5.7 A SMALL AIRCRAFT FOR MORE THAN JUST OZONE: METAIR'S 'DIMONA' AFTER TEN YEARS OF EVOLVING DEVELOPMENT

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Figure 1: MetAir's 'Dimona' during a mission in the Swiss Alps, Summer 2000 (Foto Joerg M. Hacker). Each underwing pod is containing up to 50 kg of instrumentation (fig. 2 and 3, table 1). Details about the aircraft in table 2.

1. INTRODUCTION

As Crawford et al. (in this issue) are proposing, more and more environmental parameters can be captured by compact sensors, enabling small aircraft as suitable carriers for state-of-the-art sensors (concept SERA: The Small Environmental Research Aircraft).

MetAir has started in 1990 to equip advanced, self launching double-seated motorgliders with long endurance with a variety of meteorological and chemical sensors.

It was possible to equip and certify two aircraft** with large underwing pods. In each of the two pods, 50 kg of equipment can be flown in a basically undisturbed environment. Up to another 30 kg can be carried in the fuselage.

Motorgliders, especially TMG's (touring motor gliders, a new, international JAR-category), have the following advantages:

- engine safety and endurance as high or higher as in regular single-engine aircraft (todays TMG-engines have double ignition, etc.);
- passive safety due to high aerodynamic performance (i.e. glide ratios of around 1:30 when engine is off);
- both high top altitude and save low level flights;
- low fuel consumption (15 to 20 litres/h with cruising speeds of 150 to 200 km/h);
- relatively high payload, especially with extended certification, which was possible for both the 'Stemme', and the 'Dimona';
- low noise emission;
- composite structure;
- ease of certification of modifications;

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** From 1991 to 1998, we operated the motorglider 'Stemme S-10'. After this, a similar type of motorglider ('ECO-Dimona' was equipped and is described here. Both aircraft can be viewed at http://www.metair.ch.

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On the other hand, the disadvantages (maximum of two persons on board, no IFR-operation and no night-VFR) are not important for many applications. However, they have to be considered, and in some cases, IFR in isolated clouds, occasional night-VFR in dedicated areas might be permitted by the local authorities.

Within these limits of operation, MetAir succeeded in the last ten years in as many as 30 international field experiments dealing primarily with urban plumes, and vertical air mass transport in Alpine valleys. In the following, we give an overview on the development of the instruments, and the relevant performances of the aircraft.

2. INSTRUMENTATION

The term 'evolving' in the title is true, because the system was developed in a step-by-step manner: Based on a first instrumentation package, we added new sensors; whenever possible backed up by the redundancy of the old system. After a while, the redundancy could be canceled in favor of a new system which gave way to another interesting parameter. Other sensors in the versatile system can be interchanged for different scientific purposes.

With these steps, we reached the following state of instrumentation in summer 2000 (table 1).

parameter or device	resol.	type of instrument or method
IN FUSELAGE		
position (x,y,z) and ground speed (vx, vy, vz)	2 s	GPS TANS Vector
attitude (azimut, pitch, and roll)	5 Hz	do.
height above ground	1 s	radar altimeter TERRA
3-d-wind (x,y,z)	10 Hz	post flight processing from attitude, flow angles, etc.
slow, but, precise ozone (fast see Ox below)	8 s	PSI UV-photometer with intake via right wing
fast data logging (oversampling at 100 Hz)	10 Hz	PC/104 with I/O cards, storage on hard disk
slow data logging (8 s) for housekeeping param.	8 s	ELSYS-logger, storage on memory card
fast data display		color screen in left side instrument panel
GPS data display and recording		dedicated notebook behind the crew
Gaschromatography control, display and record.		dedicated notebook with the operator on right seat
vacuum for CO-monitor		Vacuubrand MD-1 with 1/2"-PFA-tubing to left pod
IN LEFT POD (figure 2)		
flow angles, true airspeed, and pressure altitude	10 Hz	capacitive pressure sensors, calculated (p,T,u)
acceleration (vert.+long.)	10 Hz	Kistler/DLR
air temperature	10 Hz	Meteolabor fine thermocouple (rec. fact. about 1.0)
dewpoint	1 s	Meteolabor dewpoint mirror
aerosols (>0.3 and >0.5 μm)	1 s	MetOne laser particle counter
nitrogen oxides: NO_2, NOx, NOy, HNO_3, PAN	1 s	MetAir/PSI-NOxTOy: 6-channel Luminol-detector with CrO_3- and Mo-converters with controlled heating
Ox (O_3+NO_2); Ox-NO_2 is a fast response O_3	1 s	do.; 6th channel with NO-injection for titration
CO	10 Hz	Aerolaser AL-5003 (vacuum UV-fluorescence), incl. gas supply (CO_2 in Ar, and N_2)
CO_2 and H_2O (see also right pod, LICOR)	20 Hz	NOAA-IRGA (open path IR-absorption)
IN RIGHT POD (figure 3)		
speciated hydrocarbons (C4..C10)	10 min.	Gaschromatograph Airmotec HC-1010, incl. gas supply (H_2, and CO_2), and pumps
CO_2 and H_2O (see also left pod, IRGA)	5 Hz	LICOR-6262 (closed cell IR-absorption)
OPTIONAL, INTERCHANGEABLE WITH ABOVE INSTRUMENTS		
Peroxides (H_2O_2 and organic)	10 s	Aerolaser (enzymatic fluorometry)
Formaldehyde (HCHO)	10 s	IFU/PSI (Hantzsch reaction, fluorometry)
aerosols (>10 nm)	1 s	TSI condensation particle counter
SO_2	1 s	FIAMS, Adelaide (Luminol with H_2O_2)
automatic sampling units for VOC's, and for SF_6, or other tracers	on demand	steel canisters/metal bellow pump with fully automated purge/fill-cycle, or just PE-bags
IR-scanner for thermography		AGEMA / University of Bâle, Switzerland

Table 1: Current equipment of MetAir's Dimona and its distribution to the different instrument locations. The instruments are belonging to the co-operation partners FZJ, and PSI (see authors list).

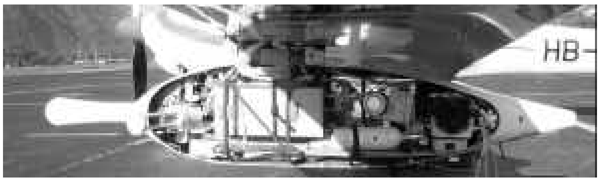

Figure 2: Left instrument pod with 5-hole gust probe with integrated pressure sensors in the nose-boom. Just behind the boom, the IRGA is visible, then the CO-monitor and the NOxTOy with external peristaltic pump and NOy-converter at the rear. All the rest listed in table 1 is in between.

Another type of redundancy lies in the split between slow and fast sensors. For many parameters, we have a pair of sensors/monitors from which one is fast, but, not very accurate, and another one which is accurate, but, has less temporal resolution. Such pairs, e.g., are:

- Ox and O_3 from photometer
- CO_2 with IRGA and LICOR
- H_2O with IRGA, LICOR, and dewpoint mirror
- redundancy for nitrogen oxides

The combination between the signals is done by linear regression within time intervals between 5 minutes and a whole flight.

Also the loggers are redundant; some parameters are recorded on both.

2.1 *Some individual instruments*

Ozone: The compact single cell UV-photometer with cycle time of 2 seconds between zero- and sampling-air is based on a Monitorlabs instrument, but, was highly modified at PSI. It is in operation since 1990 and always showed very stable and accurate response in QA/QC-exercises. It's temporal resolution is not equal to the cycling time, because it needs some averaging (about 10 seconds). A higher temporal resolution (1..5 Hz) is achieved when combined with the (Ox-NO_2)-signal.

Nitrogen oxides: Five reactive nitrogen oxides and Ox (O_3+NO_2) are measured with a parallel 6-channel Luminol-detector developed by PSI, and MetAir (Dommen et al., 1999). NO_2 is directly measured. NOx is converted to NO_2 by CrO_3 at ambient temperature. NOy is converted to NO by Mo at 350°C (with and without HNO_3 in two separate channels), then NO to NO_2 by CrO_3. PAN+NOx goes via CrO_3, and an oven at 125°C. Ox is titrated by adding 2 ml/min of 500 ppm NO in N_2 to the intake. The special design of the measuring cells allow low airflow, hence, small converters and pumps. The complete instrument including NO-cartridge weighs less than 10 kg.

VOC's: The airmotec HC-1010 gaschromatograph is a commercial instrument which was adapted to airborne operation, e.g. by minimizing the sampling time to 10 minutes, and miniaturizing the externals (gas bottles, valves, pumps). It is important, that the GC is stored and operated in clean environments, since diffusion into the column is a problem (not only contamination via the intake). An operation of the GC in a fuselage of an aircraft might be difficult by two reasons: (i) because of contamination problems; (ii) because of safety problems with the H_2. Both are avoided by carrying the whole system in the well-ventilated underwing pod and by having developed special operations procedures. The GC and its chromatograms are supervised throughout the flight by the operator.

Figure 3: Right instrument pod with gas chromatography system including pressurized gas for operation (H_2 as carrier gas, CO_2 to cool the cryo-trap). Behind: The LICOR as redundant CO_2/H_2O-instrument (closed system, with intake away from CO_2-exhaust of GC). Construction detail: The steel frame in the pod is supporting all installations; also the rest of the cover can be removed in a minute. On top, cabling and tubing is entering a 2" flexible aluminum tube which leads via the wing into the fuselage.

CO: Also this instrument is a commercially available monitor modified for our operations. It is both very accurate (1 ppb), and fast (10 Hz). Modifications: (i) it is a 'bare-bone' version, and (ii), like for the GC, externals are minimized. According to other operators of the 'same' system, they need a total of about 60 kg for monitor, pump, and gas bottles. We are using a 4-stage membrane pump (4.5 kg) which became available only this year, and we proved, that gas quality from 1-liter/12-bar-cartridges with a total mass of 200 g is sufficient. Flows could be reduced to meet the endurance of >5 h. Including the pump, which sits in the fuselage and sucks via a 5 m long 1/2" PFA-tube, the system has a mass of less than 20 kg.

2.2. *Electrical system*

The primary power for the instrumentation is 28 VDC from a dedicated 1-kW-generator, which is buffered by a 26 Ah lead accumulator. This power system is completely independent from the aircraft's main power (12 VDC from a separate generator/accumulator for engine startup, engine electronics, and avionics). This separation avoids any conflict between the two systems, and allows startup without any interrupt in the instruments power circuit. We can maintain continuous day and night operation of the instrumentation by leaving the GPU (ground power unit) connected (disconnected after engine startup, and connected after parking with idling engine). With a total load of about 17 A when all instruments are running, both airborne and ground operation of up to 1 h are possible from the accumulator.

For some 12-VCD-consumers, DC/DC-converters for 250 W are installed, and up to 300 W 230 VAC are available for other instruments, e.g. the GC.

The power is distributed via three main switches/fuses in the cockpit panel for left and right pod, and fuselage. Within these three circuits, finer distribution is done via additional fuses to the individual instruments (not reachable during flight).

2.3. *Data acquisition and processing*

As described above (table 1), the data acquisition is done by three independent PC's, and a 'black box': The backbone is a PC/104 (Alu-box of about 15 x 15 x 25 cm) with a 10-channel counter and two 16-bit-A/D-cards. The versatile data acquisition software TurboLab (by MDZ Buehrer&Partner in Germany) is managing the data stream from the I/O-cards, displaying a choice of parameters in user-definable graphics on the screen in the cockpit (2 serial ports could be used additionally). This system is very fail-save: It closes files every minute, and after a reset, it automatically starts up with new file names. In principle, this system could do calculations as well, but, we prefer to process and display raw data only in order to get the maximum sampling rate of 100 Hz, which is then averaged to 10 Hz for recording.

A few remarks on signals, and interferences: In general, we do not have severe problems with analog or digital signals. However, the PC/104 was a strong emitter of RF at the beginning, causing inacceptable background noise in the radio communication. This could partly be solved by improving shielding and applying ferrite-rings to cable connections. Vice versa, the temperature signal is disturbed by our own radio-emissions. An elegant way to overcome such problems, is to transmit counts instead of voltages: E.g. the NOxTOy and the CO-Monitor are outputting TTL-pulses, originating directly from the photo multipliers. Sending the (divided) counts via the cable through the wing to the counter inputs of the PC/104 excludes any signal deterioration (we actually are counting the photons in the sensors). However, proper shielding and line termination has to be regarded. Other advantages of this type of robust data transmission is true averaging independent of the sampling time, and cheaper hardware (a 10-channel counter costs less than 20 % of an 8-channel differential A/D card). Also opto-coupling is no problem with this system architecture. We plan to extend this principle also to other channels.

Further, two independent notebooks are communicating with the GC, and the GPS system via their serial ports. Finally, the ELSYS-logger which records some housekeeping- and backup-parameters on a memory card (old fashioned 256 k) also controls the UV-photometer for ozone. In principle, all these systems could be replaced by one system. But, until now, we did not change it, because it works fine, and - again - adds some redundancy. The problem of synchronizing the four independent systems is done during the post-processing: (i) the 10-minute-averages of the GC do not need a precise synchronisation (just checking the PC clocks before each flight); (ii) the fast PC/104-signals, and the slow blackbox-data are synchronized using a fast varying signal (a flow angle) which is recorded on both. Finally, the fine synchronization between the GPS (with highest absolute accuracy) and all the rest is done by performing the wind calculation with a sweep of time lags between the different data sources. Offset and trend between the clocks can be detected within 0.1 s and 10 ppm, resp., with this method.

All post-processing is done with Borland TurboPascal 7.0 programs under DOS or Windows-95 (eventually beeing migrated to Delphi). Graphics is done with GRAPHER/SURFER from Golden Software. Normally, we get quick-look data in the field. Afterwards, depending on the type of operation, any flight needs another 1..3 days processing (adapting mission parameters, incorporating field calibrations, and treating exceptions).

2.4 *QA/QC*

For the chemical parameters, field calibrations are done according to the stability of the systems. For the GC and the UV-photometer, a once-per-campaign calibration check or before/after is enough. On the other hand, the 6 nitrogen oxide channels need a daily multipoint calibration for their non-linear response. This is done by mixing directly NO2-calibration gas with a glass capillary in varying flow of zero air. QA/QC is an important issue where we profit from our co-operation partners in Juelich, and at PSI in Switzerland. Their calibration gases and monitors can be backtracked to NIST-standards. During joint field campaigns, we also passed several international QA/QC-exercises.

Other parameters such as temperature are checked occasionally, either by direct comparison with 'ground truth', or by intercomparison with other systems. The wind calculation has inherent quality checks (e.g. by analyzing take-off, circles, etc.). Other parameters such as the water vapor content measured by IR-absorption have their 'calibration normal' on board (dewpoint mirror). Indirectly, this is also a check for the stability of CO_2, since it uses the same optics. The comparison of mixing ratios from IRGA and dewpoint mirror showed, that on one hand, the dewpoint mirror is much faster than anticipated earlier, and the IRGA is very stable (no relevant change within a campaign of several days - without cleaning of any mirror).

For instruments measuring a mass concentration (as the IRGA), the wide pressure changes can be used to check and fine-tune the sensitivity: At altitudes, where one can assume constant mixing ratio, the span can be checked or even adjusted.

Any instrument and parameter has its important details for operation, calibration, and post-processing. Most of the procedures are documented in check-lists and source-codes, but, of course, the experience of the small team (three persons) is a substantial contribution to success too. For some instruments (e.g. for HCHO and H_2O_2) we need additional field support from our cooperation partners.

3. AIRCRAFT

The 'Dimona HK-36 TTC-ECO' from Diamond Aircraft in Vienna, Austria is a composite fibre (glass/carbon/epoxi) aircraft with the following technical data (table 2). The payload of 310 kg can be used for crew, instruments, and fuel (needs some compromises). The engine drives a constant speed, variable pitch propeller via a gearbox, allowing high engine-RPM, but low propeller-RPM resulting in high efficiency and low noise level (lowest possible noise category).

Type of aircraft	motorglider (TMG)
crew	2, side by side
wing span x length	16.3 m x 7.3 m
empty mass	620 kg, incl. electrical power system
maximum t/o mass	930 kg
engine	ROTAX-914, turbo-charged, liquid cooled 4-cyl. piston with 115 HP
fuel	2 x 55 ltr unleaded car fuel or 100 LL
endurance	5 h
ceiling altitude	far above 8000 mMSL
climb rate (normal..max)	2..3 m/s
min / cruising / max speed	100 / 150..200 / 260 km/h
interval between mainten.	100 hours

Table 2: Some technical data of the 'Dimona' (numbers given are experienced in MetAir operation, they may be different in manufacturers documentation).

The turbo-charging leads to an almost altitude-independent climb rate. A recent example during a campaign around Mont Blanc in the Swiss Alps (fig. 1) with reduced power setting: Constantly 2 m/s from 1000 to 4800 m/s. Actually, the ceiling height of the aircraft exceeds what is physically acceptable by the crew. But, with a standard on-demand oxigen system, one can safely reach the 8000 m level, where the climb rate still is >1 m/s.

The general handling of the aircraft and the ground operation with the robust tricycle gear is easy, also under cross-wind conditions, and on rough surfaces. However, one has to be careful with the small clearance between instrument-pods, and ground. The view out of the cockpit is excellent, and the comfort in the small cockpit is better than anticipated (incl. heating for winter operation, and a shadow-curtain on top plus side-windows for effective ventilation in summer). A nice practical detail is a side-door to the baggage-compartment behind the seats. This allows safe ground operation at the instruments in the fuselage from behind the wing even when the cabin is closed and the engine is idling.

4. APPLICATIONS

The original motivation to develop the system was applied research in the field of photochemistry around urban environments in Switzerland (project POLLUMET - air pollution and meteorology in Switzerland, where also UCAR/NCAR's 'King-Air' was involved (Neftel et al., 1994; Lehning et al., 1998). After this, several studies dealt with the photosmog problems we suffer near Geneva (situated in a basin; SAEFL, 1999), and between the Alps, and the large city of Milano (Prévôt et al., 1997; Staffelbach et al., 1997; Prévôt et al., 1994). Internationally, we documented urban plumes of Berlin (Germany), Vienna (Austria), and Paris (France). Most publications on these projects are in german language, or not yet written. The following papers concerning research on urban plumes are available in english: (Paetz et al., 2000; Konrad, 2000; Dommen et al., 2000; Lehning et al., 1998; Neininger, 1995). The first three already could profit from a very complete set of photochemical parameters. The same will be true with respect to Paris in 1999.

Since 1996, we also entered the field of measuring vertical eddy-fluxes of CO_2, and H_2O (Graber et al., 1998). But, the full development of this branch is 'under construction' for 2001. The integration of the redundancy for CO_2 (LICOR+IRGA) and the fast CO-monitor was an important step. The latter will allow to separate anthropogenic and biogenic CO_2-fluxes. CO is also an excellent parameter for photochemistry, since it allows to downscale the slow VOC-measurements.

Another issue is the exchange between the complex boundary layer over Alpine valleys or forelands, and the free troposphere (Kossmann et al., 1999; Furger et al., 2000; Prévôt et al., 1998). As a surprise, the VOC's revealed to be the best tracer for the daily concentration increase of pollutants at altitude due to vertical transport of polluted air from a deep valley into the lower troposphere, (Prévôt et al., 2000). Maybe CO - now available - will even be better.

In 'pure meteorology', we were involved in the MAP field phase (Mesoscale Alpine Programme, http://www.map.ethz.ch/sop-doc/catalog/index.html), where we were active in turbulence research in the 'Riviera Valley' (Rotach, 1999), and in 'FORM' (Foehn in the Rhine Valley during MAP; Richner, 1999). Also in this study, some chemical parameters such as NOx, or the aerosols proved to be valuable tracers for meteorology, e.g. to detect the mass exchange between the 'cold pool' below the Foehn flow, or in order to identify stratospheric air.

However, the focus during the last ten years was on atmospheric chemistry, revealing some gaps in the instrumentation when we dealt with turbulence 'only'. But, it is no problem to fill these gaps within the framework of the present instrumentation. Already the enhanced GPS-precision/accuracy without the 'selective availability' since this year improved a lot.

Since MetAir has to finance its activities by contracts, such improvements have to be done in a purely project-oriented way. But, this is the main problem: There is no real market for this type of environmental research. In many cases, large national facilities with large aircraft (and fewer sensors) get funding for tasks that could be done with a much cheaper and more flexible as described above, or people do not know, that airborne measurements can be realized with a comparable effort as is needed to operate a network of some ground stations, or a tethered balloon.

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