

CB NOWCASTING IN FLYSAFE : IMPROVING FLIGHT SAFETY REGARDING THUNDERSTORM HAZARDS

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Abstract : The FLYSAFE Project aims at defining and testing new tools and systems contributing to the safety of flights for all aircraft, and addresses weather hazards. A “Weather Information Management System” dedicated to thunderstorm hazard has been designed and developed for three geographical scales. It is ground-based, uses as main inputs radar and MSG satellite data and provides nowcasts up to one hour ahead in an object-oriented mode and in a dedicated GML format. Its evaluation involved research aircrafts, both in real time and in an offline setting. Offline evaluation results show the added value of the products, with respect to on-board data, especially regarding the cases of on-board radar return extinction by heavy rain, and regarding extended spatial coverage, most useful when the aircraft turns sharp. Additional potential value of the products show in the CB objects attributes like trend and hail occurrence

1 THE FLYSAFE PROJECT

In the perspective of a trebling of the flights over the period 2000-2020, the preservation of a high level of safety was retained as a priority research axis by the European Commission and ACARE (Advisory Council for Aeronautics Research in Europe). An important piece of this research has been put in place early in 2005: the FLYSAFE Project (<http://www.eu-flysafe.org/>). It is a European Commission funded project aiming at improving flight safety through the development of a Next Generation Integrated Surveillance System (NG-ISS). The NG-ISS provides information to the pilot on a number of external hazards which address the three types of threats:

- traffic collision
- ground collision
- adverse weather conditions

Also, FLYSAFE developed new systems and functions for:

- improved situation awareness
- advanced warning

- alert prioritization
- enhanced human-machine interface

One particularly innovative feature of the NG-ISS is that it is coupled to ground facilities which are being designed to provide the best possible nowcast (short range forecast up to an hour) of the most dangerous meteorological hazards. This is made possible by the development of so-called Weather Information Management Systems (WIMs). The WIMs are best thought of as advanced systems incorporating expertise, which bring together all available information about the hazard under consideration and provide an optimized nowcast for aircraft at risk (Figure 1). Individual WIMs have been developed for the weather hazards icing (ICE WIMs), clear air turbulence (CAT WIMs), wake vortex turbulence (VW WIMs) and thunderstorms (CB WIMs; Cb = Cumulonimbus). These systems provide meteorological data on the individual weather hazards over defined areas ranging from high resolution local scale over continental to global scale.

All WIMs data are sent to a ground based weather processor (GWP). By request from an

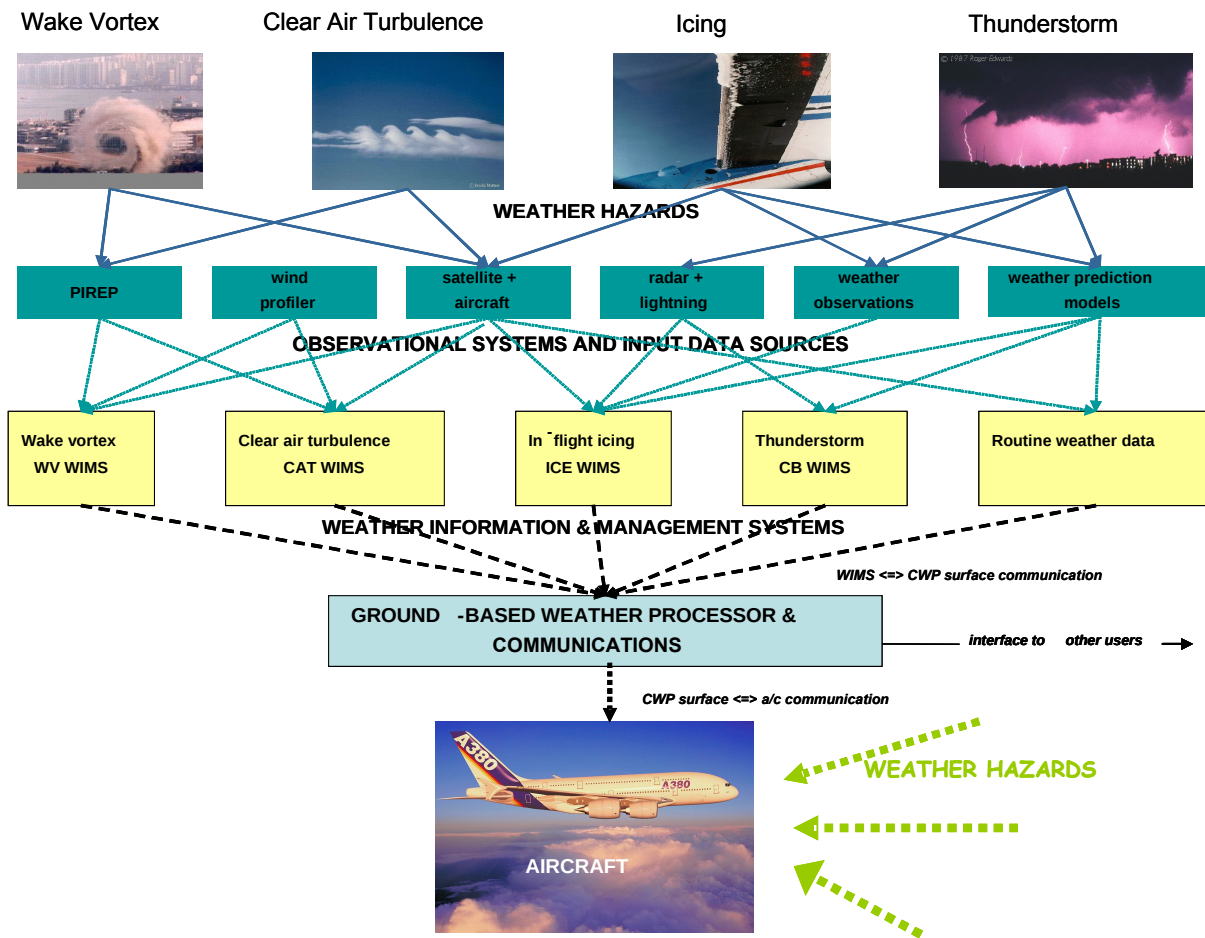


Figure 1: Weather hazards treated in FLYSAFE in Weather Information Management Systems (WIMS) and communication to the aircraft

aircraft selected information about a weather hazard tailored to a respective flight corridor is passed through the GWP to the on-board NG-ISS where a fusion not only with on-board weather data, but also with the other threats terrain and traffic is carried out in order to achieve a consolidated picture of the hazard situation. Finally, the situation is presented to the pilot by means of simple, easy to read graphics on a special display together with the possible solution on how to avoid the hazard.

The CB WIMS has been developed with involvement of partners from the German Aerospace Center (DLR), Météo-France (FMET), ONERA (Paris), the UK Met-Office and the University of Hannover. This paper describes the implementation of the Cb WIMS, the evaluation strategy, and the results gained from the flight tests.

2. THE CB WIMS APPROACH

In order to be usable by pilots or fused with other on-board weather data the information provided by a weather information system must be simple, easy to understand, of small storage size and quickly deliverable in real time. This stands in contrast to the complexity of weather features like thunderstorms which appear in various shapes and sizes and corresponding life times from a few tens of minutes to several hours. The problem of how to reduce this complexity to certain 'hazard volumes' for air traffic which are tractable and communicable to users has been discussed in [Tafferner]. The strategy followed in the development of CB WIMS was not to describe thunderstorms to any observable detail, but to identify the hazards for aircraft in thunderstorm situations, to find corresponding thresholds for the specific

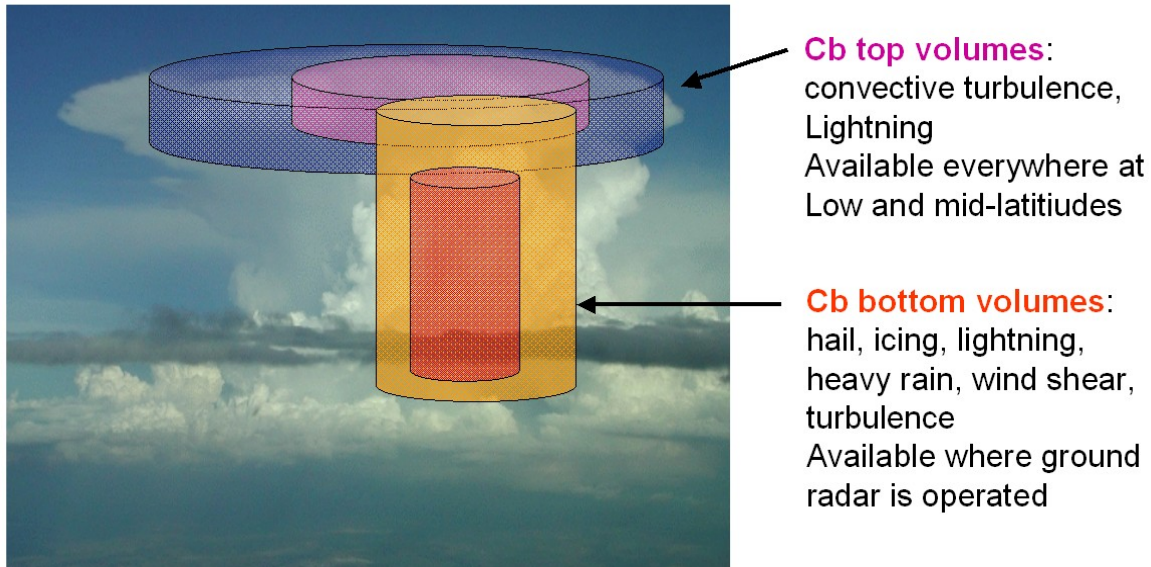


Figure 2: Thunderstorm (Cb) weather object rendered as idealized volumes (redrawn from [Tafferner]).

hazard levels “moderate” and “severe”, where severe indicates a no-go volume of air space, and based on these, to define hazard objects which represent these hazard levels. The task of CB WIMS is therefore to detect and forecast these hazard objects on the very short term, e.g. for up to one hour in advance.

Figure 2 renders a schematic depiction of such thunderstorm hazard objects (re-drawn from [Tafferner]). The various threats an aircraft is exposed to when flying into a thunderstorm, e.g. during flight phases landing and take-off or en-route, are indicated in the figure. The volumes have been given the names Cb top and Cb bottom. In addition, volumes may be nested due to the prescription of two levels of severity. As will be shown later the volumes are not cylinders as depicted here, but are polygon surfaces with bottom and top

3. CB WIMS DEVELOPMENT AND FEATURES

The role of the various partners involved in the development of CB WIMS is detailed in [Tafferner]. However, for quick reference and in order to ease understanding in what follows in

the evaluation the main parts of development and features of Cb WIMS shall be listed here briefly.

Based on meteorological input data, including remote sensing observations and numerical model data, the CB WIMS provides thunderstorm information on three different scales, i.e. areas. The different scale products developed by the CB WIMS partners which underwent evaluation are as follows.

- Local or TMA scale, where TMA stands for Terminal Maneuvering Area of an airport, derived from systems developed at Météo-France and DLR.

- Continental scale derived from systems developed at Météo-France, and DLR

- Global scale provided by the UKMET-Office' global forecast model

These scale products differ not only in terms of area covered, but also in spatial resolution and time between updates. For the evaluations however only the local and continental scales are considered. The continental product covers an area such as that of Central Europe, while the local (TMA) product is limited to roughly 300 km around an airport (Paris Charles de Gaulle in this case). These products are generated independently by the partners and delivered to the ground

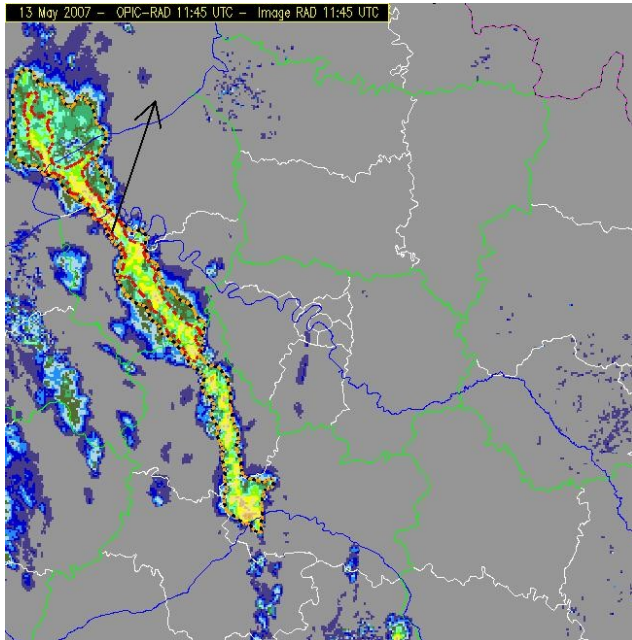


Figure 3: Cb bottom contours marked in colors of orange for hazard “moderate” and red for “severe” overlaid on radar imagery for TMA Paris on 13 May 2007, 1145 UTC. The arrow indicates the forecast moving direction of the bottom object’s gravity center.

based weather processor (GWP) in the form of thunderstorm bottom and top volumes.

For providing bottom volumes Météo-France has set up a real-time processing of 3-dimensional radar data for five radars surrounding the Paris TMA. This processing suite has been implemented at a refresh rate of 15 minutes and with corresponding spatial resolutions of 2 km in the horizontal and 500m in the vertical. Technically, the 3D fields are computed following [Bousquet], using a concept developed several years ago [Bousquet] in a research context and now applied in an operational environment. A downscaling technique has also been implemented in order to reach the required 1 km² x 5 minutes space-time resolution over the central part of the TMA by taking advantage of the frequent low elevation scans. The 3D data is used in the CONO software [Hering] for better defining the echo top height and maximum reflectivity of objects. The

computation of objects at two severity levels has been implemented, using reflectivity thresholds of 33 and 41 dBZ which were shown to best match the thunderstorm occurrences in METAR reports for towering Cumulus and Cumulonimbus, respectively and are in close agreement with a previous study [Rhoda]. Figure 3 shows an example of bottom volumes over the TMA Paris for 13th May 2007 at 1145 UTC. Outlines of volumes over radar reflectivity are given in orange for severity 1 (moderate) and red for severity 2 (severe). Also indicated is the direction of movement of the thunderstorm cells. Taking advantage of the dual polarization capacity of the Trappes radar located in the center of the TMA, a hail diagnostic was implemented in order to document the hail occurrence attribute of the bottom objects. At the continental scale, Météo-France applied the same CONO algorithm to a large area radar composite which was designed for this project and included all France neighbours national composites available, from Spain to UK and Germany.

For the detection of CB top volumes DLR uses its cloud tracker Cb-TRAM which detects convective clouds in the three stages

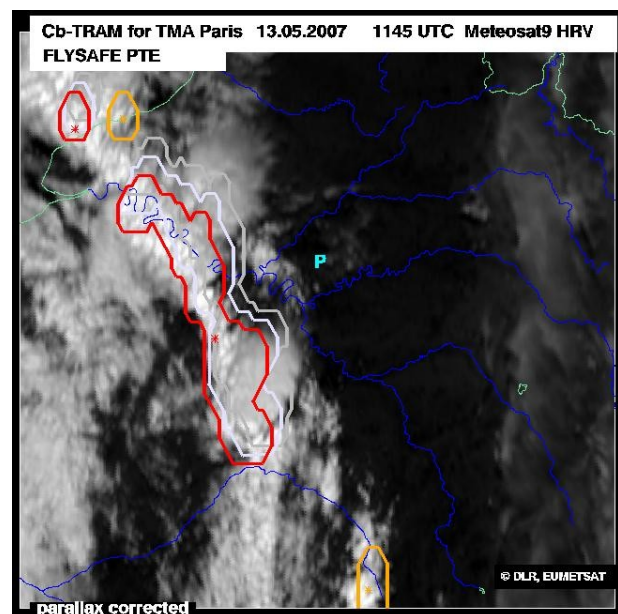


Figure 4: Cb top contours marked in colors of orange for “rapid development” and red for “mature thunderstorm”, overlaid on satellite imagery in the high resolution visible channel. Also marked are nowcast positions after 30 and 60 minutes in white and grey. TMA Paris on 13 May 2007, 1145 UTC

“initiation”, “rapid growth” and “mature” using a special three-channel combination of METEOSAT data. Details of the algorithm can be found in [Zinner]. For delivery to the GWP only volumes containing mature thunderstorm cells are selected, because growing cells have not reached tropopause level (yet) and therefore do not represent thunderstorm tops. CB TRAM is used for both the TMA and regional scales. However, METEOSAT rapid scan data with a refresh rate of 5 minutes are used for the TMA whereas conventional METEOSAT with a refresh rate of 15 minutes are used for the continental scale. Thus, the refresh rates for both Cb bottom and top volumes are the same for TMA (5 min) and the continental scales (15min). Lightning data from the LINET network [Betz] are used for CB top volumes to discriminate between severity levels moderate and severe, where ‘severe’ is used when at least for 50 % of the pixels within the top volume a lightning observation is found next to them within five minutes. Figure 4 shows an example of detected thunderstorm top volumes at the same time as shown for the bottom volumes.

Besides detection and tracking the bottom and top hazard volumes both algorithms provide also nowcasts of future positions and development up to an hour ahead in time. In Figure 4 the grey contours show the extrapolated positions of the mature cells (in red) after 30 and 60 minutes. Besides location, the Cb objects are provided with a number of attributes. These are:

- Area covered, as a polygon
- confidence level
- hail occurrence flag
- layer (top or bottom)
- moving direction
- moving speed
- gravity centre location
- severity
- trend on area
- trend on vertical development
- upper boundary
- lower boundary

As seen from the list, a confidence level is included which expresses the confidence

which the CB WIMS producer has in the validity of the product. It is a number between 0 and 5 (for lowest and highest confidence, respectively) and is based essentially on the availability of relevant input data to the CB WIMS and on forecast range. In addition to the parameters listed the WIMS’s output files contain also a “Status Weather Product” section containing a set of parameters describing mainly the origin and validity of the data available to the CB WIMS. This is the so-called meta-data section. It provides also information on the product scale (local, regional, or global scale) including the coordinates of the coverage area.

Regarding data coding and communication issues, the Cb WIMS output is formatted in an advanced XML/GML format which was also developed within the framework of FLYSAFE [Mirza]. This output is

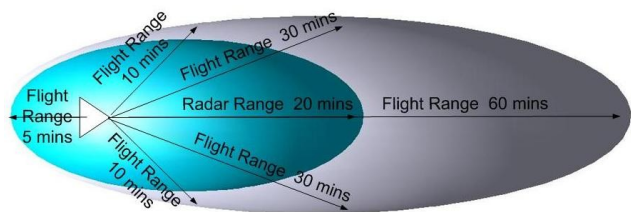


Figure 5: Weather corridor around an aircraft

transmitted in real time to the GWP from which, after request from the aircraft, the Cb objects are transmitted together with CAT WIMS and ICE WIMS data via satellite link to the on-board NG-ISS. Only those data are transmitted from the GWP which correspond to a specific weather corridor, i.e. an ellipsoidal shaped region that surrounds the aircraft and will be traveled during the next 10 to 60 minutes, depending on flight direction (Figure 5).

4. EVALUATION USING A FLIGHT SIMULATOR

The Full Flight Simulator experiment focused on the improvement of the WIMS display in the cockpit, on the expected impact on flight safety and on finding out the degree

of acceptance of the new information through the pilot. Therefore, the simulator tests had the following evaluation objectives:

- Weather data fusion of onboard radar and WIMS

- Cockpit HMI

- Operational aspects

- Impact on safety

The FFS involved the use of NLR's Flight Simulator [Heesbeen]. The experimental set-up was to feed both the WIMS CB and the on-board weather radar simulator of the Flight Simulator with actual ground network radar composite and additional assumptions regarding the vertical profile of reflectivity. This was performed for a set of four cases for flight

paths from Innsbrück to Paris with significant thunderstorms. For comparing on-board weather and WIMS products, on-board radar images were simulated as would be seen in a flying aircraft and displayed to the pilots. Also weather objects were fused with the simulated on-board radar and shown on display. This set-up enabled to test the data flow and the fusion of the objects, as shown on Figure 6. Detailed results of this evaluation are documented elsewhere. The main results regarding WIMS CB design were the good consistency WIMS CB objects with simulated on-board radar data, their usefulness in the Strategic Conflict Detection algorithm, and the need for improving the exchanges with

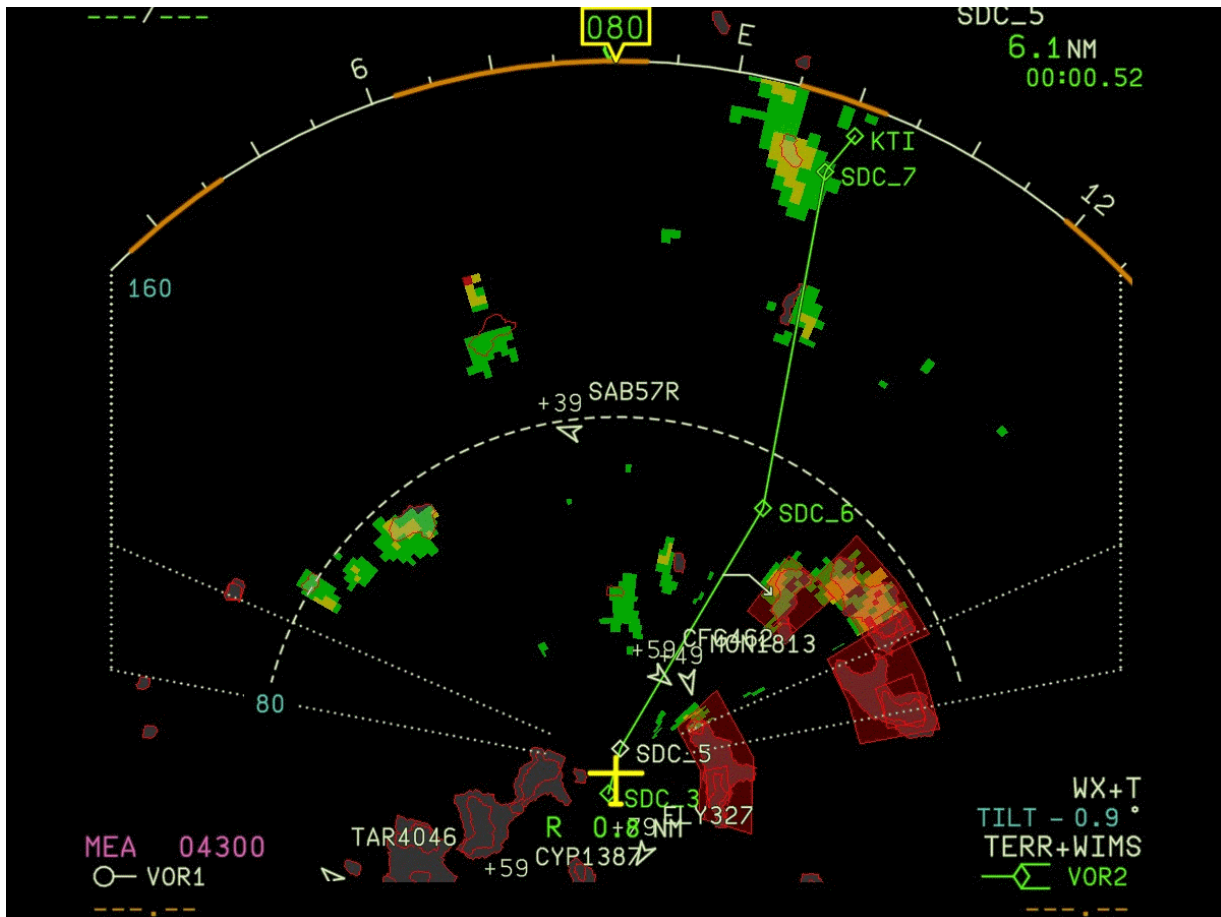


Figure 6: Flight Simulator Screen. Simulated on-board radar data shows in the background. Red thin contours are WIMS CB objects. Hatched polygons represent fusion of on-board radar data and WIMS-Cb objects. Points labeled SDC along the predicted trajectory show CB avoidance solutions by the SDC algorithm.

partners developing the HMI and the data fusion for bringing the best of WIMS CB value to the pilots

5. EVALUATION THROUGH FLIGHT TESTS

5.A. Flight tests setting

Flight tests were organized in summer 2008, involving two research aircrafts : the ATR42 from SAFIRE French atmospheric research aircrafts unit (<http://www.safire.fr/>) and a Metro Swearingen II operated by the dutch NLR (<http://www.nlr.nl>). The goals were different for the two aircrafts.

NLR flights aimed at testing the data-link from all WIMS through the GWP up to the aircraft; it also aimed at demonstrating the on-board, real-time, fusion of CB WIMS products with data from an enhanced on-board weather radar; this through a display of both kind of data and of fused data

Because the advanced radar did replace the Metro on board radar, but was not fully qualified at that time, flights were performed in VFR conditions, and did not occur close to embedded CB conditions.

SAFIRE flights were devoted to the recording of in-situ and conventional onboard radar data for offline evaluation of the products from WIMS CB, ICE and CAT. Among the in-situ measurements capabilities, the turbulence and vertical speed recordings were the most useful for CBs. The ATR42 on-board radar is a SPERRY Primus 800 1.2 kW radar, with a 3cm wavelength, an 18" antenna and a 5.6°



Figure 7: NLR Metro Swearingen research aircraft

beam width; setting up a digitized recording of the full radar data proved to be intractable in the time schedule of the project. Therefore, a video recording of the on-board radar screen was settled. The geo-location of images from video recording was performed through an automatic pattern recognition algorithm which compensates for the changes in camera attitude, and which analyzes the images for identifying the range setting. Gain setting recording was manual.

Around 10 ATR flights produced useful data. One of the main issues for performing flights at the TMA scale was the set of ATC constraints, which imposed a very strict geometry for the flight path around the Paris airports, and also imposed to plan the flight take-off in a +/- 1h time frame and this on the day before. This posed a challenge to the CB onset forecast, which was not met in the kind of synoptic setting which prevailed during summer 2009 and given the flat setting of Paris surroundings. Accordingly, interesting data were collected for 9 cases at the regional scale, with a quite strong convective activity for 6 cases : august 6, 7, 12, 14 and 19, and september 3rd. Most of them occurred over France

5.B. Results regarding radar return attenuation and extinction

Figure 9 and Figure 11 illustrate the information usually available to the pilot regarding the description of CBs. This case



Figure 8: SAFIRE ATR42 research aircraft



Figure 9: CB anvil photograph in front of the aircraft at 13h40UTC , 12th august

occurred on August 12th, at 1340 UTC, in the setting described ten minutes earlier by Figure 10. The out-of-the-window look shows a well-developed CB anvil (Figure 8) and the on-board radar (Figure 11) confirms that a quite powerful convective cell occurs on the left of the aircraft path, up to a range of 20 nautical miles. In contrast, ground weather radar data from 5 minutes earlier, when roughly re-mapped to the on-board radar view (and with similar colors, Figure 12), clearly shows that a well-organized line of convective cells extends up to ranges of 60 nm. This information could be of high value to the pilot in such a case for deciding whether to pass to the left or to the right of the line, in order to avoid crossing it.

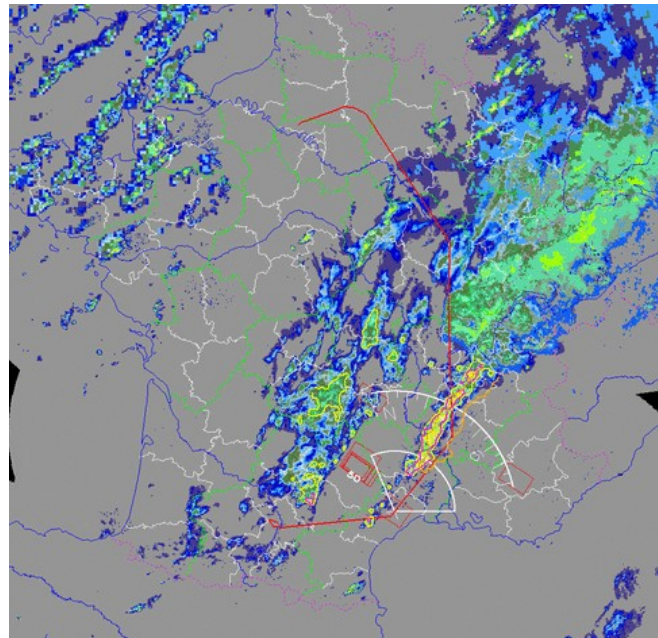


Figure 10: Ground radar composite at 13h30 UTC with aircraft path in red and on-board radar sector lines in white



Figure 11: On board radar screen at 13h40 UTC

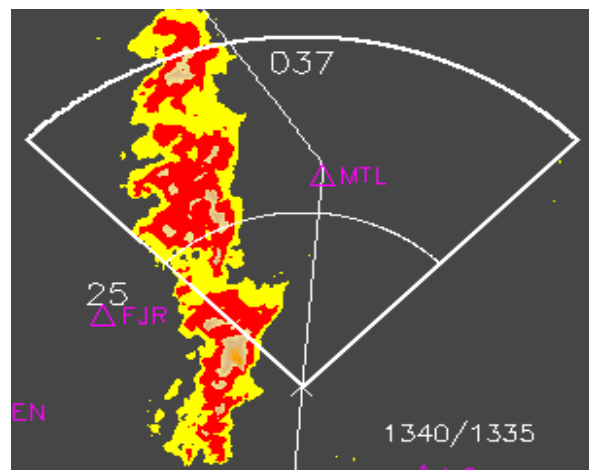


Figure 12: Ground radar data at 13h35 re-mapped to the on board radar geometry for 13h40

This case however does not actually show WIMS Cb objects and hence does not address the question of the level of simplification of the ground radar data by the object representation. Figure 13 provides a first example of this representation. A quite powerful Cb on August 19th occurred on the Pyrenees range. At 15h23 UTC , the WIMS CB depiction , which shows as magenta and yellow contours for the two severity levels of the bottom object, closely match the on-board radar depiction. In that case, the cell was not developed enough in order that a Cb top objects was detected.



Figure 13: On board radar screen and Wims Cb objects for 15h23 on 19 august. Magenta and yellow contours show bottom objects of severity level 2 and 1 and are 3 minutes forecast. Red line is the aircraft actual track.

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In contrast, another example of strong mismatch and under-detection by the on-board radar, which is also clear using WIMS CB objects is shown by the set of three panels on Figure 14; all three panels refer to the same geographical domain and show the same WIMS CB objects, which are valid at 14h05 UTC on August, 19th. The radar images times are different : 14H05, 14h15 and 14h25 UTC

A hazard area identified at 14h05 by WIMS CB top and bottom objects (marked by a blue ellipse) is not sensed by the on-board radar at that time, but is sensed 10 minutes later, at 14h15. The same applies for the area marked by a cyan square at 14h05, which is further from the aircraft, and which is sensed only from 14h25 (red square)

Another advantage of the WIMS CB objects also shows on the top panel of Figure 14 : on the left of the aircraft, some 50 to 80 nm ahead, a large area of strong radar returns is showing, which is not met by any WIMS CB objects; these returns actually proved to be ground clutter generated by the Devoluy and Vercors mountain ranges in southern Alps.

A last example shows that attenuation can be caused even by a convective cell of moderate activity and extent. On Figure 16, the cell located some 20 nm ahead of the aircraft actually hides the next one, some 45 nm ahead, shown by the WIMS CB bottom object and confirmed by the aircraft trajectory change (in red).

The interpretation for this onboard radar under-detection of heavy cells is that the radar return is strongly attenuated by the rain encountered by the radar beam across the rain cells at short range, and may reach complete extinction. Due to the short wavelength used for on-board radar (3cm), attenuation is much stronger than for the ground radar (which wavelengths usually are 5 or 10 cm); additionally, the ground composite radar image do benefit from the radar network effect, which allows multiple lines of sight from multiple radars to a common cell, and hence minimizes the effect of attenuation.

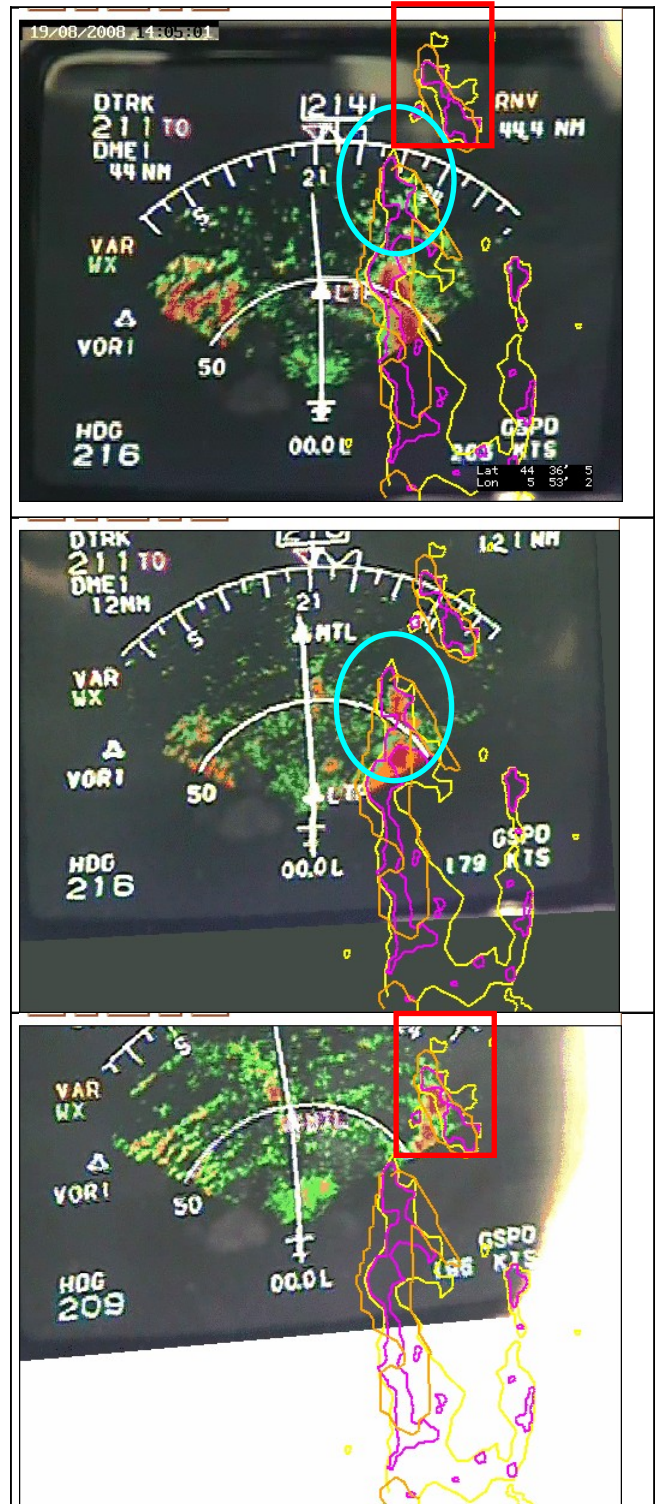


Figure 14: On board radar images for 14h05, 14h15 and 14h25 on 19th August. Last two images are remapped to the on board radar location at 14h05. WIMS CB objects for 14h05 show on all images. Contours as in previous figure, plus orange contours showing CB top objects

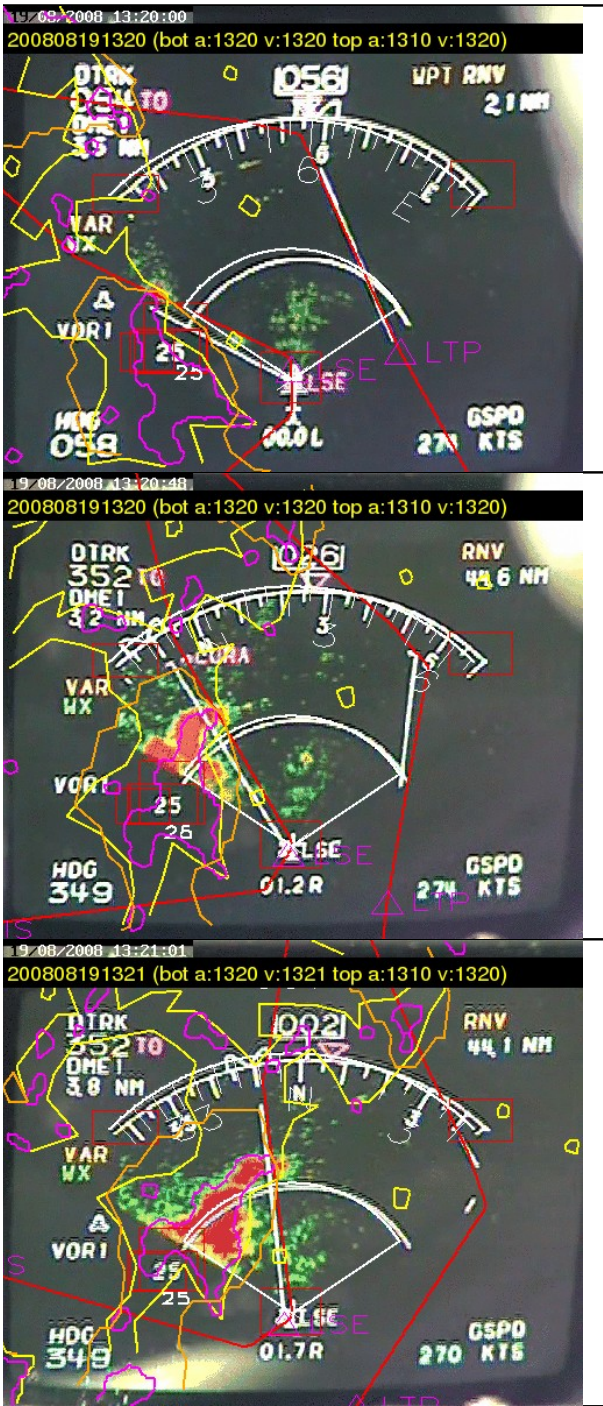


Figure 15: On board radar images and Wims CB objects during a sharp turn. Top image at 13h20'0" on august 19th, next images 40 and 61 seconds later. Objects are diagnosed using data from 13h20

Another factor could be invoked for the on board radar under-detection : a lack of automated agility for scanning at various tilt angles, which could cause a horizon effect at long ranges, i.e. that an almost neutral tilt would fit the need for sensing at short ranges but would cause the radar beam to be too high at longer ranges due to earth curvature. This explanation only applies when the convective cells causing the attenuation have a top which lies under the flight level, and so only for cells in the developing stage when they are encountered during high altitude cruise.

5.C. Results regarding spatial coverage

The on-board radar scans ahead of the aircraft over a sector which is usually 90 to 120° degrees wide. When the aircraft has to turn sharp, this can cause a temporary blindness which can be detrimental to the safety, or at least to the smoothness of aircraft operations. Figure 15 shows an example of such a case : on Augusts, 19th, the aircraft reached Lyon (LSE waypoint) at 13h20'00" (first panel) where he has to turn left sharp; the WIMS CB objects were depicting severity level 2 bottom objects and a top object close to the aircraft predicted path (red line), at a location not yet covered by the on-board radar; some 48 seconds later, the on-board radar showed a strong reflectivity pattern which matched very closely the bottom object, and was confirmed at 13h21'01". In such a case, where the WIMS CB objects also showed that convection was scattered at longer ranges and to the right of this hazard, such an information could have help in delaying the turn for safer operations. Another kind of situations where this extended spatial coverage could significantly help pilots of course is the take-off and landing maneuvers where strong turns are much more constrained for aligning with the runways and can occur also without any visibility in case of embedded convection

5.D. Further results

a. General agreement : beyond the few examples shown above, careful examination of the data from the six flights showing the heaviest convection allows to confirm that there is almost always a good agreement between WIMS CB objects and on-board radar patterns. The bottom objects derived from the ground radar are the one matching most closely the latter, at severity level 2, while the (satellite-derived) top objects generally show a moderately wider extent. Bottom objects of severity level 1 (based on 33 dBZ ground radar threshold) frequently over-estimate the hazard spatial extent with respect to on-board radar. In some occasions, this simply occurs because vertical development of the cells is not as high as the on-board radar scanning height, given the tilt used, and ground radar do sense at a lower altitude.

b. Radar-void areas : while the CB top objects do successfully encompass the hazard zones once the Cbs have developed up to the tropopause, and are available from low to mid and mid-high latitudes from geostationary satellite data, the developing phase of Cbs cannot be described by the radar-based bottom objects in some radar void areas, like oceans or steep orography. Nevertheless, in a number of occasions, objects derived from satellite data can provide a valuable depiction of these Cbs, like illustrated on Figure 16; the limitation to this capacity of course is to the development of a cloud shield aloft, like in the case of Mesoscale Convective Systems where the anvil of first CBs do merge and prevents the detection of the next ones from space.

c. Products timeliness : An important issue which appeared in the course of the real-time experiment is the data timeliness : in the flight test experimental setting used, the overall delay between data observation time and availability on-board the aircraft was frequently larger than 15 minutes, which resulted in the use of nowcasts for the same range; some qualitative checks confirmed the well established finding that, in phases of CB

development, this can lead to a significant mismatch with actual Cb intensity or extent, which can be an operational issue. Nevertheless, two series of actions can compensate for insufficient timeliness; first the communication mechanism proved to be suboptimal, with the aircraft requesting the data from the ground quite un-frequently and without taking care of the production schedule, while this could easily be done; second, the WIMS production refresh rate could be improved for the regional scale from a 15 minutes period to a 5 minutes one; this would be easy regarding CB top objects by the use of Meteosat Rapid Scan data, and this is also feasible for the CB bottom objects on large parts of the European territory given the today characteristics of most national radar



Figure 16: On board radar image for 7 August, 12h20 UTC. Contours as in previous figures, except for the addition of blue contours showing the satellite depiction of developing cells

networks, and the upcoming setup of the EUMETNET Opera radar compositing center for Europe [Chèze]; at a longer time horizon, Meteosat Third Generation refresh rate should include a 2.5 minutes scheme [Eumetsat], and airport dedicated weather radars could help in scanning the TMA at a similar or even better rate.

d. Pilots feedback : the Flysafe project involved expert pilots in the assessment phase; the results regarding the off-line evaluation of the WIMS CB lead them to recognize the Potential operational value of WIMS Cb, and to consider that among Wims-CB objects, severity 1 bottom objects and top objects can be seen as places outside which there is definitely no hazard, which is a valuable information. They took note that accuracy and details of the on-board radar data is nevertheless of fundamental value at shortest ranges, and that more than two levels of WIMS CB objects severity could be used. WIMS-CB objects trend and lightning counts were felt interesting for the pilot,

and atmospheric analyses from ground with on-board information

- and hence it provides a "complete" picture
- Future inclusion of (advanced) operational numerical weather forecasts of thunderstorms, incorporating advances in meso-scale data assimilation, ensemble forecasts, etc... will definitely improve the forecast quality and smooth the transition from nowcast to forecast time horizons.

6. CONCLUSIONS

In the course of the Flysafe project, for prototyping the new generation of aircraft safety systems, the concept of a Weather Information Management System devoted to the provision of thunderstorm nowcasting has been designed and developed up to a real-time demonstrator. It makes use of all remotely-sensed data (radar, satellite, lightning detection) Its off-line testing allowed to reach the following conclusions ;

- Thunderstorms can be represented by relatively simple bottom and top volumes in a meaningful way for aviation (pilots and controllers)
- WIMS CB data are especially useful at the strategic time scale, namely beyond 10 minutes and in combination with Strategic Data Consolidation and Conflict Detection & Solution functions on-board an aircraft
- There is a real potential of the WIMS CB concept for safety in aviation since ...
 - it surveys a much larger area than a single radar on-board the aircraft
 - it fuses data from lightning, satellite (multiple channels), polarimetric C and S band radar

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