC system (Nédélec et al., 2003). It was also proved to be very reliable during MOZAIC and suitable for routine operation over at least 6–12 months. However,



the native concentration lower detection threshold given by Thermo Scientific is only 40 ppbv averaged over 30 s. Therefore, we environed the CO cell with all the modifications done for MOZAIC to improve the CO analyser performances. These are a regulated optimised IR detector, the cell pressurisation, air drying and frequent zeroing. All these modifications and validations are fully described in Nédélec et al. (2003).

Schematic for Package1 CO measurements is shown in Fig. 5. CO line and components are located downstream the internal pump. To increase the signal/noise ratio, the CO measurement cell is pressurised to 2 bar by the pressure regulator. The pressure differential also allow air to dry through Nafion tubes.

The CO measurements are performed by IR correlation at 4.67 mm with an optimised IR detector cooled to  $-30^{\circ}\text{C}$  using Peltier elements.  $\text{O}_3$  and water vapour are filtered prior to the measurements preventing any interference with the CO absorption signal. Periodic concentrations zeroing are made by passing air into a Sofnocat filter. It is done continuously on ground, then 10 min after take-off and finally every 20 min or if the Package1 internal temperature varies more than  $1^{\circ}\text{C}$ . This is to ensure that important temperature variations do not alter the instrument zero concentration level.

The compact CO processing board developed for the Package1 calculates concentrations averaged over 30 s using the Beer–Lambert law:

$$T = \frac{I}{I_0} = e^{-\alpha x C} \quad (2)$$

$T$  is the gas light transmittance to the detector,  $x$  is the cell length,  $C$  is the CO concentration in ppm,  $I$  is the IR light intensity after absorption by the CO and  $I_0$  is the IR light intensity at zero CO concentration.

As the same technology used in the previous MOZAIC systems is used, the specifications achieved for a 30-s integration time (instrument response time to flush the absorption cell) are as follows: measurement precision is  $\pm 5$  ppbv CO (signal noise)  $\pm 5\%$  (sum of NIST CO traceable bottle 500 ppm:  $\pm 2\%$ , dilution system:  $\pm 2\%$ , pressure regulator:  $\pm 1\%$ ). The minimum detection limit is 10 ppbv. As the Airbus A330/A340 aircraft maximum cruise speed is nearly  $250\text{ m s}^{-1}$ , the Package1 CO analyser samples at a horizontal resolution of about 7.5 km during cruise and a vertical resolution of about 450 m during ascents and descents. The measurement date is centred within the 30 s of integration time interval.

Similar to the  $\text{O}_3$  instrument, a laboratory CO calibration is performed by the CNRS before and after each flight operation period. The Package1 CO calibration uses NIST referenced CO cylinders (CO in  $\text{N}_2$ , 500 ppmv) and a

dilution system. Calibration is done for several CO levels to also check the linearity of the instrument within 2%. These levels are 0, 250, 500, 750, 1000 and 1500 ppbv. The dilution system is yearly controlled by the French LNE for flowmeters calibration.

### 3.5. Package1 operation

The Package1 operates fully automatically in aircraft. All functions are controlled by the PC104 block using a dedicated software. The PC104 Arinc-429 reception card is connected to the aircraft computer for acquisition only (bus Arinc-429 ADR3 and EFIS3, see parameters list in Table 1) and the data storage is done every 4 s. The Package1 is started when power is available in the aircraft, at least 2 h before take-off, which is a sufficient time for the  $\text{O}_3$  UV lamp to start (about 20 min) and for the instrument to be almost stabilised in temperature. Indeed, it is needed for IR CO measurements, which are very sensitive to the instrument's internal temperature. Pressurisation pumps from the pump box are started before take-off when the aircraft moves from its parking position and are stopped after landing. As one pump is normally sufficient for providing the requested flow in altitude (up to 12.5 km), only one pump is used (alternate every day) to increase pump lifetimes. Data acquisition starts during take-off (ground speed  $>25\text{ m s}^{-1}$ ) and stops after landing (ground speed  $<25\text{ m s}^{-1}$ ). Using 'Landing gear up and locked' and 'Engine 2 oil pressure' analogue aircraft signals, the BCP is started about 1 min after take-off and stopped when landing gear is descended prior to landing. BCP data are recorded via a CPU serial port RS232 and are stored every 4 s.  $\text{H}_2\text{O}$  sensor measurements (Rosemount RH and Air Temperature) are analogue voltages stored every 4 s.

**3.5.1. Data transmission.** Concerning the data transmission, when the aircraft is on ground and uses 'Weight on wheels' and when the Forward cargo door opened', the aircraft analogue signals the Global System for Mobile (GSM) and the Package1 flight data (about 1 Mb for each flight) are transmitted via General Packet Radio Service (GPRS) to the CNRS receiver station. It can take several minutes depending on the airport network quality. When the Package2 is installed (only on Lufthansa aircraft for now), Package2 data are sent first to the Package1 via an Ethernet connection and then transmitted. Due to the possible short duration of the cargo door opening or possible bad GSM network quality, the data transmission is not successfully achieved after each flight (estimation of 30–40% up to now). An evolution of the Package1 is planned for 2015 with a 3G modem, which will ensure a much better transmission rate.

Table 4. Measured parameters stored during flights by the Package1

File Name 'Refvol' is P1 SN	Content	Number of parameter	Frequency
AYYYYYMMDDHHMNSSIN.txt	CO zeroing parameters	8	10–20 min
CYYYYMMDDHHMNSSIN.txt	BCP data	17	4 s
DYYYYMMDDHHMNSSIN.txt	CO module functional parameters	11	1 min
EYYYYMMDDHHMNSSIN.txt	Flight chronological events	2	n/a
HYYYYMMDDHHMNSSIN.txt	H <sub>2</sub> O and T voltages	3	4 s
MYYYYMMDDHHMNSSIN.txt	Aircraft parameters	14	4 s
SYYYYMMDDHHMNSSIN.txt	Pump Box flow	3	1 min
VYYYYMMDDHHMNSSIN.txt	CO measurements	3	1 s
XYYYYMMDDHHMNSSIN.txt	O <sub>3</sub> and pressure measurements	3	4 s
YYYYYMMDDHHMNSSIN.txt	O <sub>3</sub> module functional parameters	11	1 min
ZYYYYMMDDHHMNSSIN.txt	O <sub>3</sub> in-flight calibration levels	9	2 h

YYYY, year; MM, month; DD, day; HHMMSS, hour, minutes, seconds in UTC (take-off time); IN, instrument number (Package1).

**3.5.2. Maintenance.** Since commercial aircraft have to spend a maximum of time in flight, maintenance actions are constrained by scheduled layovers. Maintenance optimisation is an important part of the IAGOS team task and success. The Package1 and the pump box have planend to operate 6 months on-board. This period can be either reduced if a failure occurs in the instrument or can be extended up to 12 months if the instrument works perfectly or if no spare parts are available. To receive a release to service certificate (EASA Form 1), all maintenance tasks must be performed and documented in compliance with predefined procedures set out in the contract between CNRS and the Maintenance Organization responsible for continuous equipment airworthiness. In addition to the Component Maintenance Manual (CMM), which describes all maintenance actions and planning, specific maintenance actions can be performed in case of failure or malfunctioning of any components.

Before going back to operation, the Package1 and pump box are compared in Laboratory with a complete MOZAIC system used as the reference. This MOZAIC rack we use (see photo in Fig. 1) has been removed from aircraft and remounted in laboratory. O<sub>3</sub> and CO comparisons are done during several days before IAGOS instruments are released to service.

#### 4. Data quality control for O<sub>3</sub> and CO

Started in 2011 and planned to operate for decades, the IAGOS programme as a direct continuation of the MOZAIC programme provides high-quality atmospheric data measured aboard commercial Airbus aircraft. The IAGOS instruments for O<sub>3</sub> and CO measurements have been realised with the same technology as MOZAIC and special cares are given to ensure the same data quality control.

#### 4.1. Functional parameters check and flight data visualisation

First, all Package1 and pump box functional parameters (see Table 4) are recorded during flights. These are sent along with O<sub>3</sub> and CO raw data to the CNRS receiver station after each flight. Then, the data files are automatically scanned by the reception software and a technical report file is generated. The latter summarises instrument status during flight and provides a list of errors if parameters were not in the expected ranges (e.g. if internal pump air flow is below 4 L min<sup>-1</sup>, O<sub>3</sub> cells flow, CO signal noise, etc.). It is very important to make sure that the instruments are working properly to guarantee the same performances as MOZAIC (see summary in Table 5) and to anticipate any maintenance.

For each flight, a quick-look is automatically generated to visualise the flight data. An example is shown in Fig. 7. These quick-look pictures display the raw data (without any filters or corrections) to immediately identify any dysfunctioning that directly impact the O<sub>3</sub> and CO measurements. As a critical parameter, the internal pump flow (here in Volts) is shown in green for good functioning and in red if the flow is insufficient. Rosemount humidity (here also

Table 5. Summary of the IAGOS O<sub>3</sub> and CO instrument characteristics

	O <sub>3</sub>	CO
Technique	UV absorption	IR correlation
Noise and integration time	±2 ppbv; 4 s	±5 ppbv; 30 s
Precision	±2%	±5%
Horizontal resolution (cruise speed 250 m s <sup>-1</sup> )	1 km	7.5 km
Vertical resolution (max vertical speed 15 m s <sup>-1</sup> )	max 50 m	max 450 m

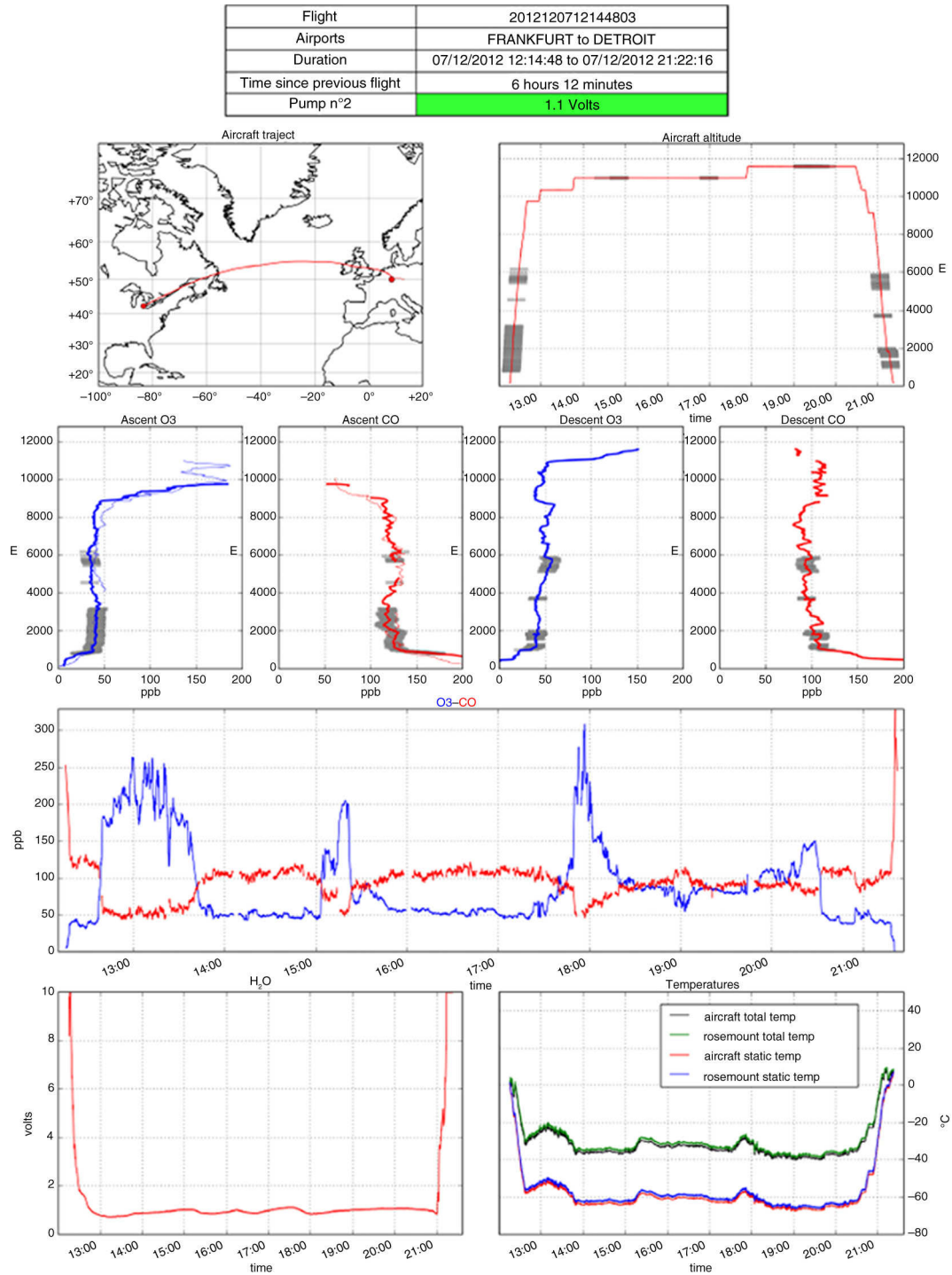


Fig. 7. Quick-look example. On top, flight information and external pump flow check (here displayed in Volts). Graphs of the flight route, flight altitudes, O<sub>3</sub> and CO vertical profiles and time series with clouds detected by the BCP shaded in grey. On the profiles, the thin dash lines represent the profile of the previous flight. On bottom, time series of H<sub>2</sub>O sensor voltage, and the total and static temperatures measured by the aircraft and by H<sub>2</sub>O sensor in its Rosemount housing (raw data not calibrated).

in Volts and it will be calculated later by the FZJ) and temperature measurements are also checked along with the independent aircraft temperature sensor. On ascent pro-

files, the flight data are shown along with the profiles of the previous flight if it landed maximum 8 h before. The latter gives an idea upon the measurements quality consistency.

The quick-look is always sent to the PIs and co-PIs to continuously verify the good functioning of the measurements on a daily basis. It allows to rapidly note any failure and to provide to the airline technical staff the necessary fixing instruction (e.g. system check, instrument replacement). Here, we insist on the fact that the IAGOS team succeed in establishing an efficient communication network between the scientists team and the airlines. Indeed, as MOZAIC over 20 yr, the IAGOS system installation has never caused any delays in the flight schedules.

#### 4.2. Data validation

The data validation by the PI (Philippe Nedelec, CNRS Laboratoire d'Aérodynamique) represents the pass from the L0 raw data to the L1 validated final data (the data processing is fully described in a IAGOS overview paper, Petzold et al., 2015). At the beginning of the IAGOS programme and regarding the large number of data received every day, several attempts were done to automatically filter data points resulting from instrument failures or not resulting from a natural physical processes outside the aircraft. Fully automatic data processing actually reveal to be too complex and almost impossible to achieve efficiently. This is mainly due to the large diversity of issues that can occur to the measurement chain, from sampling inlets to the data reception at CNRS, and the lack of experience on long-term operation with the IAGOS system. Actually, automatic data processing (filtering noisy data) has resulted in losing valid and interesting data. Therefore, it was chosen to manually valid each flight because of our concern in providing users with the best quality data and not losing any data with possible valuable scientific interest. For that, a dedicated graphical-user interface software has been

developed to archive the data according to their level of validation and to easily visualise any system parameter either from the flight itself or from the whole package operation period (6 months time series). The latter allow some actions to correct or remove data that are not valid.

#### 4.3. Flight intercomparisons

IAGOS is currently mounted on six aircraft flying about two or four times a day worldwide. Figure 8 shows a world map with all the airports that have been visited at least one time by a MOZAIC/IAGOS aircraft. Since the beginning of IAGOS, in July 2011, 147 airports have seen a MOZAIC/IAGOS aircraft land and take-off, sometimes several times a day. It has frequently happened that several of the MOZAIC and IAGOS aircraft have land or take-off at the same airport within a time window narrow enough to perform relevant instrument intercomparisons. These flight intercomparisons are automatically generated within the database as soon as at least two flights landed or took off at the same airport in <3 h and are particularly useful to detect any drifts in an instrument functioning. It is also a good way to compare the MOZAIC system performances to the IAGOS system for O<sub>3</sub> and CO measurements during operation.

Figure 9 shows a flight profile intercomparison over Frankfurt on January 10, 2013. Since July 2011, 988 profile intercomparisons are currently available in the database but the example presented in this study was chosen because three different MOZAIC systems are compared with two different IAGOS systems. It also represent data that have been validated by the PI. The intercomparison figures always display tables summarising the flight schedules (see Fig. 9a and b). The flights are always named with the departure

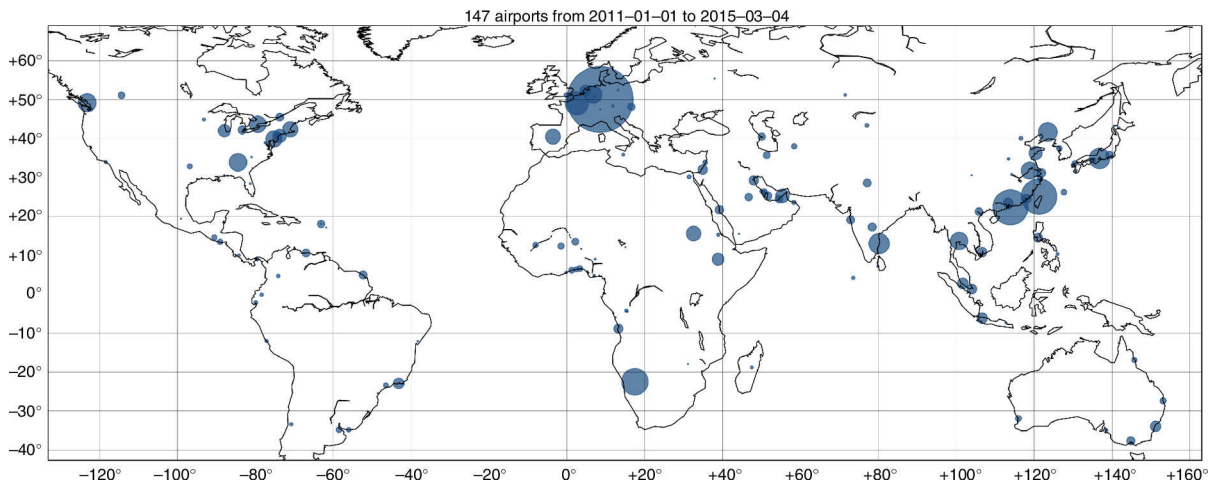


Fig. 8. The combined MOZAIC and IAGOS fleet have landed in more than 147 different airports around the world since July 2011. Symbol sizes are proportional to the total number of landings and takeoffs for a location. Monthly map of flights are available on the IAGOS website ([www.iagos.fr/web](http://www.iagos.fr/web)).



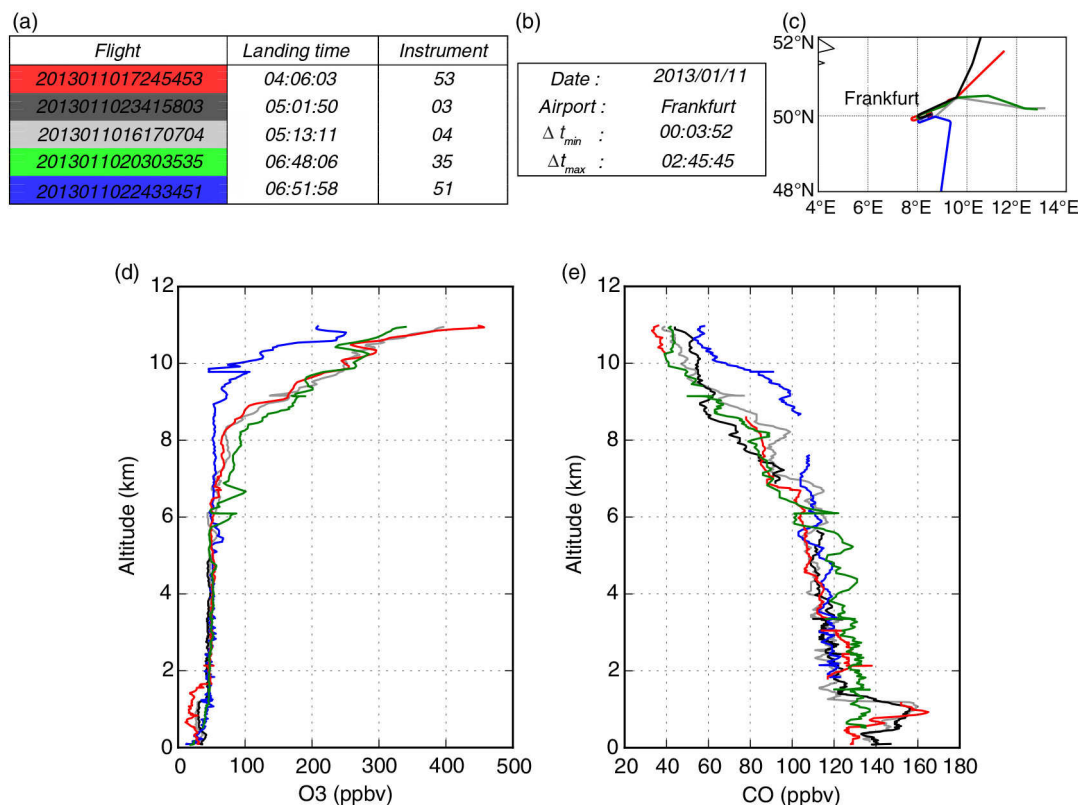


Fig. 9. Examples of flight profile intercomparison automatically made available within the IAGOS database as soon as at least two flights land or take-off within a 3-h time window at the same airport. 53, 35 and 51 are the MOZAIC instruments, and 03 and 04 are the IAGOS instruments. Colours found in the profile plots correspond to the flight in the table on top. (a) Flight landing times at Frankfurt, (b) quick information, (c) routes around Frankfurt, (d) O<sub>3</sub> profile and (e) CO profile.

time and with the last two digits being the instrument number. Here, 53, 35 and 51 are the MOZAIC instruments and 03 and 04 are the IAGOS instruments. Also, Fig. 9b shows the minimum and maximum landing time difference between flights, and Fig. 9c shows the flight descent approach routes to the airport. As it can be seen in Fig. 9d and e, O<sub>3</sub> and CO concentration profiles show very similar values in the lower free troposphere between about 2 and 6 km. It should be noted that measurement uncertainties (see Table 5) were not added to the plot for more clarity. Below 2 km, in the planetary boundary layer (PBL), mixing processes and local pollution impact the profiles greatly and make instrument comparisons less straightforward. It is well emphasised in Fig. 9. The aircraft with the instrument 53, 03 and 04 landed the earliest at night when urban nitrogen oxide concentrations build up into the PBL and cause the O<sub>3</sub> destruction. Peaks of pollutions are well shown on CO concentrations (see red, black and grey curves). These peaks are not seen on the two last profiles (green and blue curves). Indeed, the aircraft mounted with the instrument 35 landed 1 h 35 min after the aircraft with the

instrument 04 and the wind direction changed by 30° at about 1000 m. The aircraft with the instrument 51 landed 7 min after 35 and approached the airport from the south. It may explain why the influence of Frankfurt plumes is less seen on the two profiles. Upper in the troposphere, above 6 km, instrument 51 shows more CO and less O<sub>3</sub> compared with the other instruments. It can be explained regarding the aircraft routes in Fig. 9c, the stratospheric influence being more important in the north.

Figure 10 compiles all available profile intercomparisons between the MOZAIC and IAGOS systems between July 2011 and December 2012. Measurements made after have not been validated yet. It represents scatter plots of 32 and 55 intercomparisons with only PI validated data (L1) for O<sub>3</sub> and CO measurements, respectively. Dashed line is the 1:1 line and shaded area represents the total uncertainties for both MOZAIC and IAGOS instruments (see Table 5). Most of the data points are within uncertainty (93% for O<sub>3</sub> and 81% for CO) and most of the dispersion is due to high CO values and low O<sub>3</sub> values confined in the layer below 1000 m, where local source of pollution can vary greatly in

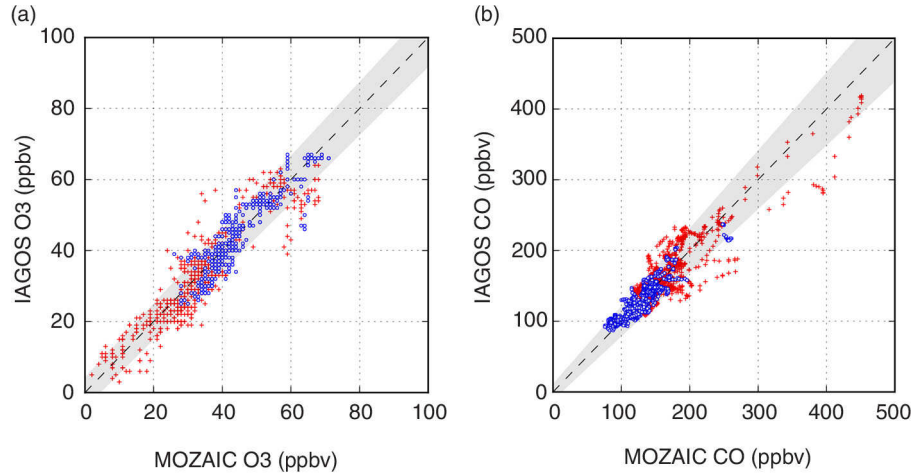


Fig. 10. Flight intercomparison scatterplots between the MOZAIC and the IAGOS instruments for  $O_3$  and CO concentrations measured during ascent and descent profiles. Scatterplots compile 32 and 55 validated (L1) intercomparison profiles, respectively, for (a)  $O_3$  and (b) CO recorded between July 2011 and December 2012. Dashed line is the 1:1 line and the grey shading represents the total instrument uncertainties. Red crosses and blue dots are the data measured below and above 1000 m, respectively.

space and time with CO emissions and the  $O_3$  destruction. For altitudes  $>1000$  m, the root mean square deviations between the MOZAIC and the IAGOS measurements are 4 and 12 ppb for  $O_3$  and CO, respectively. Taking in account the comments made for Fig. 9 about natural variability close to the surface and the upper part of the atmosphere, it can be concluded that the performances of the IAGOS instruments compared with the MOZAIC instruments are excellent.

In the near future, we expect to do the same data analysis for flight intercomparisons for cruising altitudes. For the moment, only 134 intercomparisons have been identified in total, including non-validated data and not enough cases comparing the MOZAIC and the IAGOS systems to be statistically significant. However, an individual example is shown in Fig. 11. The latter presents a flight intercomparison between two aircraft following the same route (between  $38^\circ E$  and  $12^\circ E$ ) with only an 18-min time difference and during more than 2 h at the same altitude. 53 is the MOZAIC instrument and 02 is the IAGOS instrument.  $O_3$  and CO measurements are presented in Fig. 11c and d along with longitudes. As it can be noted, excellent comparisons are made between the historical MOZAIC system and the new IAGOS system as soon as the two aircraft flew at the same altitude.

## 5. Conclusions and perspectives

Routine aircraft observations have provided invaluable information about atmospheric composition and large-scale transport for a long time, helping to improve our understanding of global and regional air quality as well as the potential impact of greenhouse gases on climate change.

Important results using MOZAIC and CARIBIC observations of  $O_3$ , water vapour,  $NO_y$  and CO, looking at their global distributions and trends, have been published. Several of these studies contributed to the recent Task Force on Hemispheric Transport of Air Pollution (TF HTAP, 2010) and the Intergovernmental Panel on Climate Change (IPCC, 2014) report.

Such  $O_3$ –CO combined instrument allows IAGOS to keep its statute of unique programme in the world providing the longest time series of  $O_3$  (and CO) uninterrupted since 1994 (2001). This is of particular value to assess  $O_3$  and CO trends in complement to other networks for reactive gases as reported in a recent GAW paper (Schultz et al., in press). Delivering measurements in near real-time and possibly real-time is also of particular interest for the Copernicus Atmosphere Monitoring Service (CAMS). IAGOS is the only programme for in situ data at global scale in the troposphere and the UTLS (see the use of IAGOS  $O_3$  and CO data in this context; [www.iagos.fr/macc](http://www.iagos.fr/macc)). The Global Monitoring for Environment and Security (GMES) and the Monitoring Atmospheric Composition and Climate projects have made routine uses of MOZAIC–IAGOS data (Elguindi et al., 2010; Ordóñez et al., 2010; Gaudel et al., 2015), which have been particularly useful for independent validation of the products developed in the projects. Their potential for use in data assimilation (either as an ‘anchor’ for bias-correction schemes or in ‘active’ assimilation) has also been explored. The future deployment of a larger fleet (20 aircraft in 2020) of IAGOS-equipped aircraft measuring a wider variety of atmospheric constituents is a very important perspective for CAMS. The near real-time processing and data transmission capabilities of IAGOS will also make it possible to include the

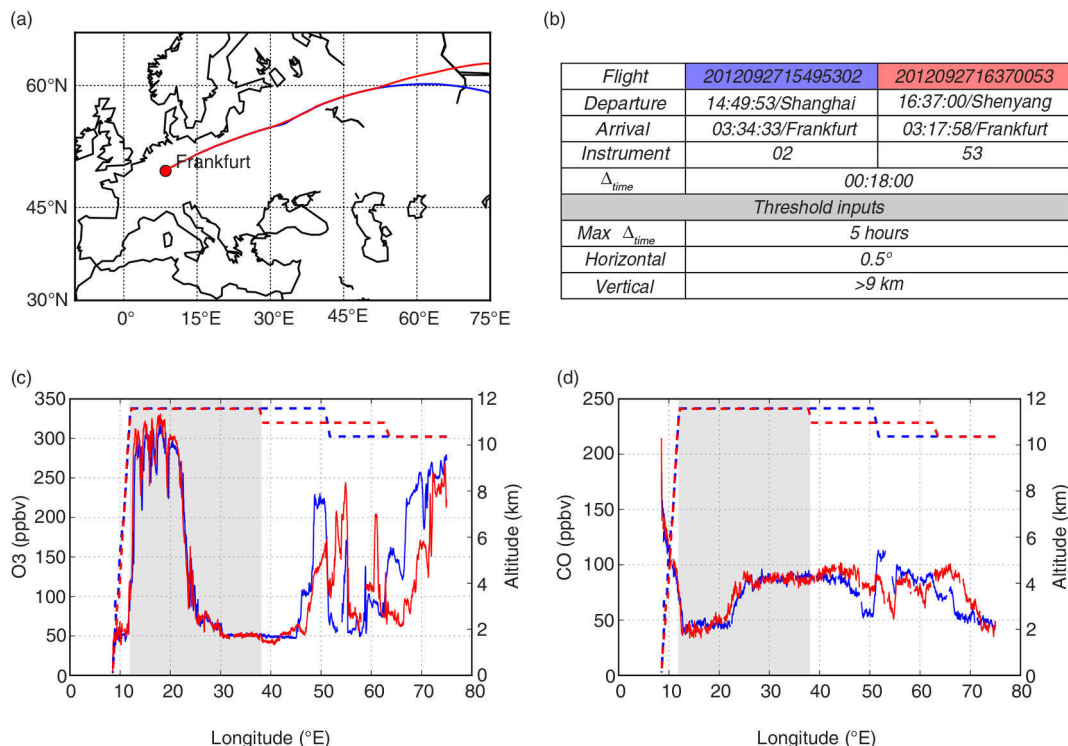


Fig. 11. Example of flight intercomparison at cruising altitudes (>9 km). Plots are automatically made available within the IAGOS database as soon as at least two flights shared the same route distant by <0.5° of latitude/longitude and within in a 5-h time window. (a) Flight routes, (b) flight intercomparison summary table, (c) O<sub>3</sub> and cruising altitude and (d) CO and cruising altitude.

corresponding data stream into operational processing, similar to the aircraft meteorological data relay that is used for numerical weather prediction.

Continued IAGOS operation has been assured through sustainable funding in the framework of international observing strategies such as Global Earth Observation System of Systems and its European component Copernicus, as well as from national funding institutions. IAGOS builds on previous European initiatives using novel technological developments and there is a strong emphasis on expanding the network to cover the Pacific, North America and further into the Southern Hemisphere. Its success relies heavily on the willingness of airlines to support operations.

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