**Nationaal Lucht- en Ruimtevaartlaboratorium**
National Aerospace Laboratory NLR

## Executive summary

# Flight Testing of Real-time On-board Weather Data Fusion

**Problem area**
Air traffic is expected to triple world-wide within the next 20 years. With the existing on-board and on-ground systems, this would lead to an increase of aircraft accidents, in the same, or a higher proportion. Despite the fact that accidents are rare, this increase is perceived as unacceptable by society.
The FLYSAFE project aims to improve the integration of information flows in the cockpit, which, in turn, will raise the pilot's 'situational awareness', thus allowing pilots to better anticipate potentially dangerous situations. FLYSAFE therefore focuses on reducing accidents. The flight testing presented in this paper only concerns aspects related to weather conditions.

**Description of work**
This paper presents the flight testing of an on-board weather data fusion system as performed in the summer of 2008. Weather forecasts are uplinked from the ground to the aircraft and consist of weather products developed within the FLYSAFE project. The inputs or the real-time on-board fusion consist of aircraft weather radar data and the uplinked weather products. Objectives of the flight test program are mainly focused on assessing the feasibility of uplinking and real-time fusing of weather data onboard the aircraft, rather than on evaluating the suitability of the system for operational use. The latter has been the objective of the FLYSAFE simulation campaign performed in the flight simulation facilities of the National Aerospace Laboratory NLR in 2009.

**Results and conclusions**
In the summer of 2008, 21 flights (40 hours) have been performed to test on-board weather data fusion. During these test flights, WIMS weather forecasts have been successfully uplinked to NLR’s Swearingen Metro II research aircraft through a satellite link and fused with on-board weather radar data, thus proving complementary nature of both sources for weather hazards avoidance

**Applicability**
Flight test results need further evaluation in the field of fusion functionality and operational use of the system, since the flight test campaign was mainly focused on assessing the feasibility of uplinking and on-board fusion of weather data.

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# Flight Testing of Real-time On-board Weather Data Fusion

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## Summary

This paper presents the flight testing of an on-board weather data fusion system as performed in the summer of 2008. This system has been developed and flight tested as part of the European project FLYSAFE (Airborne Integrated Systems for Safety Improvement, Flight Hazard Protection and all Weather Operations). A functional description of the system, as well as a description of its parts, is given, followed by an overview of the most important flight test preparation and execution issues.

Weather data fusion examples from one of the test flights are discussed and several aspects of datalink performance are addressed.

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# Contents

# Abbreviations

| | |
|---|---|
| CAT | Clear Air Turbulence |
| CB | Cumulonimbus (thunderstorm cloud) |
| DADC | Digital Air Data Computer |
| DSP | Datalink Service Provider |
| FAR | Federal Aviation Regulations |
| FMS | Flight Management System |
| GLB | Global |
| GPS | Global Positioning System |
| GWP | Ground Weather Processor |
| HMI | Human Machine Interface |
| IRS | Inertial Reference System |
| LOC | Local |
| METAR | Aerodrome routine meteorological report |
| MPDS | Mobile Packet Data Service |
| REG | Regional |
| SANTA | Satellite Network Transport Architecture |
| SATCOM | Satellite Communication |
| SPU | Surveillance Processor Unit |
| TAF | Terminal Aerodrome Forecast |
| TMA | Terminal Manoeuvring Area |
| WIMS | Weather Information Management Systems |

# 1 Introduction

Air traffic is expected to triple world-wide within the next 20 years. With the existing on-board and on-ground systems, this would lead to an increase of aircraft accidents, in the same, or a higher proportion. Despite the fact that accidents are rare, this increase is perceived as unacceptable by society and new systems and solutions must be found to reduce or at least maintain the number of accidents at its current low level. As safety of flight depends to a large extent on flight crew actions, it is essential that crewmembers are supplied with reliable information that can be used at all times.

The FLYSAFE project aims to improve the integration of information flows in the cockpit, which, in turn, will raise the pilot's 'situational awareness', thus allowing pilots to better anticipate potentially dangerous situations. The better a pilot understands his/her position, the position of other aircraft, and the weather patterns, the better able the pilot is to make correct decisions.

FLYSAFE therefore focuses on reducing accidents caused by collisions with other aircraft or terrain, and accidents caused by bad weather. The flight testing presented in this paper only concerns aspects related to weather conditions. To this end, a datalink system, fusion functionality and weather products have been newly developed and flight tested on-board a research aircraft. Other aspects of the performance of the overall ground/air system were assessed in other flight tests using a specialist atmospheric research aircraft.

# 2 Objectives

The flight test objectives are three-fold:

- To uplink weather forecasts
- To fuse weather data on-board
- To display weather information

Weather forecasts are uplinked from the ground to the aircraft and consist of weather products developed within the FLYSAFE project. Traditional weather products including TAFs and METARs were considered at the design phase but were not implemented in the flight trial. The inputs for the real-time on-board fusion consist of aircraft weather radar data and the uplinked weather products. All of the three parts (uplinked weather product, aircraft weather radar image and the fused result of both) are to be displayed on specific displays in the aircraft cabin.

Objectives of the flight test program are mainly focused on assessing the feasibility of uplinking and real-time fusing of weather data onboard the aircraft, rather than on evaluating the suitability of the system for operational use. The latter has been the objective of the FLYSAFE simulation campaign performed in the flight simulation facilities of the National Aerospace Laboratory NLR in 2009.

# 3 Set-up

## 3.1 Functional Overview

A concise functional overview of the flight test set-up is given in Figure 1. Some of the functions are associated with the aircraft, others with the ground segment of the set-up. The two parts interact with each other via the datalink communication function.

Good weather awareness starts with weather detection. In the set-up, this is realised both in the aircraft as well as on the ground. In the aircraft (section 3.6), a newly developed multi-scan weather radar system is installed (subsection 3.7.3). On the ground, weather data is collected from ground radars and satellites and transformed into newly developed weather forecasts, called WIMS products (section 3.2). These WIMS products are sent to the Ground Weather Processor (GWP), where they are stored in the WIMS ground database. Datalink communication (section 3.3), using a high-speed satellite communication system (subsection 3.7.2), ensures that WIMS products can be received on-board the aircraft.

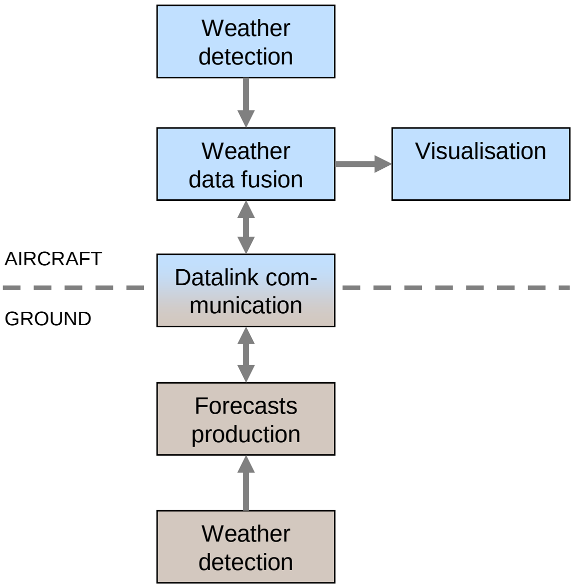

*Figure 1 Concise overview of flight test set-up*

Both weather data streams (uplinked WIMS products and aircraft weather radar data) are fused on-board the aircraft (section 3.4) and displayed in the cabin. The aircraft weather radar image is displayed on a control and display unit (subsection 3.7.3), the WIMS products and fused images are displayed on a Weather Display laptop (subsection 3.7.6). Finally, many parameters were recorded (section 3.5) – both in the air as well as on the ground – for post-flight analyses with regard to the system’s performance.

## 3.2 Weather Products

### 3.2.1 WIMS – Future system

The FLYSAFE project envisages that dedicated WIMS at airports provide nowcasts for meteorological conditions around a TMA. National Meteorological Centres provide medium and longer term forecast data for the following atmospheric hazards that affect flight operations (Ref.1):

| | |
|---|---|
| – Clear Air Turbulence | (CAT WIMS) |
| – Thunderstorms | (CB WIMS) |
| – Icing | (ICE WIMS) |
| – Wake vortices | (WAKE WIMS) |

All data are made available on-demand through a network of data-hubs, the GWP, accessible to any user, anytime, anywhere. A network of WIMS would generate forecasts for each of the atmospheric hazards at all spatial and temporal scales (not only for Local TMA scale):

- Global = Low resolution, long range
- Regional = Medium resolution / range
- Local = High resolution, short range

Such spatial and temporal range will cover all phases of flight from planning, departure, enroute to arrival.

Figure 2 illustrates the components of the ground based architecture. Each component is a node within the architecture. Point based observations are reported as measurements by a variety of sensing devices. They are assimilated into numerical models of the atmosphere which predict the future state of the atmosphere. WIMS take as input these forecasts to generate forecasts of the atmospheric hazards.

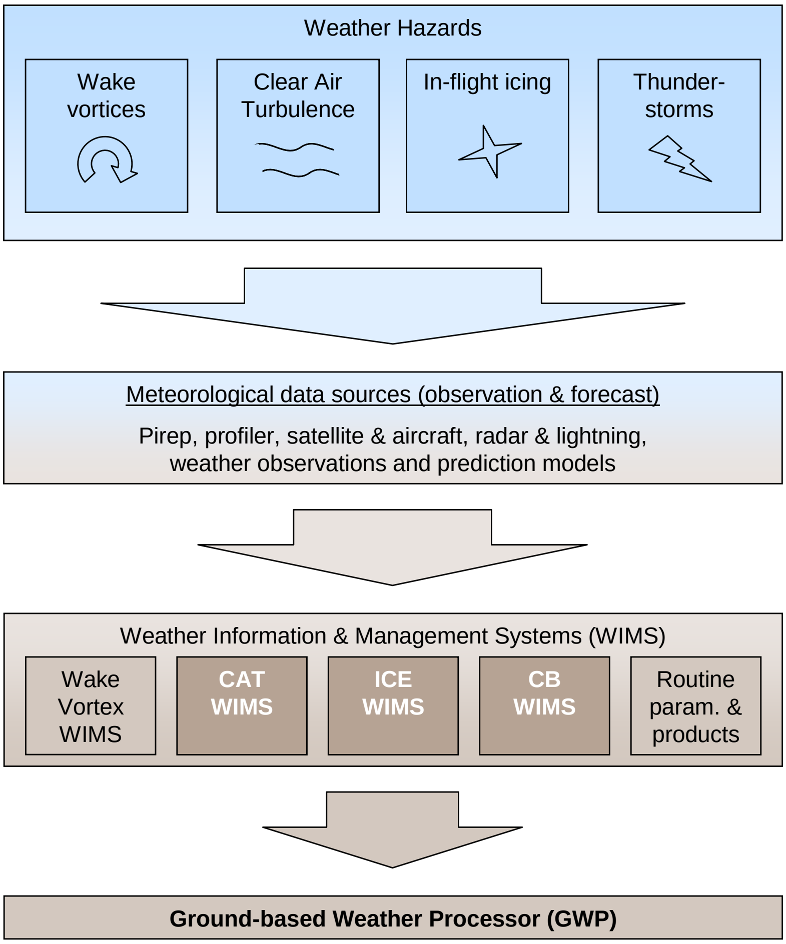

*Figure 2 Overview of ground side set-up. (CB-, ICE- and CAT WIMS have been used during the flight tests.)*

### 3.2.2 WIMS – Flight tested system

A GWP node was assembled at Météo France. The following WIMS products were produced over a two month period in which the test flights took place:

| | |
|---|---|
| – CB WIMS | Local and Regional |
| – CAT WIMS | Local and Regional |
| – ICE WIMS | Local, Regional and Global |

The weather information service providers were DLR, UK Met Office, University of Hanover and Météo France. The refresh rate of the WIMS products varies from 5 minutes to 6 hours.

## 3.3 Datalink Functionality

Datalink traffic is controlled on request from the aircraft. Requests for weather forecasts are down-linked to the GWP.

The downlinked requests are predefined, periodic and scheduled over a certain time frame in order to receive up-to-date weather forecasts while reducing the required bandwidth as much as possible. The request periods match the update rate of the WIMS products in the GWP: Local WIMS are queried every 5 minutes, Regional WIMS are queried every 15 minutes and Global WIMS are queried every 30 minutes (see Table 1).

*Table 1 WIMS request schedule from aircraft to ground*

```
T0+XX:                        LOC = LOCAL WIMS
T0=START OF SEQUENCE          REG = REGIONAL WIMS
XX=ELAPSED TIME IN MIN        GLB = GLOBAL WIMS

T0    CB  LOC           T0+15 CB  LOC
T0+01 CB  REG           T0+16 CB  REG
T0+02 ICE LOC           T0+17 ICE LOC
T0+03 ICE REG           T0+18 ---
T0+04 ---               T0+19 ---
T0+05 CB  LOC           T0+20 CB  LOC
T0+06 CAT REG           T0+21 ---
T0+07 ICE LOC           T0+22 ICE LOC
T0+08 CAT GLB           T0+23 ---
T0+09 ICE GLB           T0+24 ---
T0+10 CB  LOC           T0+25 CB  LOC
T0+11 ---               T0+26 ---
T0+12 ICE LOC           T0+27 ICE LOC
T0+13 ---               T0+28 ---
T0+14 ---               T0+29 ---
```

The Request-Reply-Manager module queries the GWP to retrieve WIMS products for the area of interest (called: weather corridor) and for the time window of interest. As no FMS was available on board the Metro II aircraft, the weather corridor is computed based on current aircraft position and heading.

The down-linked requests are first received at a ground focal point of a chosen Data Link Service Provider and are then routed to the GWP. As a result, the WIMS ground database is queried and the results are uplinked to the aircraft. After reception of the WIMS products on-board the aircraft, they are stored in the on-board WIMS database.

### 3.4 Fusion Functionality

A simplified overview of the on-board fusion process is given in Figure 3.

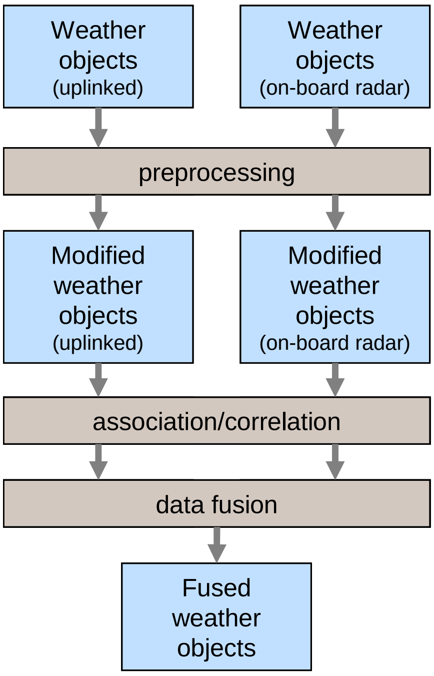

*Figure 3 Overview of on-board fusion process*

The on-board weather data fusion functionality uses two sorts of input: first, weather objects from the aircraft's radar and second, weather objects from the uplinked CB WIMS products. The fusion uses the CB WIMS products that are stored in the WIMS on-board database and is triggered on every on-board weather radar sweep reception (i.e. every 4 sec).

Both inputs are first preprocessed in order to have them all in the same reference system, in the same resolution and for the same geometrical plane. Furthermore, in order to have inputs that refer to the same instant in time, the two closest CB WIMS forecasts are interpolated to match the time of the applicable radar sweep.

The resulting modified weather objects – uplinked from ground and from on-board radar – are then associated with each other. This means that the weather objects which designate the same convective cell are associated based on a spatial correlation. When the interpolated CB WIMS objects correlate with the weather hazards as seen by the airborne radar, the weather data fusion function computes:

- A simplified envelope that delineates the horizontal extent of the weather hazard to avoid. This envelope is based on minimum, mean and maximum values of relative distance and relative azimuth of the CB WIMS forecast. Moreover, the envelope is interpolated for the time of the on-board weather radar observation (polygon of 6 points).
- Other attributes such as altitude, severity, growing/decaying trend and presence of hail.

### 3.5 Data Recording

During the flight tests, many parameters have been recorded, both in the aircraft and on the ground, for post-flight analyses. It is beyond the scope of this paper to give a full account of all recorded parameters, however, the parameters related to following areas:

- Aircraft data:
  - Navigation data from IRS and GPS
  - Air data from DADC
- On-board weather radar data
- Fused weather data
- Uplinked weather data (WIMS products as received in the aircraft)
- Stormscope data
- Video recordings:
  - Direction of flight from cockpit
  - Weather displays in cabin
- Output of numerical weather prediction models and observations (like ground radar imagery and satellite imagery)
- WIMS outputs (and inputs to regenerate WIMS):
  - CB- , ICE- and CAT WIMS (all scales)

### 3.6 Research Aircraft

The Swearingen Metro II research aircraft (PH-NLZ) of the National Aerospace Laboratory NLR has been used for the flight tests. The Metro II is a twin turboprop aircraft, modified for aerospace research and certified in accordance with FAR Part 23 airworthiness standards. The aircraft is equipped with all required civil communication, navigation and avionics systems, GPS and a Flight Director / Autopilot, although no FMS was available. For the flight tests described in this paper, amongst others, a new multi-scan weather radar was installed on the nose of the aircraft and a satellite antenna was installed on an antenna box on top of the fuselage of the aircraft. Both are visible in Figure 4. Equipment details are provided in section 3.7.

*Figure 4 NLR's Swearingen Metro II research aircraft with multiscan weather radar attached on the nose and satellite antenna on top of aft fuselage during preparation for FLYSAFE flight tests in the summer of 2008. See Figure 6 and Figure 7 for details.*

## 3.7 Equipment

### 3.7.1 Overall system architecture

A simplified architecture of the flight tested system is given in Figure 5. The main hardware parts in this figure are described in the remaining subsections of this section. Together with the functional descriptions in the previous sections of this chapter, a sufficient knowledge and understanding of the tested system can be obtained.

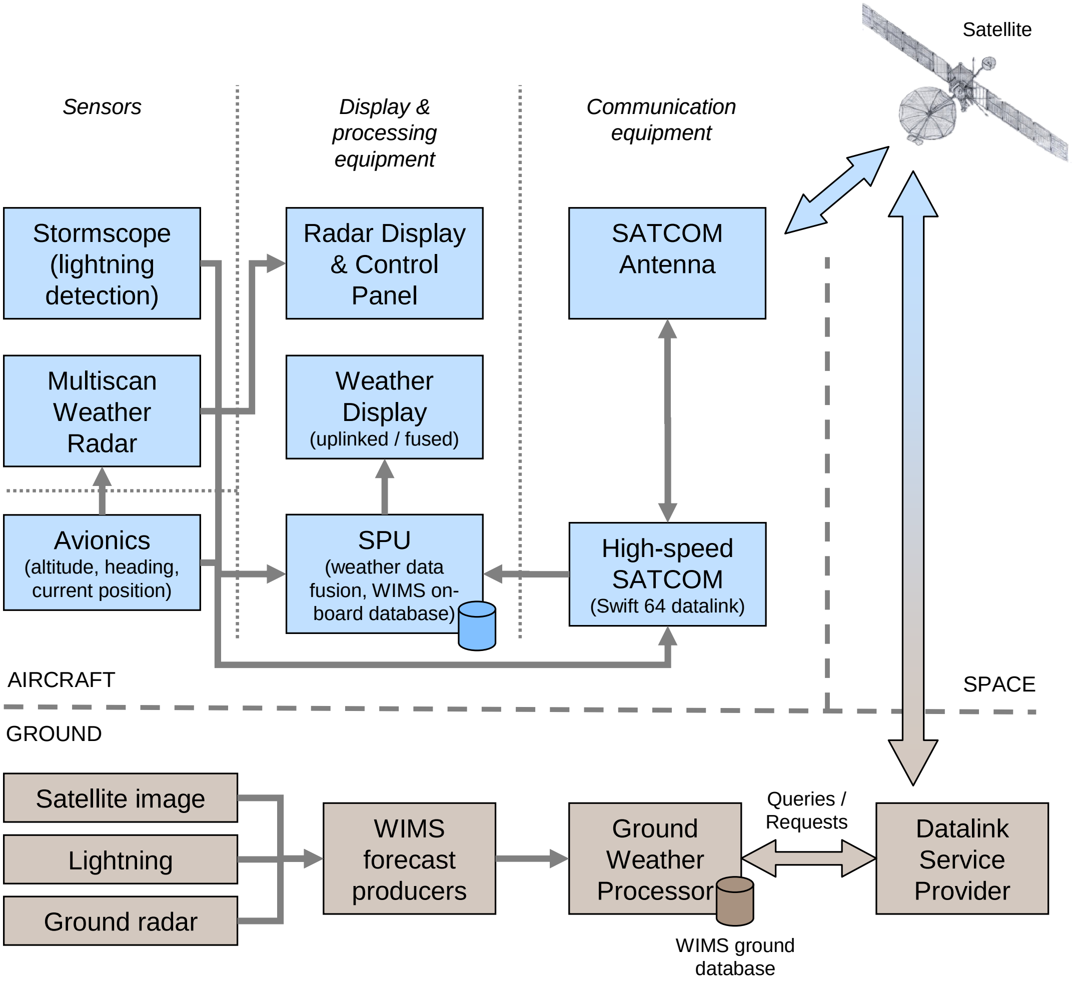

*Figure 5 Architecture of flight tested system*

### 3.7.2 Datalink system

A high speed SATCOM system Rockwell Collins HST-2110 ™ / SRT-2100 ™ (Swift 64 service) was installed in the aircraft cabin. It was coupled with an IP protocol enhancer (called SANTA) from Skysoft that speeds up data exchanges. The high-gain SATCOM antenna (HGA-7001) was attached to the aircraft's antenna box on top of the aft fuselage. An impression of the system is given in Figure 6.

*Figure 6 High speed SATCOM system (black coloured boxes in avionics rack on left with SANTA lap-top on top). Side and front view of SATCOM antenna attached to antenna box are shown at the upper respectively lower right.*

### 3.7.3 On-board weather radar system

A new weather radar Rockwell Collins RTA-4118 Multiscan $^{\text{TM}}$ was installed on the nose of the aircraft, replacing the existing radar. As this new radar could only be used for experimental purposes (not yet fully certified), special attention had to be paid to the flight test preparations (see section 4.1).

The multiscan radar analyzes and determines actual weather hazards, not simply atmospheric moisture content. The multiscan radar system is derived from extensive operational experience to create a fully automatic, hands-free airborne radar system that reduces pilot workload and enhances safety and passenger comfort by minimizing unexpected turbulence encounters, and provides optimal clutter-free weather displays up to 320 Nm through automatic tilt management and ground clutter suppression functions.

The radar system consists of an 18 inch antenna plate and a processing unit. For the test flights, the radar image is displayed on a radar control & display unit Rockwell Collins WXI-711A $^{\text{TM}}$ in the aircraft cabin. Both radar system and display unit are shown in Figure 7.

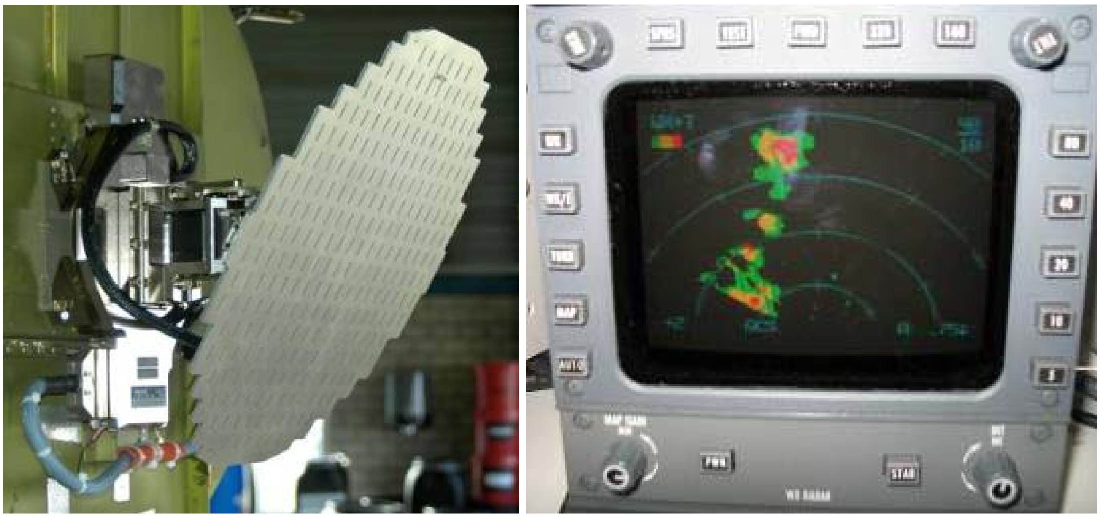

*Figure 7 Multiscan radar system and display unit*

### 3.7.4 Stormscope system

A stormscope is a system that detects lightning strikes or more precisely, electrical discharges. The WX-500 stormscope from L3-Communications was installed in the aircraft. This system has a range of up to 200 Nm, 360 degrees around the aircraft. The system consists of a processing unit and an antenna (Figure 8). Its output was integrated with the aircraft's Garmin 430 system (Figure 9).

The stormscope was installed for two reasons:

- Collection of lightning data for post-flight analyses
- Indication of storm cell build-up (see section 4.1)

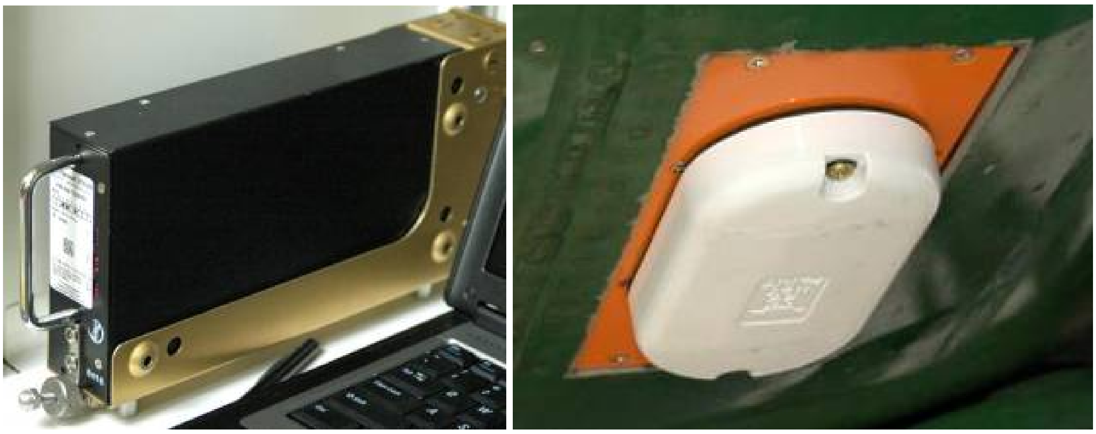

*Figure 8 Stormscope processing unit and antenna*

*Figure 9 Stormscope detected lightning activity indicated on Garmin 430 (bottom) together with corresponding cockpit view in direction of flight (top). Aircraft symbol is indicated by arrow. Yellow markings at 10-11 o'clock position indicate lightning activity. Test flight over North of Spain via Biarritz to Toulouse.*

### 3.7.5 Surveillance Processor Unit

The Surveillance Processor Unit (Figure 10) is a PC that hosts following functions:

- Request-Reply-Manager sends requests to the GWP to uplink WIMS products and stores the uplinked WIMS products into the on-board weather database.

- Data Fusion acquires data from the on-board weather radar, CB WIMS products from the on-board weather database, fuses these data and stores the fused objects into the on-board weather database.

Figure 10 Surveillance Processor Unit is hosted by one of four PCs

### 3.7.6 Work positions and displays

Two work stations are available on the operator console halfway of the aircraft cabin (Figure 11). One for NLR, the other for FLYSAFE applications. By using a keyboard-video-mouse switch, the latter station can operate all FLYSAFE PC systems.

The operator console also houses the Weather Display laptop (Figure 12) that hosts a basic HMI developed by GTD Sistemas de Información. This laptop can show uplinked WIMS products from the on-board data-base or the weather data fusion results.

Figure 11 Operator console in aircraft cabin

No loc ICE reg ICE loc CB found.
No loc fused CB reg fused CB found.

*Figure 12 Weather Display laptop showing a CB WIMS product*

# 4 Flight Test Operation

## 4.1 Preparation

A full account of the flight test preparations can be found in Ref.2. One FLYSAFE-specific item regarding flight test operations with an experimental weather radar is addressed in this section.

Since the new on-board weather radar (see subsection 3.7.3) replaced the existing one and was not fully certified – experimental use only –, the test flights had to be performed as if no weather radar was on-board. As a result, specific weather limitations were applicable. This, however, partly conflicted with the project's interests. The FLYSAFE project is interested to fly around in weather situations with lots of CB clouds including embedded thunderstorms. This situation is a worst case scenario in terms of weather data amount to be uplinked to the aircraft. Embedded thunderstorms could, however, not be evaluated, as the pilots were not able to visually distinguish the thunderstorm clouds from the other type of clouds, which could then lead to flying into a too dangerous weather situation. Therefore, in case of forecasted or reported embedded CB, a test flight had to be postponed.
A stormscope was installed and integrated in the cockpit. Operationally, the stormscope was both meant as a safety precaution, as well as a means to help finding the isolated CB clouds.

Besides using the regular aviation meteorological services, test flight planning for FLYSAFE could always rely on detailed daily forecasts from Météo France depicting the expected convective weather areas over Europe for the coming days. An example of such a forecast is given in Figure 13.

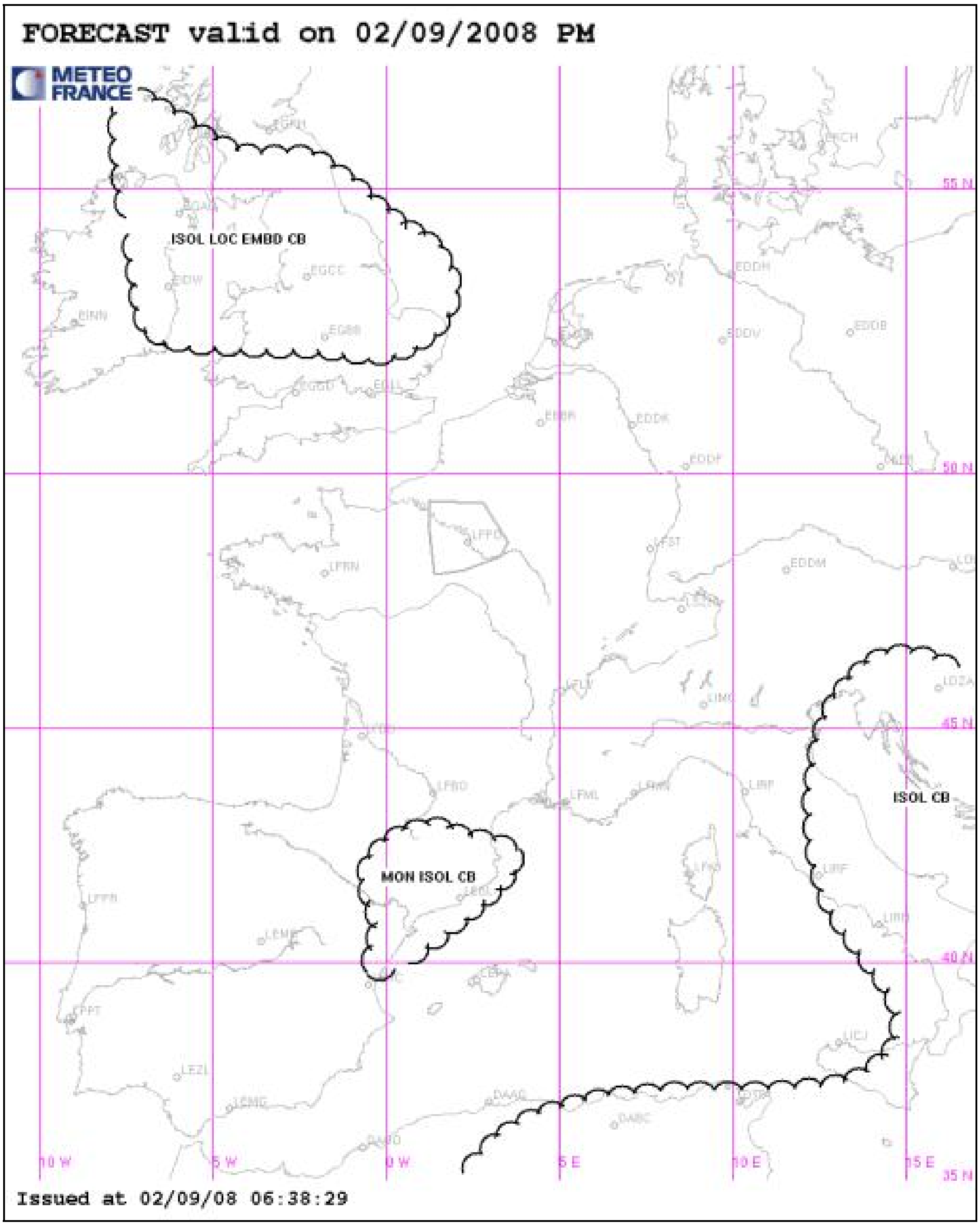

*Figure 13 Example of convective weather forecast*

## 4.2 Execution

Over 40 hours of testing have been accumulated in 21 flights performed in the period from August 6th through September 10th, 2008. The first two flights were shakedown flights in order to check the installation in flight (including weather radar alignment checks). Three flights were ferry flights to position the aircraft for the required weather. The remaining sixteen flights were test flights. Two types of test flight were defined:

- Local WIMS test flight
- Regional WIMS test flight

Local WIMS flights are performed in the Paris TMA, because the Local WIMS products are produced for this area only. Regional WIMS flights could be flown more-or-less arbitrary over Europe mainly depending on the weather, as Regional WIMS products are available for a much broader area over Europe.

Given the characteristic of the Local WIMS products (more data points per unit area, i.e. smaller data grid, and faster refresh rate based on high quality ground radar data), Local WIMS test flights were the main interest of the project. However, due to the weather situation in the summer of 2008, only one Local WIMS test flight could be flown in the Paris TMA. The fifteen remaining flights were Regional WIMS flights. During one of these Regional flights, the Paris TMA could still be approached and scanned with the on-board weather radar.
Convective weather has been found over following countries: The Netherlands, Germany, France and Spain (Figure 14). A detailed account of all performed test flights can be found in Ref.3.

*Figure 14 Convective weather over the Pyrenees*

# 5 Results

## 5.1 Fusion Examples

Through fusion of on-board weather radar data and uplinked WIMS data, regions of weather hazards have been delineated on a basic HMI. During the flight trials, uplinked WIMS products, used for fusion, mainly consisted of the CB WIMS Bottom type, which are mainly derived from ground radars. CB WIMS Tops, which are derived from satellite images, are only available for vertically developed CB clouds extending through 35,000 feet, which were only met occasionally.

In the remainder of this section, two examples that illustrate the weather data fusion are given, while more evaluations can be found in Ref.4. The examples in this section correspond with two moments taken from the only Local WIMS flight performed during the flight test period. The aircraft is flying at FL200.

Figure 15 shows the on-board weather radar image. The selected radar range is 80 NM. The axes of the figure however, represent the aircraft's X and Y body axes in km. The Xb(ody) axis of the aircraft is the longitudinal axis through the aircraft's plane of symmetry. The Yb(ody) axis of the aircraft is the lateral axis and – for this application – can be regarded as running through the radar antenna plate on the nose of the aircraft.

A green weather cell (15-25 dBz – light precipitation intensity) can be observed. This cell is growing and developing rapidly. Further recorded radar sweeps show higher reflectivity level (yellow cores of 25-35 dBz – see next example) and uplinked WIMS forecasts present a "growing trend" attribute.

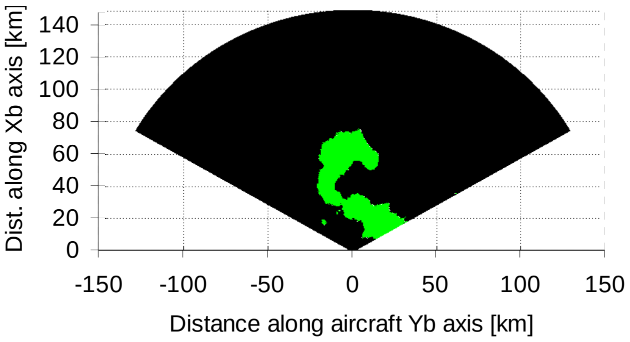

*Figure 15 On-board weather radar image. (Range: 80 Nm.)*

The corresponding CB WIMS Regional (Bottom) products are shown in Figure 16. They represent the forecast just before and after the radar sweep of Figure 15. The yellow ones have a Forecast Horizon of 20 min, while the green ones have a Forecast Horizon of 25 min. The reflectivity for all is 33 dBz (moderate precipitation intensity), which differs from what is sensed by the on-board weather radar.

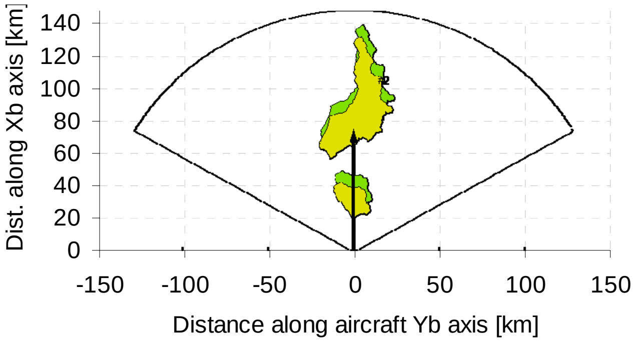

*Figure 16 CB WIMS Regional products before (yellow) and after (green) the radar sweep in Figure 15.(Range: 80 Nm.)*

The weather data fusion process interpolates between the two CB WIMS forecasts of Figure 16, in order to get the weather image that exactly relates with the time of the radar sweep in Figure 15. The result is given in Figure 17.

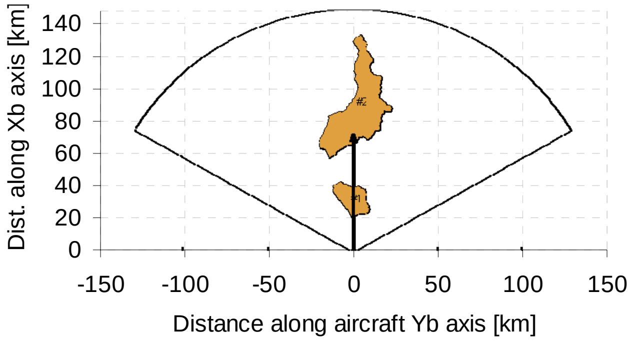

*Figure 17 Interpolated CB WIMS Regional product relating to the radar sweep in Figure 15. (Range: 80 Nm.)*

Since the interpolated weather image in Figure 17 intersects with the area of reflectivity seen by the on-board weather radar in Figure 15, the weather data fusion computes a simplified envelope of the interpolated WIMS products (see section 3.4). The fused image (magenta) is given in Figure 18. The superimposed interpolated CB WIMS product (blue) is only shown here for illustration purposes and was not visible during the test flights.

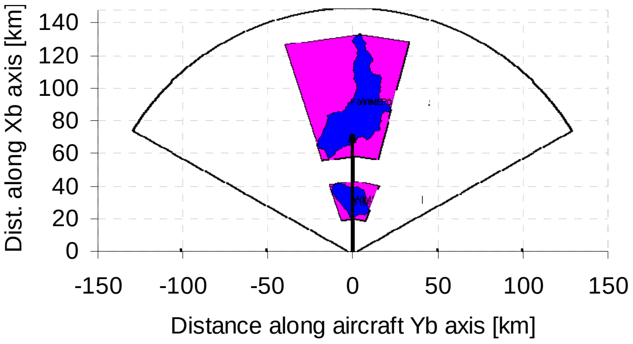

*Figure 18 Fused weather image (magenta) with interpolated CB WIMS (blue) superimposed. (Range: 80 Nm.)*

In above example, there are differences between what is seen by the on-board weather radar and what is forecasted by the uplinked CB WIMS products in terms of severity and morphology of the CB cells. Even when comparing with a shorter forecast horizon – by post-flight reprocessing of CB WIMS products –, differences remain.

Convective intensity near the surface of the earth will generally be higher than intensity at higher altitudes, and thus reflectivities will generally be higher near the earth's surface than at higher altitudes. The vertical dispersion of reflectivity (cell maturity is a large factor in how the reflectivity decreases as a function of height) and the fact that ground radars and airborne radars do not scan the same slice of atmosphere are key factors to explain the observed differences. Another reason is that ground-based and on-board weather radars have different intrinsic characteristics (e.g. polarisation, resolution, wavelength).

Figure 19 through Figure 23 correspond to the same CB cell five minutes later at the same flight level. In Figure 19, yellow cores (25-35 dBz) are now detected by the on-board weather radar, confirming the growing trend of this cell.

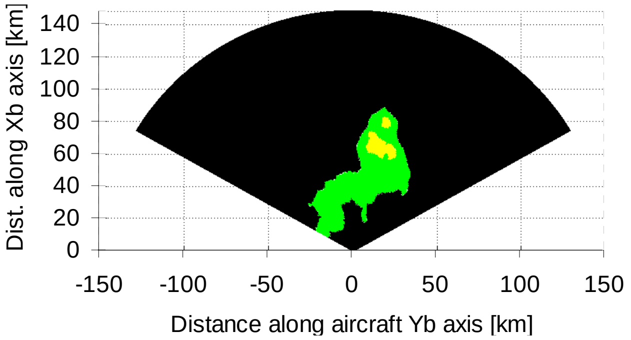

*Figure 19 On-board weather radar image 5 min after Figure 15. (Range: 80 Nm.)*

Figure 20 presents Local CB WIMS products with 10 respectively 15 minutes of Forecast Horizons, while Figure 21 presents the interpolated Local CB WIMS. The reflectivity for both CB WIMS Local forecasts is 33 dBz.

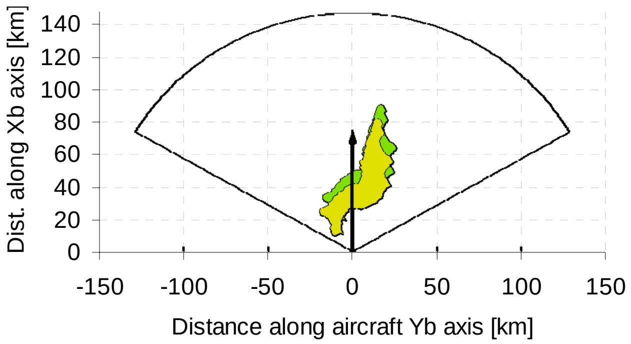

*Figure 20 CB WIMS Local products before (yellow) and after (green) the radar sweep in Figure 19. (Range: 80 Nm.)*

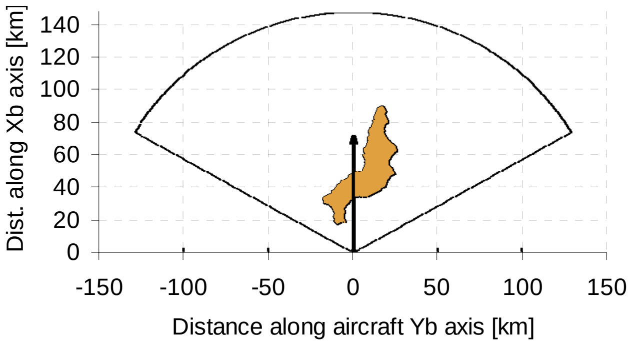

*Figure 21 Interpolated CB WIMS Local product relating to the radar sweep in Figure 19. (Range: 80 Nm.)*

The CB WIMS Local forecast sees a larger area of high reflectivity than the airborne radar at current flight level (compare blue with yellow area in Figure 22).

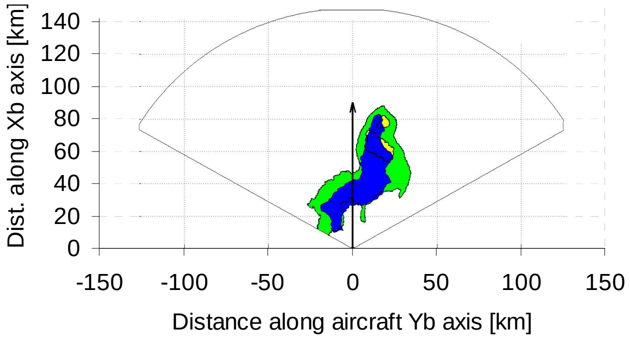

*Figure 22 Interpolated CB WIMS Local product (blue) superimposed with on-board weather radar image. (Range: 80 Nm.)*

The corresponding fused image is shown in Figure 23. Benefits of using more points to represent fused CB objects (instead of a simplified rough envelope of 6 points) have been demonstrated to closer match with pilots' expectation to circumnavigate and fly through short-range CBs.

Finally, it is noted (again) that, given the experimen-tal context, the flight tests were primarily focused on assessing the feasibility of uplinking and on-board fusing of weather radar data with live-fed WIMS products, rather than on evaluating the suitability of the system for operational use.

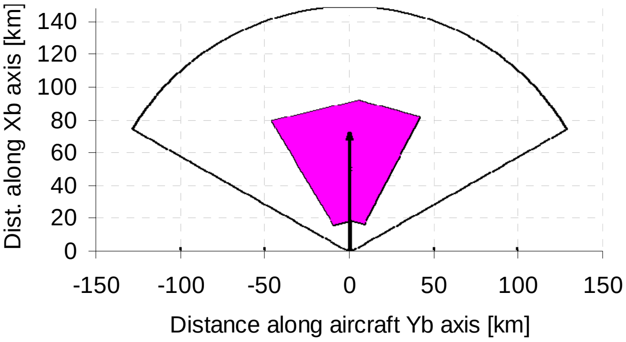

*Figure 23 Fused weather image (Range: 80 Nm).*

## 5.2 Datalink Performance

### 5.2.1 Uplinked data size

Figure 24 presents an overview of the (~80% gzip-compressed) sizes of the uplinked WIMS products as recorded during the flight tests campaign. The base of the bars start at the minimum observed size, while the (labels at the) tops indicate the maximum values.

The Local WIMS data sizes are based on two flights (one in and one near Paris TMA – there are few collected data for CB WIMS Local products). Therefore, these data sizes should be regarded as preliminary results. Nevertheless, in general, the volume of uplinked Local CB products for a TMA will most probably remain smaller than for Regional CB products, due to the limited extent of coverage area.

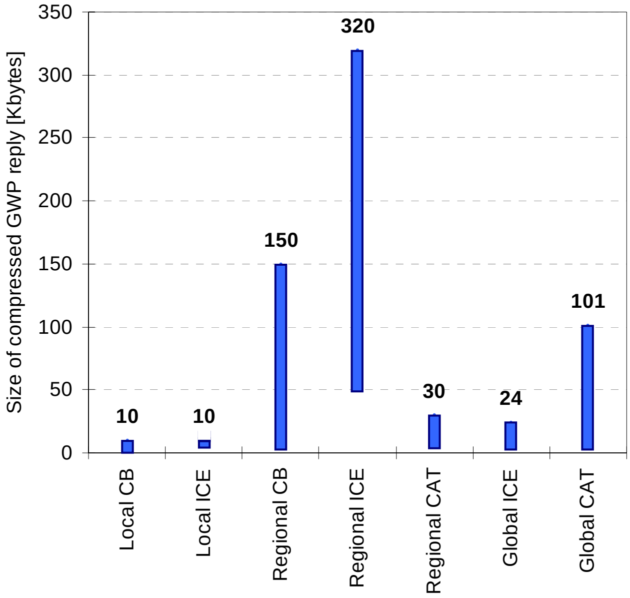

*Figure 24 Maximum and minimum data size per WIMS*

The maximum data sizes for CB WIMS products in Figure 24 relate to isolated CB conditions, since the test flights were limited to these weather conditions (see section 4.1). Therefore, in case of more intense thunderstorm activity (e.g. squall line), the maximum size of the uplinked CB WIMS products will increase.

The uplinked Regional WIMS ICE products have the largest size of all WIMS products.

The volume of data which is uplinked could be significantly reduced by a number of independent techniques, including the use of binary XML and a reduction in the number of points used to describe an individual weather object. This would obviously reduce costs (see subsection 5.2.4).

### 5.2.2 Uplink rate and time

The uplink rate R (in Kbits/s) for a GWP reply file for a specific type of WIMS product has been calculated according to:

$$R = \frac{S * 1024 * 8}{(T_1 - T_0) * 10^3} \qquad (1)$$

With S being the size of the WIMS product in Kbytes, $T_0$ being the time at which the request is sent from the SPU to the SATCOM unit and $T_1$ being the time at which the WIMS product is received on-board and stored into the on-board weather database. The elapsed time $T_1$-$T_0$ (both recorded in datalink log files) is in seconds. Transmission time between sending the (smallsized) request from the SPU and reception of it by the GWP is assumed to be negligible, thereby making R the uplink rate.

A selection of WIMS products from several flights has been used to assess the uplink rate. The results are shown in Figure 25.

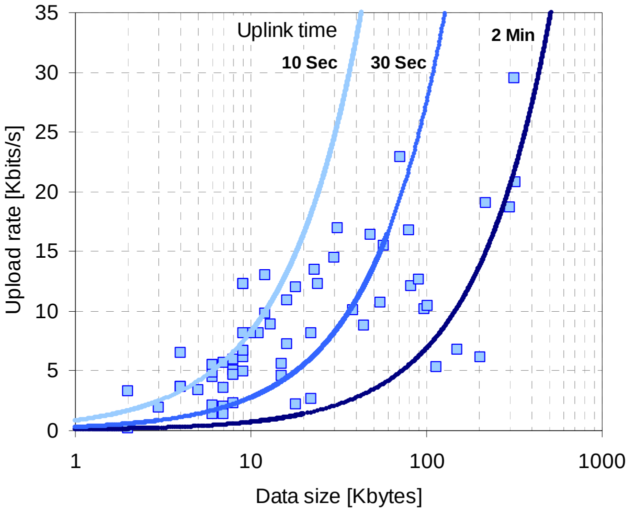

*Figure 25 Upload rate as function of data size accompanied by curves indicating equal uplink time*

Although WIMS products of same size can be uplinked with different rates (depending on available bandwidth and number of users on the SATCOM network), generally, the uplink rate increases with increasing data size.

Most of the uplink times take between 10 sec and 2 minutes, while most of the uplink rates are between 2 and 20 Kbits/s (Figure 25).

### 5.2.3 Overall WIMS transmission delay

The overall WIMS transmission delay is defined here as the time between on-ground weather sensor observations and WIMS products reception on-board the aircraft. This delay can be divided into three parts:

1. Preparation

   Elapsed time between ground sensor observations and WIMS products availability at GWP level.

2. Synchronization

   Elapsed time between WIMS products availability at GWP and aircraft queries to GWP. The WIMS products in the GWP are updated at predefined intervals. The aircraft periodically requests WIMS products according to predefined intervals. These two events are not synchronized and therefore produced delays.

3. Communication
   Elapsed time between start of upload and storage onto the on-board weather data base. This is the uplink time from subsection 5.2.2.

Figure 26 shows the overall WIMS transmission delay for the three types of CB WIMS products uplinked during the flight trials. Note that the indicated time delays are worst case.

For the Regional CB Top product, it takes relatively much time before it is available in the GWP (18 min worst case). Most of this delay is attributed to satellite image generation. The other Regional CB products use ground weather radar data.

The worst case synchronization delay equals the period at which requests are downlinked from the aircraft to the GWP (see Table 1 in section 3.3). It corresponds with the situation in which a request from the aircraft is received (and replied) by the GWP just before a new update of the requested product is stored in the GWP. The period for Local CB and Regional CB is respectively 5 and 15 minutes.

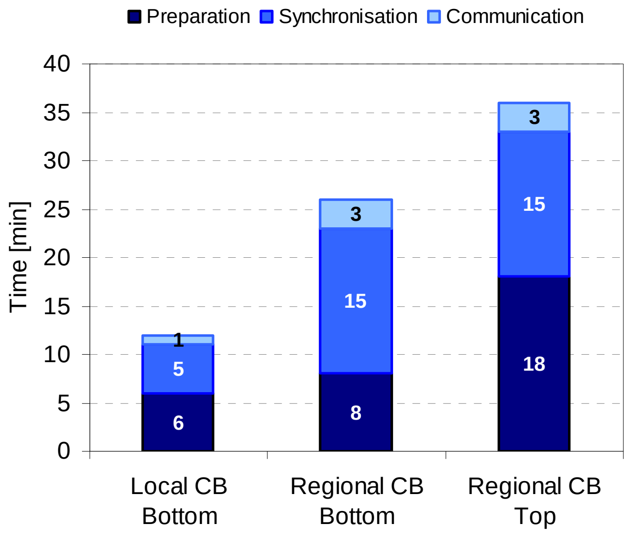

*Figure 26 Worst case overall delays for CB WIMS*

The worst case overall WIMS transmission delays in Figure 26 (i.e. 12, 26 and 36 minutes) provide a rough estimation of the minimum forecast horizon for each product. Applying shorter forecast horizons could lead to on-board reception of outdated forecasts.

During the flight trials, typical observed overall WIMS transmission delays, with the aircraft periodic queries as in Table 1, are:

- 7 - 12 min Local CB Bottom
- 10 - 20 min Regional CB Bottom

Note: CB WIMS Tops are only available for vertically developed CB clouds extending through 35,000 feet, which were only met occasionally.

Worst case delays for CB Top products have been observed for these few collected CB Tops and could have been reduced with a better synchronization between WIMS availability at GWP and aircraft requests.

### 5.2.4 Datalink cost

The cost of using a Swift 64 MPDS service (i.e. a channel on which the bandwidth is shared with all online users and therefore there is no guarantee of specific bandwidth allocation) is determined by the amount of transmitted / received data, not by the amount of time spent on line. The chosen Satellite Service Provider used INMARSAT service for which a contract has been concluded for the flight test period.

Figure 27 shows the cost per Kbyte of exchanged data. Every data point represents a test flight in the test period.

Transmission of one Kbyte of data costs approximately between € 0.20 and € 0.56.

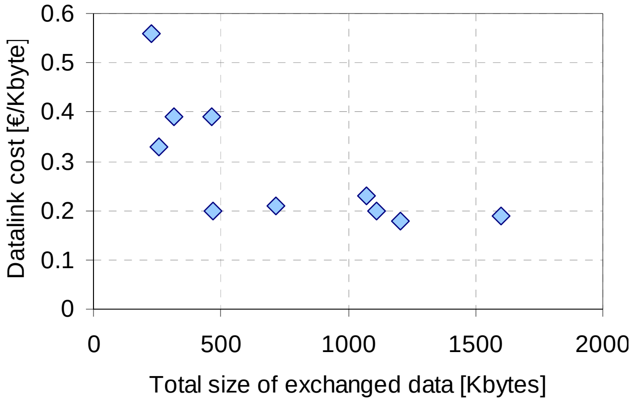

*Figure 27 Datalink cost as function of exchanged data size for 10 performed test flights*

The datalink costs are given here for reasons of completeness. They are given as preliminary results of weather datalink costs with a satellite link. It should be noted that these costs are related to the contract that was subscribed with the chosen DSP for this experimental flight tests campaign. As a result, it is difficult to translate these costs to costs for a much wider use of a future system. It is expected that, based on large amount of data transmissions, airlines would negotiate better rates for operational use.

# 6 Conclusions

Following conclusions are drawn:

1. In the summer of 2008, 21 flights (40 hours) have been performed to test on-board weather data fusion as part of the FLYSAFE project.

2. During these test flights, WIMS weather forecasts have been successfully uplinked to a research aircraft through a satellite link and fused with on-board weather radar data, thus proving complementary nature of both sources for weather hazards avoidance.

3. The observed amounts of uplinked data were larger than expected, mainly due to the large size of Regional and Global WIMS products. The size is believed to grow further when flying in deteriorating adverse weather conditions like e.g. a squall line (which – as far as they were embedded – were not allowed to be performed during the flight test period due to the use of an experimental (i.e. not fully certified) weather radar).

4. Most of the uplink rates are between 2 and 20 Kbits/s at application level, which is in agreement with prior expectations.

5. Overall WIMS transmission delay (i.e. time at which the WIMS product is available on-board minus the time at which ground observations are made to produce the WIMS product) can sometimes be significant, thereby limiting the WIMS use, as minimum usable forecast horizons of WIMS products available on-board increase.

6. Overall WIMS transmission delays may be reduced by (i) synchronising WIMS availability on ground with upload request from the aircraft and (ii) using upcoming weather services in the near future that will produce satellite images and compose ground radar images faster.

7. It is not straightforward to label the datalink costs as expensive, since this test project and datalink contract are not representative for a much wider use of such a system in future.

Nevertheless, a comparison with other datalink solutions – supporting the large data volume requirement for weather datalink applications – could be useful.

8. Further evaluations are required in the field of (i) consistency between WIMS products and on-board radar data, (ii) fusion functionality and (iii) operational use of the system, since the flight test campaign was mainly focused on assessing the feasibility of uplinking and on-board fusion of weather data.

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