Journal of Air Transportation
Vol. 24, No. 4, October 2016

Satellite-Based Real-Time Thunderstorm Nowcasting for Strategic Flight Planning En Route

Caroline Forster*
DLR, Deutsches Zentrum für Luft- und Raumfahrt, 82234 Wessling, Germany
Andreas Ritter†
Deutsche Lufthansa AG, 60546 Frankfurt, Germany
and
Steffen Gemsa,‡ Arnold Tafferner,§ and Dennis Stich¶
DLR, Deutsches Zentrum für Luft- und Raumfahrt, 82234 Wessling, Germany

DOI: 10.2514/1.D0055

The added value of a satellite-based thunderstorm detection and nowcasting system with respect to flight safety and efficiency is shown by comparing onboard observations carried out by Deutsche Lufthansa AG and Deutsches Zentrum für Luft- und Raumfahrt pilots to the detection and nowcasting information in both postflight analyses and in real time. For the first time, detection and nowcasting data could be successfully uplinked into the cockpit of aircraft during flight in real time, thereby demonstrating that these data are in good agreement with the returns of the onboard radar, and furthermore provide an overview of the thunderstorm situation around the aircraft and along the aircraft's flight track. Pilots can use the detection and nowcasting information to strategically plan their route up to 1 h ahead in time. The result is safer flight routes that avoid inadvertent flights through areas where thunderstorm-related hazards like turbulence, icing, and hail occur. In addition, the improved strategic planning enables smarter flight routes, resulting in fuel savings, reduced delays, and less deviations to alternates.

I. Introduction

THUNDERSTORMS and their accompanying phenomena (like turbulence, icing, heavy precipitation, hail, and lightning) are among the most hazardous weather events for aviation. Pilots prefer to avoid thunderstorms whenever possible. En route, and especially during nighttime over the ocean, the only information source about the current weather situation is the onboard weather radar. The reliable range of the onboard radar, however, is only limited to typically 150 n miles (corresponding to about 20 min of flight time) and can only scan a limited sector in front of the aircraft. Pilots can therefore not see whether there are thunderstorms behind and sideways to the aircraft, which is critical when they have to fly avoidance maneuvers. In addition, the precipitation in strong thunder cells attenuates the onboard radar beam with the consequence that further thunder cells located behind are not detected, thus providing an incomplete picture of the thunderstorm hazard [1]. Ice crystals in the upper parts of the thunder cells (i.e., at levels where aircraft fly) are another problem, as they cause only weak radar returns, with the effect that the cells might not be recognized. Another source of uncertainty for assessing the thunderstorm threat arises from the nature of the storms, as they are quickly developing phenomena with typical lifetimes of only 30 min [2]. All these constraints make it difficult for pilots to find the safest possible route through regions with thunderstorm activity and increase the stress level in the cockpit. The results are detours leading to increased fuel burn, delays, and diversions, as well as inadvertent flights through convective cells, with all resulting in considerable costs [3–5].

For flight planning, pilots mainly rely on weather charts according to the International Civil Aviation Organization's (ICAO's) Annex 3, provided by the World Area Forecast Centers (WAFCs). Examples are significant weather charts (SIGWXs) and turbulence and icing forecasts. During flight, no updates of these charts are available, and weather information can only be provided through oral conversations with the air traffic control and other aircraft, as well as with encoded text messages like meteorological aerodrome reports, significant meteorological phenomena (SIGMETs), and terminal aerodrome forecasts (TAFs) transmitted over the Aircraft Communications Addressing and Reporting System (ACARS). Weather charts are thus outdated when used, especially during long-haul flights. In addition, weather forecast charts lack sufficient detail in space and time, and they provide only a rough estimate of the future atmospheric state. The content of these charts is generated from the output of global numerical weather prediction models that calculate the atmospheric state hours and days in advance, based on physical equations describing the thermodynamic state of the atmosphere. The initial state for such calculations is not exactly known, as observations of the atmospheric state are not available everywhere on the globe in the necessary density. Furthermore, the grid resolution of global models is only about 25 to 50 km, which is by far not enough to resolve small-scale features like convection and turbulence. Therefore, weather forecasts from these models cannot predict the exact location and time of the occurrence of thunderstorms and are not suitable to adjust flight routes. For example, Fig. 1 displays a SIGWX issued by the Washington WAFC valid for flight levels (FLs) 250–630 at 06 United Time Coordinated (UTC) on 18 August 2015 and the corresponding Meteosat infrared (IR) 10.8 μm observation valid for this time overlaid with thunderstorms as detected by a cumulonimbus tracking and monitoring system (Cb-TRAM; described in detail in Sec. II) on top. The area of the Meteosat observation corresponds to the area marked by the rectangle. Mature thunderstorms and rapidly intensifying thunderclouds are indicated by contours. The SIGWX indicates a huge area with embedded thunderstorms over the Central Atlantic between about 5 to 40°W and 5 to 15°N. Indeed, thunderstorm activity was observed west of 30°W at this time, but only a few small thunderstorms occurred between 20 and 30°W. In

Received 30 September 2016; revision received 24 January 2017; accepted for publication 2 February 2017; published online 13 March 2017.

*Scientist, Institut für Physik der Atmosphäre, Oberpfaffenhofen; caroline.forster@dlr.de.

†Aircraft Captain and Head of Flight Operations Procedures and Technology Group Airlines, LH-Basis; andreas.ritter@dlh.de.

‡Test Pilot, Flugexperimente, Oberpfaffenhofen; steffen.gemsa@dlr.de.

§Scientist, Institut für Physik der Atmosphäre, Oberpfaffenhofen; arnold.tafferner@dlr.de.

¶Scientist, Institut für Physik der Atmosphäre, Oberpfaffenhofen; dennis.stich@dlr.de.

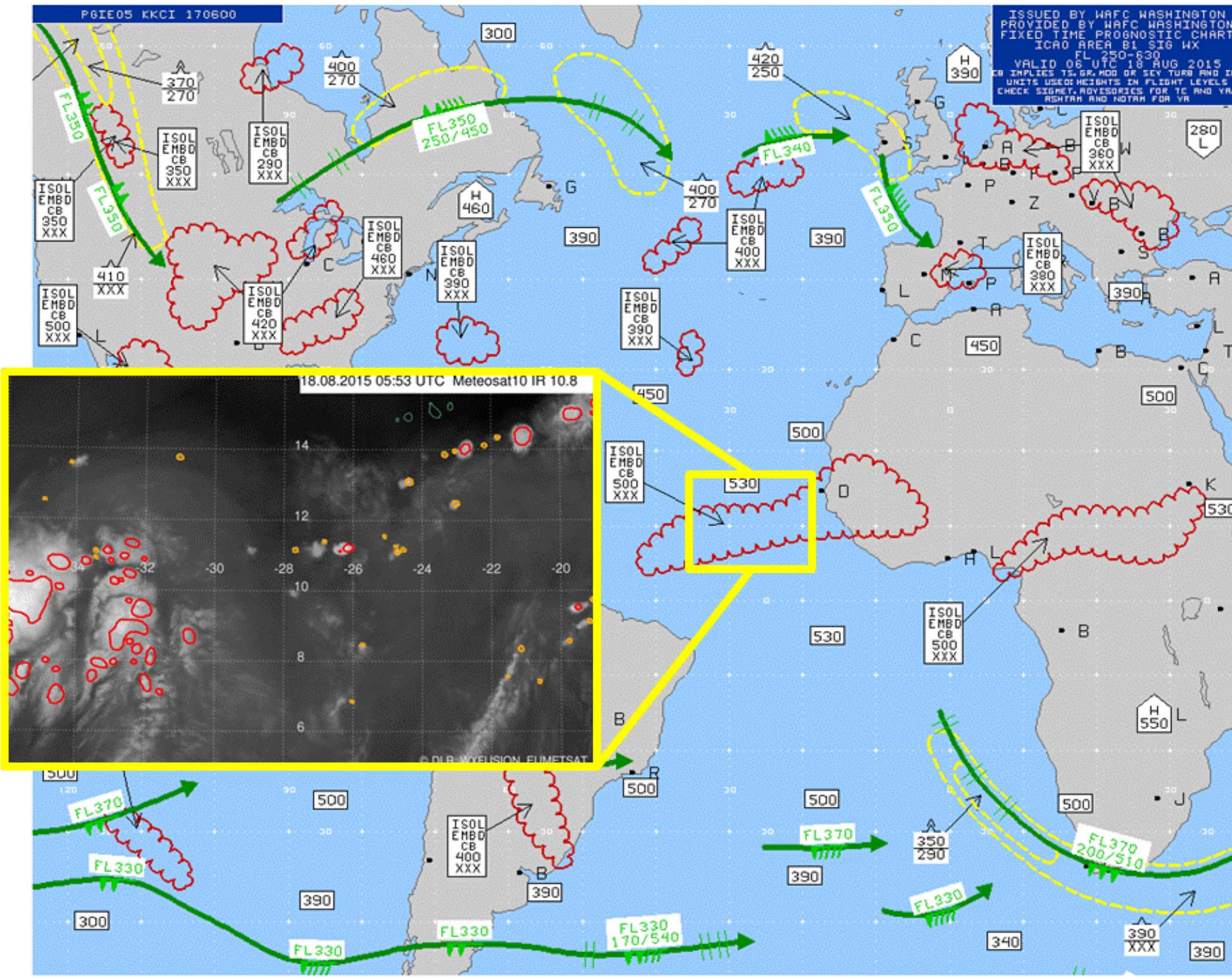

Fig. 1 SIGWX overlaid with corresponding Meteosat observation including Cb-TRAM contours.

particular, the SIGWX could not depict the location of the thunder cells and the gaps in between.

Many efforts have been undertaken in order to improve thunderstorm forecasts for aviation. Expert systems have been developed that combine model forecasts with satellite, radar, lightning, and further ground-based observations in order to get a more complete picture of the current weather situation, thereby improving its forecast for the next hours. Examples are the Integrated Terminal Weather System [6], an auto-nowcast system [7], and the Weather Forecast User-Oriented System Including Object Nowcasting (WXFUSION) [8,9]. Most of these systems provide thunderstorm detections, deterministic forecasts of thunderstorm cells up to the first hour, and a probability or likelihood of thunderstorm occurrence beyond. Deterministic thunderstorm forecasts are based on technologies that extrapolate observations from (for example) radar or satellites up to 1 h into the future (called nowcasting). Several radar-based nowcasting systems have been developed [10–13]. While these are limited to applications over land where ground weather radar measurements are available, satellite-based systems cover much larger areas and can be applied over the ocean and regions where other observations are rare. A variety of algorithms have been developed in the past, with some focusing on the convection initiation stage [14–17] and others focusing on the detection, tracking, and nowcasting of mature thunderstorms [18–24].

Satellite-based detection and nowcasting systems are very useful for the situational awareness of hazards for pilots en route because they provide a precise overview on the location of currently active thunderstorm cells and their movement in the near future in regions where other observational data are rare (e.g., over the oceans and Africa). In particular, the information provided extends the onboard radar range. If this information was uplinked into the cockpit of aircraft in real time, pilots could strategically plan and eventually adjust their flight route in time, instead of searching for gaps between the thunder cells. The benefits are increased flight safety, increased comfort for passengers and crew, and less detours and diversions, resulting in fuel savings and reduced costs. The added value of real-time weather information in the cockpit has already been shown in several studies (e.g., [1,3,4,25]) and projects like FLYSAFE [26], Weather Technology in the Cockpit (WTIC) [27], and eFlightOps [28]. These studies highlighted the potential for cost savings and flight safety: in particular, the advantage of the overview provided by a graphical display instead of a text message and the common situational awareness, if the information is shared among pilots and dispatchers.

Although the technical feasibility of the ground–air datalink of graphical weather hazard information has already been demonstrated in the past (e.g., [3]), the display of this information in primary flight displays is still within the domain of research and development. Many hurdles related to institutional issues like regulation, certification, and quality management have to be overcome before ground-based weather information can be part of avionic systems. However, the increasing use of electronic flight bags (EFBs) and iPads in the cockpit offers new opportunities because they are not part of the avionic systems. Originally, EFBs and iPads were introduced to replace the extensive paperwork (manuals, flight charts, etc.) in the cockpit; but, in combination with Internet protocols (IPs) and modern satellite communication links via (for example) Iridium and Inmarsat, they can also be used to display up-to-the-minute information uplinked from the ground. Now, activities are going on to equip more aircraft cockpits with satellite-connected EFBs. Next to flight-relevant data like actual position reporting, flight level and speed changes, and notices to airmen (NOTAMs), the connectivity of the EFBs shall be used to also send real-time weather information and graphically display it to the pilots. Lufthansa is one of the first commercial airlines in terms of developing the necessary airside and groundside data transmission infrastructures required for establishing a datalink system into the cockpit. This system was used to transmit Cb-TRAM data to an EFB in real time, as described in Sec. IV.

In this paper, we focus on the merit of thunderstorm information from Cb-TRAM with regard to flight safety and fuel savings, and we explain in detail how Cb-TRAM data can help to optimize the flight routing in combination with the onboard radar. We present postflight analyses as well as observations from one research and one commercial flight, where Cb-TRAM data have been uplinked in real time for the first time by using modern satellite communication technologies. The paper is structured as follows: Sec. II provides a description of Cb-TRAM; Sec. III introduces some postflight validations of Cb-TRAM in close cooperation with Lufthansa pilots; in Sec. IV, the real-time in-flight datalink tests are presented; followed by discussion and conclusions in Secs. V and VI, respectively.

II. Cb-TRAM

One of the goals in several research projects at the Deutsches Zentrum für Luft- und Raumfahrt (DLR) was the development of thunderstorm information systems specifically tailored to the needs of users in the aviation sector. One of them is Cb-TRAM. During thunderstorm situations, aviation stakeholders have to make quick and appropriate decisions in order to mitigate the thunderstorm's impact on the operational procedures and to guarantee flight safety, i. e., they need information that is easy to interpret at a glance. In addition, because satellite communication techniques still offer only limited bandwidths (e.g., Iridium on the order of a few bits per second, Inmarsat on the order of 0.5 Mbits/s) and the costs for the up- and downlink of data packages are high, the thunderstorm information to be uplinked has to be reduced to small data amounts and packed in formats that are highly compressible. To meet all these requirements, thunderstorms are rendered as simple objects in Cb-TRAM, representing hazardous areas for aircraft. Analyses and nowcasts of thunderstorm objects as well as specific attributes like moving speed, moving direction, top height, and trend are output in a standard extensible markup language (XML) format [29] which is extendable, compatible with any displays and systems, allows fast selectable reading, and can be compressed to small data amounts of a few kilobytes, enabling inexpensive uplink to the flight deck.

Cb-TRAM uses spectral channel data from the geostationary meteorological satellite Meteosat-10 (Fig. 2), which covers Europe, the Middle East, Africa, the South Atlantic, parts of the North Atlantic, and parts of South America; and it provides data for this viewing area with an update rate of 15 min [23,24]. Two infrared (IR 10.8 μm and IR 12.0 μm), one water vapor (WV6.2 μm), and the high-resolution visible (HRV) channel are combined in order to identify three different stages of thunderstorms, as illustrated in Fig. 3 for a thunderstorm situation over Germany and neighboring countries on 5 July 2016 at 16:45 UTC: clouds that potentially grow to a thunderstorm (development stage 1, yellow contours), rapidly vertical developing clouds (development stage 2, orange contours), and mature stage (development stage 3, red contours). The tracking and nowcasting up to 1 h of the thunderclouds (dashed contours in Fig. 3) are based on a sophisticated image-matching technique that does not only account for the overall movement of the clouds but also for their individual development, including growth and decay. Note that Cb-TRAM does not simply encompass the whole anvil area but the most active parts of the thunderclouds, i.e., those areas where turbulence and lightning can be expected. The accuracy of Cb-TRAM has been verified by a comparison with lightning data over Europe and South Africa for several months [24]. The algorithm provides robust results for these very different climate regions with a probability of detection up to 95% for the analysis and up to 70% for the 1 h nowcast.

Fig. 2 Meteosat coverage area. Source: EUMETSAT.

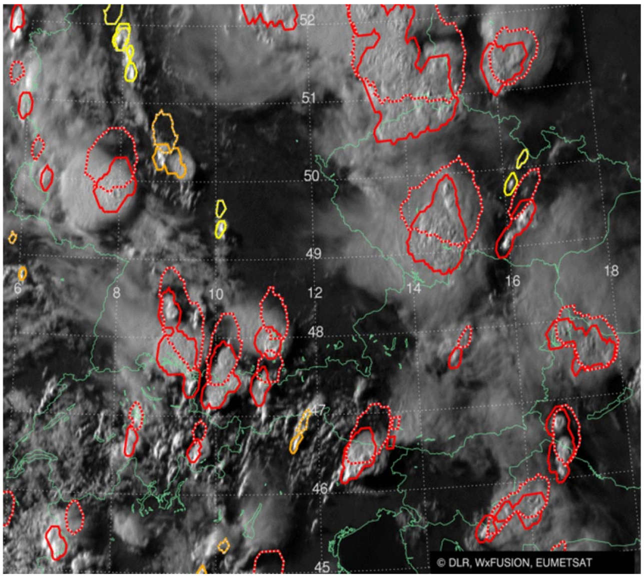

Fig. 3 Meteosat-10 HRV observation with Cb-TRAM detections and nowcasts.

Figure 4 emphasizes the value of the Cb-TRAM information for pilots. It shows a Meteosat-10 IR 10.8 μm image with Cb-TRAM detections and nowcasts over the equatorial Atlantic, displayed as in Fig. 3. Let us assume that an aircraft is on the way on its planned flight route along the white dashed line during nighttime and has just passed waypoint VUKIR. The range of the onboard radar is indicated by the outlined yellow sector. In this case, the pilot can most probably see the thunder cell located in the front left of the aircraft at about 0.5°S/29.5°W, and he may also recognize the rapidly developing cell close to waypoint DIGOR on his onboard radar under favorable circumstances. However, he does not yet see the thunderstorm clusters coming up between 2 and 3°N. If he had Cb-TRAM displayed in the cockpit as additional information on an EFB at this time, he could plan an alternate route, also taking into account the moving direction and the development of these cells. For instance, he could divert to the flight route along BODAK-RAKUD further to the west and ask for clearance of this alternate route without time pressure, instead of following his original route until the thunder cells appear on the onboard radar and not until then start searching for gaps between the thunder cells.

III. Validation of Cb-TRAM with Postflight Analyses

In close cooperation with Lufthansa, Cb-TRAM detections and nowcasts of thunderstorms have been validated in postflight analyses.

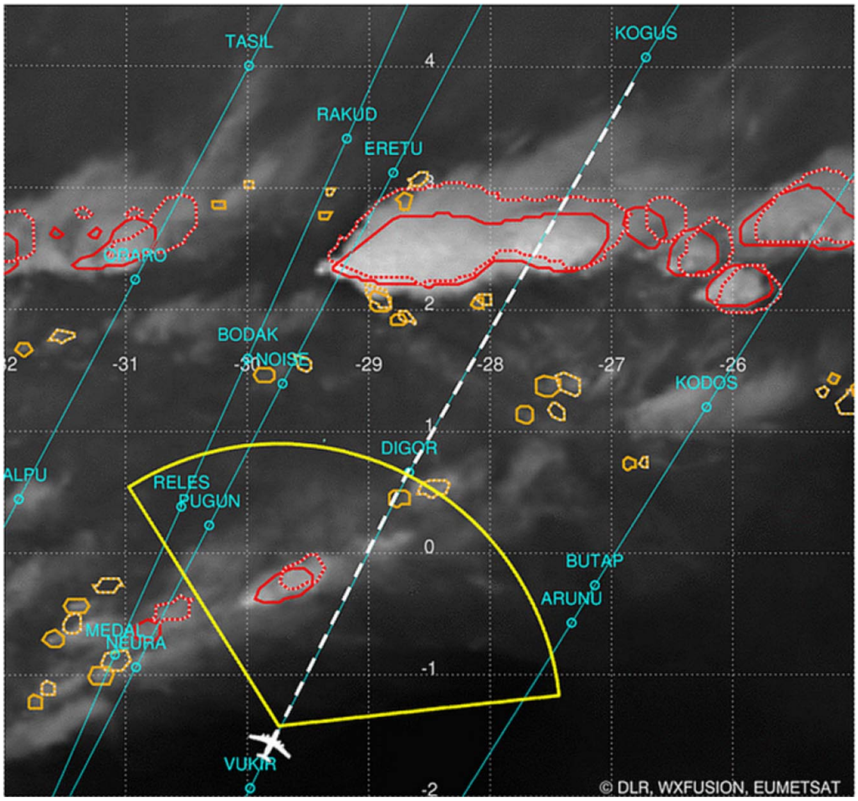

Fig. 4 Meteosat-10 IR 10.8 μm image with Cb-TRAM contours as well as flight routes and waypoints.

During flights over the South Atlantic and over the Mediterranean area, Lufthansa pilots documented the thunderstorm activity on their flight route with photographs of the thunderstorms, onboard radar images, and notes, e.g., on position and time of occurrence of the thunderstorms. The documentation was then compared to Cb-TRAM results, and the accuracy and added value of Cb-TRAM was assessed. Two of these validations are presented next.

The first one was performed for a flight from Frankfurt (Germany) to Rio de Janeiro (Brazil) during the night from 14 to 15 February 2014. The SIGWX from the briefing package at 06:00 UTC on 15 February 2014 (Fig. 5) warned of isolated embedded thunderstorms (ISOL EMBD CB) to the west and occasional thunderstorms (OCNL CB) to the east of the planned flight route (black line): both up to FL450 in the region between 4°N and 4°S of the equator. This area was crossed between 5:45 and 6:28 UTC, exactly at the applicability of this chart.

At 5:45 UTC, when the aircraft was at 5°N 35°W at FL340, the first thunderstorms were visible on the onboard radar (Fig. 6a) about 200 n miles ahead of the aircraft and located directly on the planned flight route toward way point JOBER at 0.95°S/37.05°W (dashed line in Fig. 6a). According to the onboard radar, the gap to the west seemed larger; therefore, the pilots asked for permission to deviate 30 n miles to the west. At this time, the onboard radar was the only information available to the pilots. No SIGMET warning was issued for flight information region (FIR) "Atlantico," where they were currently flying through. There was a SIGMET for the FIR "Recife" further to the south, but this was misleading because the coordinates of the SIGMET warning region closely followed the boundaries of FIR Recife, although thunderstorms existed in the neighboring FIR Atlantico too. When the aircraft was as close as 60 n miles to the thunderstorms, the onboard radar image confirmed that the decision to deviate to the west was correct. At 05:54 UTC, at a distance of

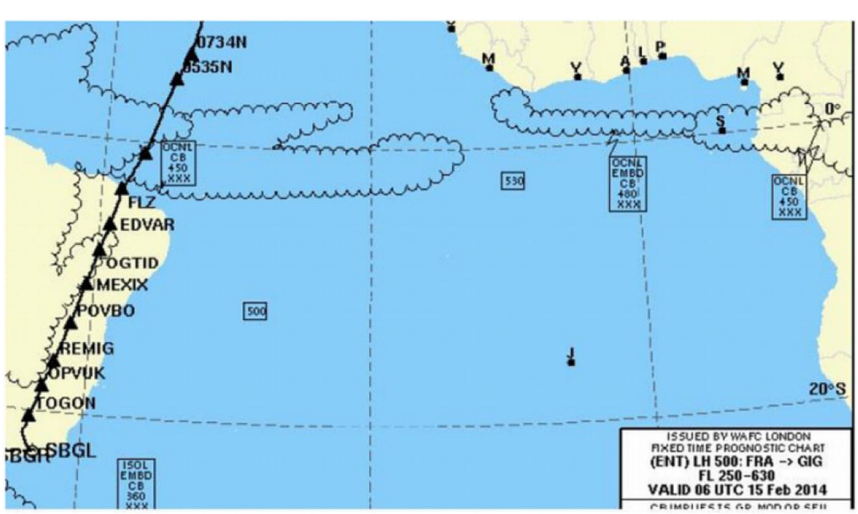

Fig. 5 SIGWX flight route and waypoints (triangles). The unmarked triangle just south of the equator is waypoint JOBER.

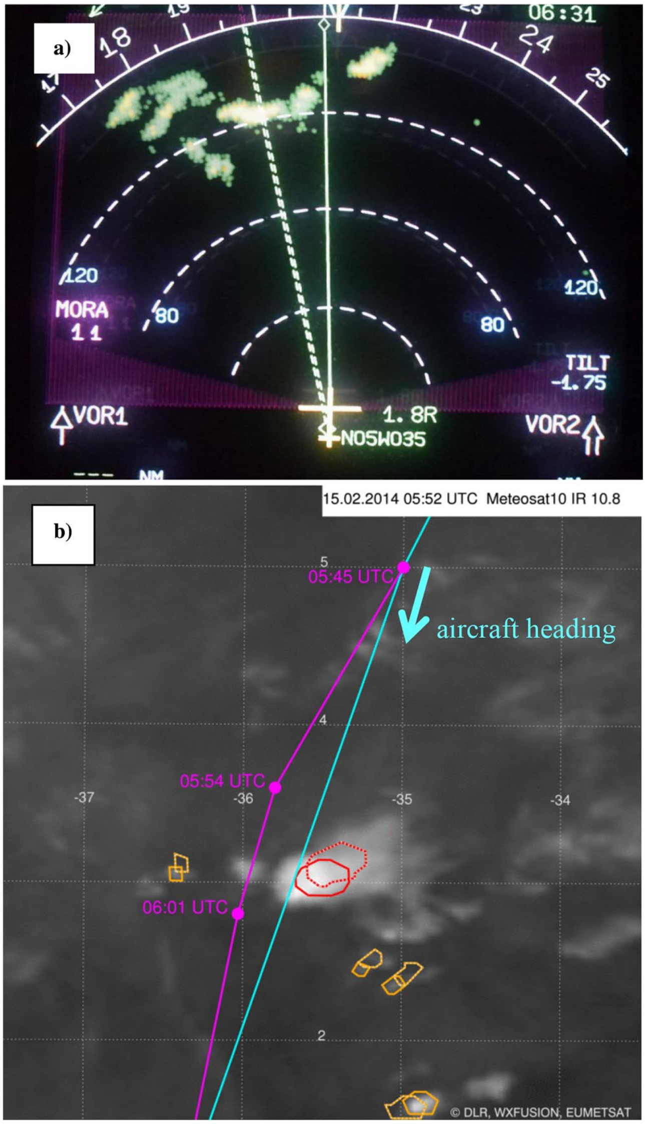

Fig. 6 Representations of a) photograph of the onboard radar display and b) Meteosat-10 IR 10.8 μm with Cb-TRAM contours and flight routes.

about 30 n miles from the thunderstorm cells, the onboard radar returns got weaker because the radar beam, still tilted at 1.75 deg down, started to sweep over the thunderstorm tops. The pilots observed cloud tops at altitudes slightly lower than the cruising height of the aircraft (FL340).

Figure 6b shows the Cb-TRAM postanalysis at 05:52 UTC, which is the closest corresponding time to the onboard radar image in Fig. 6a. The overview of the situation shows a mature thunderstorm on the original flight route at 3°N 35,5°W, which was forecast to propagate in a northeasterly direction within the next hour, and rapidly developing cells located at 3°N 36,5°W and 2,5°N 35°W. All these cells were confirmed by the onboard radar, which reflected the situation from a North–South perspective (Fig. 6a). The leftmost line indicates the deviation that was flown with aircraft positions at 05:45, 05:54, and 06:01 UTC.

Looking at the Cb-TRAM image that was valid about 40 min before the thunderstorms appeared on the onboard radar, it can be seen that the mature thunderstorm at 3°N 35,5°W was already there and was forecast to move in a northeasterly direction within the next hour (Fig. 7). If this information would have been available during flight, the pilots would have been aware of the existence of the thunderstorm well in advance. Moreover, the Cb-TRAM images would have shown much earlier than the onboard radar that a

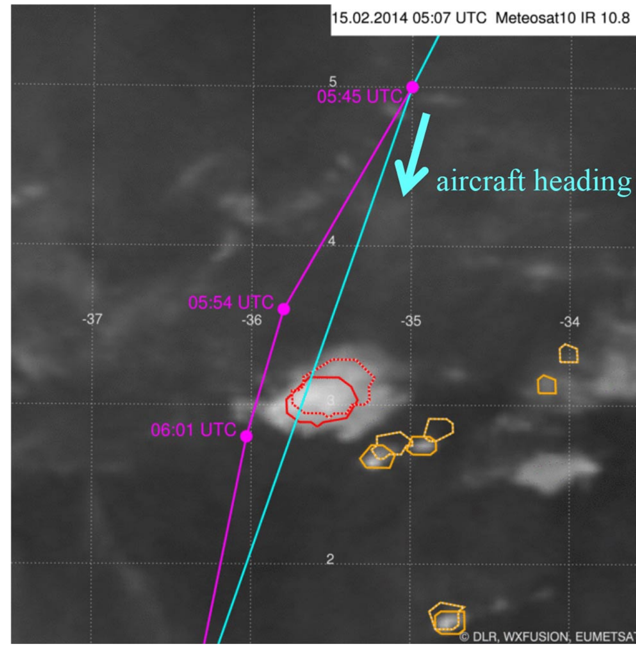

Fig. 7 Same as Fig. 6b, but for 05:07 UTC observation time.

deviation to the west was the right choice, given the indicated moving speed and moving direction of the mature thunder cell and the rapid developments to the east.

About half an hour later during this flight, between 06:15 and 06:30 UTC, further but smaller thunder cells appeared on the onboard radar, especially west of the waypoint JOBER (Fig. 8a). The pilots estimated the cloud tops to be below FL340. Indeed, these cells were detected by Cb-TRAM as not yet mature but rapidly intensifying cells (Fig. 8b), and they could finally be confirmed by a photograph out of the cockpit (Fig. 9): the cells were growing but had not yet developed the anvil, which is a typical signature of a mature thunderstorm.

The second validation was done for a Lufthansa flight from Accra (Ghana, Africa) to Frankfurt (Germany) during the night from 24 to 25 July 2014. Over the Mediterranean Sea, thunder cells appeared in the onboard radar and were visible by a view out of the window (Fig. 10).

The onboard radar image at 01:17 UTC, about 2 min before the photograph in Fig. 10 was taken, shows several thunder cells about 30 to 40 n miles ahead of the aircraft (Fig. 11a). All these cells were also detected by Cb-TRAM: partly as mature storms, and partly as rapidly developing cells (Fig. 11b). Even the cell 10 n miles at the right-hand side of the aircraft (Fig. 11a) was identified as a rapidly developing thunderstorm (Cb-TRAM contour at 38,4°N 5,5°E in Fig. 11b). An inspection of the Cb-TRAM analyses and nowcasts 1 h before (not shown) revealed that the thunderstorms seen at 01:17 UTC rapidly developed within a strong westerly flow and propagated eastward with a moving speed of about 15 m/s. Also in this example, Cb-TRAM would have raised the pilots' awareness of the thunderstorms, their development, and their moving direction and speed in advance, if the Cb-TRAM data would have been available in the cockpit.

IV. Real-Time Uplink of Cb-TRAM into the Cockpit

For the uplink into the cockpit, Cb-TRAM provides analyses and nowcasts in real time based on the latest available Meteosat observation. Thereby, the typical latency between the Meteosat observation of one region (the time of the scan of that region) and the availability of the Cb-TRAM output for that region is typically 7 min with a variability of $+/-1$ min, depending on the number of thunderstorms occurring in the area. Both the XML data and graphics were provided on a ftp/http site at DLR. Users could either pick up and transfer the data to their own systems and displays or, if they preferred, directly view the graphics in a Web browser.

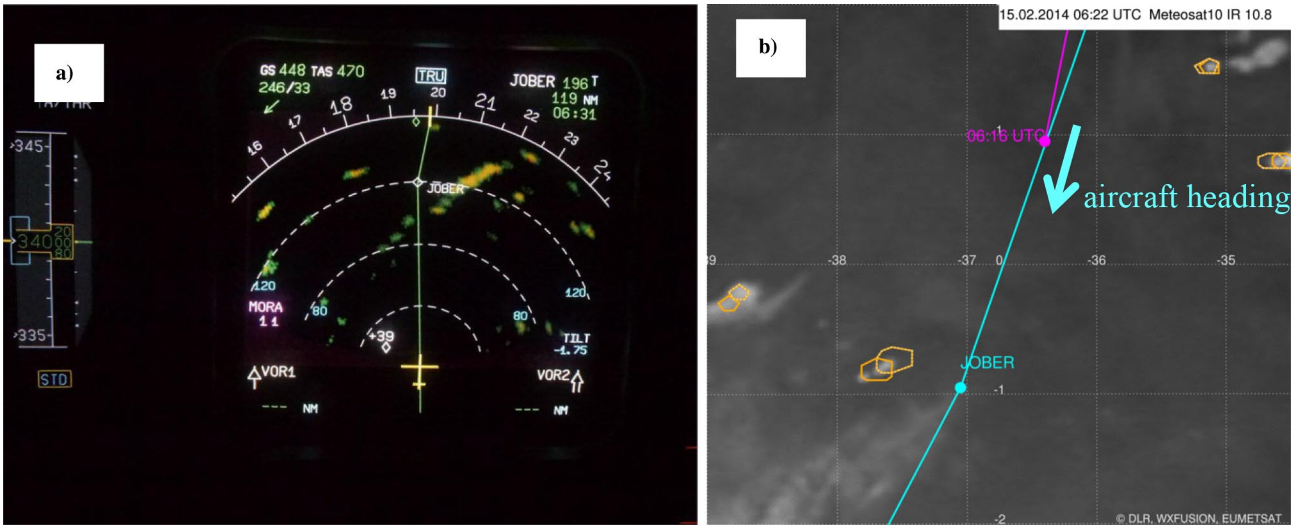

Fig. 8 Same as Fig. 6, but for 06:16 UTC in a) and 06:22 UTC in b).

Fig. 9 Photograph out of the window to the west about 20 n miles north of JOBER at 06:27 UTC.

Fig. 10 Photograph out of the window to the northwest at 38.40°N 5.25° E on 25 July 2014 at 01:19 UTC.

The very first uplink test with Cb-TRAM was successfully performed during a research flight of the DLR High-Altitude and Long-Range Research Aircraft (referred to as HALO), which is a modified Gulfstream G-VSP (G550) aircraft. Although HALO is equipped with an Iridium datalink, this link could not be used because there was no device connected that could display the Cb-TRAM XML or graphic data. However, the gimballed limb observer for radiance imaging of the atmosphere measurement instrument (GLORIA) was on board in the cabin, and its own Iridium datalink was used to control the instrument from the ground. In the aircraft, a laptop was coupled to this datalink, providing the opportunity to connect to the Internet and display the Cb-TRAM real-time graphics with a Web browser. This opportunity was used on the way through the Intertropical Convergence Zone (ITCZ) from the Cape Verde Islands to Cape Town on 11 September 2012. Shortly after takeoff, when HALO had just passed waypoint RAMOL and headed toward waypoint MOGSA at 08:07 UTC, the pilots saw a thunderstorm in the front right of the onboard radar image in about a 250 n mile distance (Fig. 12). The thunderstorm was only partly detected by the onboard radar due to its limited scanning sector in front of the aircraft. The captain of the aircraft then went into the cabin and started to download the latest Cb-TRAM real-time image at about 41,000 ft altitude by using the GLORIA Iridium link. Due to the limited bandwidth of the Iridium connection, the image with a size of about 200 kB (satellite image overlaid with Cb-TRAM contours) took about 4 min to be uplinked at 08:15 UTC. It showed the Meteosat IR 10.8 μm satellite image at 07:45 UTC with a big thunderstorm system detected by Cb-TRAM between 10 to 20°N and 22 to 24°W, which was predicted to grow within the next hour (Fig. 13). Compared to the onboard radar image (Fig. 12), Cb-TRAM gave the bigger picture, thereby not only showing the whole extent of the thunderstorm but also the development of this storm within the next hour and that the planned flight route was not affected by thunderstorms beyond the waypoints MOGSA and TITOR.

Further successful datalink tests have been performed in cooperation with Lufthansa, SITA, and Lufthansa Systems in Fall 2012 and Spring 2013 within the Lufthansa Ground Air Datalink Communication project. The goal of this project was the deployment of a new eEnabling communication infrastructure for LH by using media independent aircraft messaging, which is a communication standard allowing the exchange of binary data over ACARS and IP communication links. Three different links were implemented to transmit data from a LH ground server to EFBs on board an aircraft: 1) cell-phone IP for 3G/3G+-equipped LH Cityline aircraft while they are on the ground; 2) FlyNet IP, for FlyNet-equipped LH aircraft, while they are flying above 10,000 ft (FlyNet is the satellite communication link originally developed for cabin entertainment in Lufthansa aircraft); and 3) ACARS when feasible (dependent on bandwidth requirements).

First, Cb-TRAM images were picked up in real time by LH from the DLR ftp/http site, transmitted to the LH ground server, and then sent to the EFB via the 3G cell-phone IP link while the aircraft was on the ground (Fig. 14). Next, Cb-TRAM XML data were integrated and

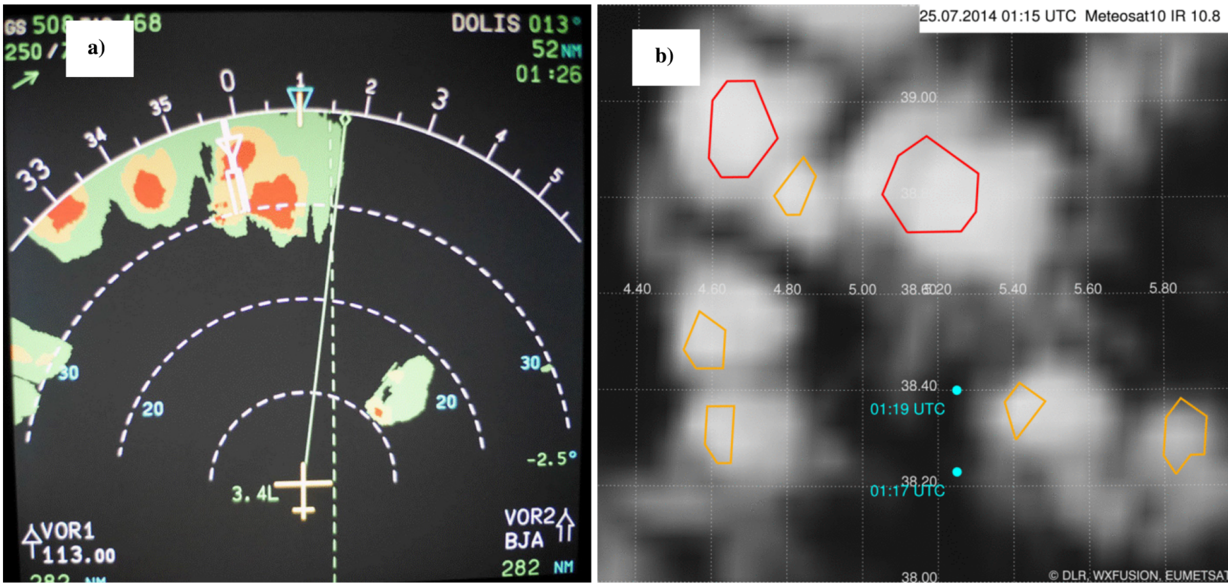

Fig. 11 Same as Fig. 6, but for 25 July 2014 at a) 01:17 UTC and b) 01:15 UTC.

Fig. 12 Photograph of the onboard radar display in HALO on 11 September 2012 at 08:07 UTC.

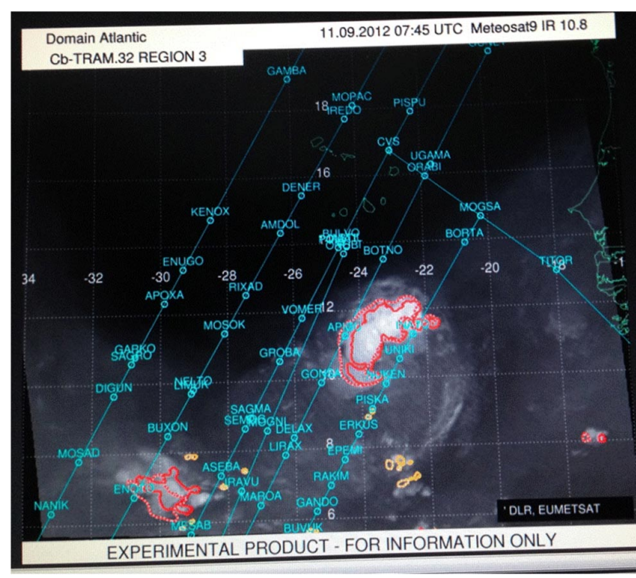

Fig. 13 Photograph of the GLORIA laptop screen on board of the DLR HALO on 12 September 2012 at 08:15 UTC.

displayed in the LH eRouteManual (eRM) where they could be overlaid with other flight-relevant data and maps, and then uplinked in flight via FlyNet IP or ACARS. Figure 15 shows an example screenshot. The darkest areas represent Cb-TRAM-detected regions that were currently affected by thunderstorms, the lightest areas represent regions that were predicted to be affected by thunderstorms within the next hour, and arrows indicate the moving direction within the next hour.

For the uplink, only those Cb-TRAM thunder cells were extracted that were relevant for the respective flight, and the resulting information was highly compressed. For instance, 54 thunder cells with a total of 451 coordinate points describing their contours could be reduced to about 1 kB and easily sent to the aircraft, even via ACARS.

In February 2013, the first in-flight real-time uplink tests with Cb-TRAM XML data were performed via FlyNet over the South Atlantic in a series of four flights. Again, Cb-TRAM XML data were picked up in real time by LH from the DLR ftp/http site and transmitted to the LH ground server. On request by the pilot, the latest data were then uplinked via FlyNet and displayed in the eRM on the EFB. During one flight from Rio de Janeiro to Frankfurt on 4 February 2013, the whole uplink chain could successfully be demonstrated, and the value of the Cb-TRAM information for flight safety and fuel savings could be shown. According to the SIGWXs (Fig. 16), thunderstorm activity was expected in the area of the Cape Verde Islands. Around the equator in the ITCZ, however, thunderstorms were predicted mainly west of the flight route. The captain calculated that, at around 03 UTC, they would encounter the margins of the large cloud system moving into their flight path from the west, which could be easily circumnavigated with a minor deviation, and that they would only be facing thunderstorms much later over the Cape Verde Islands. Therefore, he decided to take his mandatory rest during the first part of the flight and leave the navigation to his two copilots until they approached the Cape Verde Islands, where he intended to uplink and validate the Cb-TRAM data. By the time the aircraft approached the ITCZ at around 03 UTC, the onboard radar showed that they were heading straight into an extensive area of thunderstorms with intense thunder cells. Having in mind the SIGWX forecast with the

Fig. 14 Photograph of Lufthansa EFB with a Cb-TRAM image on board of a Lufthansa A340 aircraft on 1 October 2012.

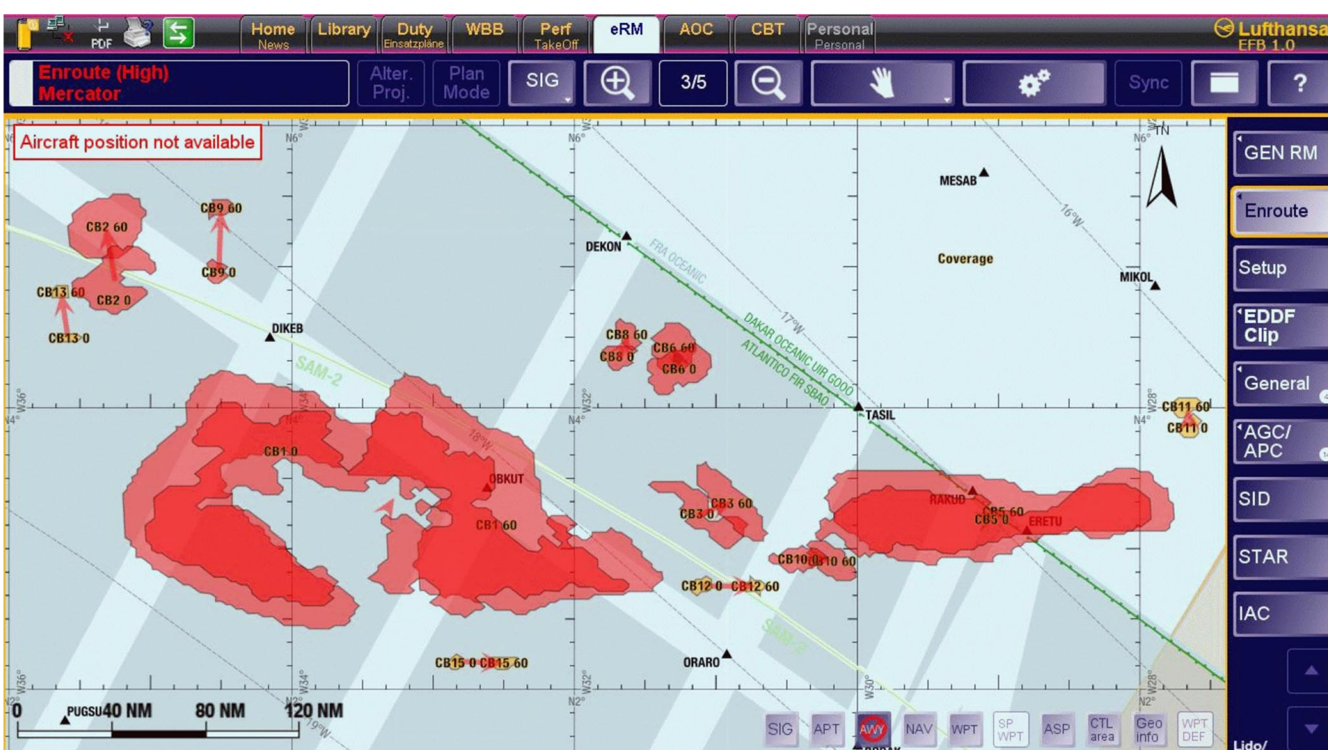

Fig. 15 Screenshot of the LH eRM with Cb-TRAM data displayed on an aeronautical chart (nautical miles shown as "NM" in figures).

thunderstorm activity predicted mainly to the west of the flight route, the copilots asked the air traffic control for a deviation to the east, for which they got clearance at 03:21 UTC. When the captain was woken up by his copilots as planned at 03:35 UTC, the copilots had already deviated from the original flight path to 120 deg, which had taken them completely off their original course of 90 deg and in the direction of South Africa (Fig. 17). The captain quickly uplinked the latest Cb-TRAM data to the Lufthansa eRM at 03:55 UTC and was provided with a much broader picture 1 min later (Fig. 18). At this time, the aircraft was at the position indicated by the mouse cursor in Fig. 18. The overview provided by Cb-TRAM showed that, earlier on, they had missed a gap between the thunder cells (flight route along waypoints ORARO–TASIL) that would have allowed them to stay much closer to their original course. The

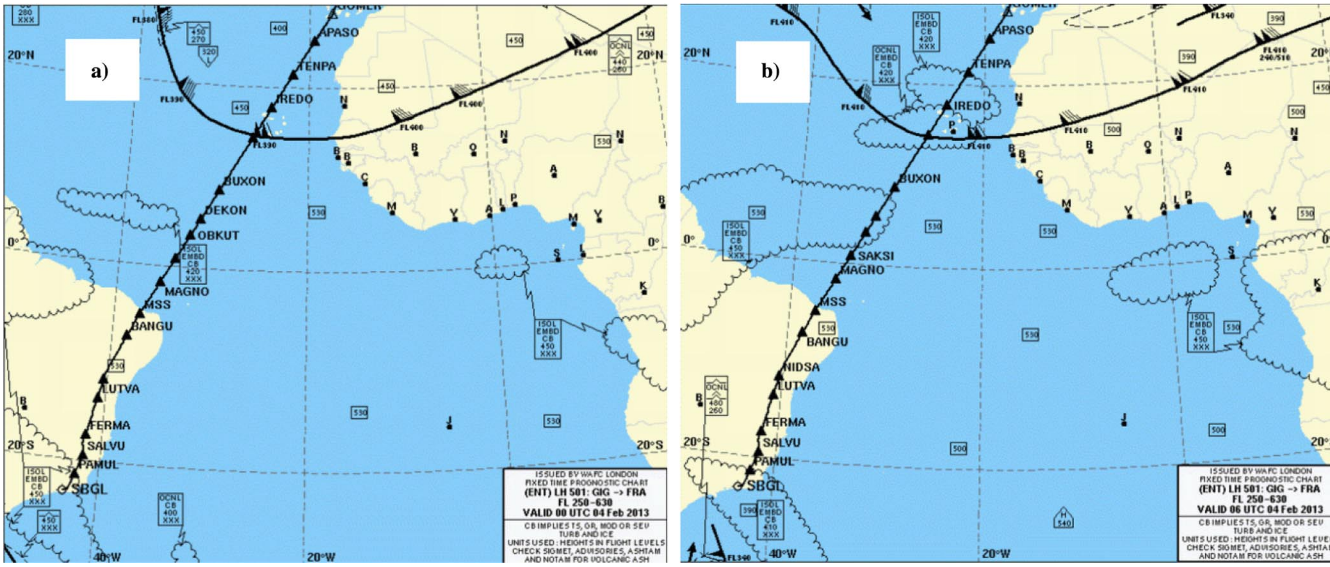

Fig. 16 SIGWXs valid on 4 February 2013 at a) 00 UTC and b) 06 UTC.

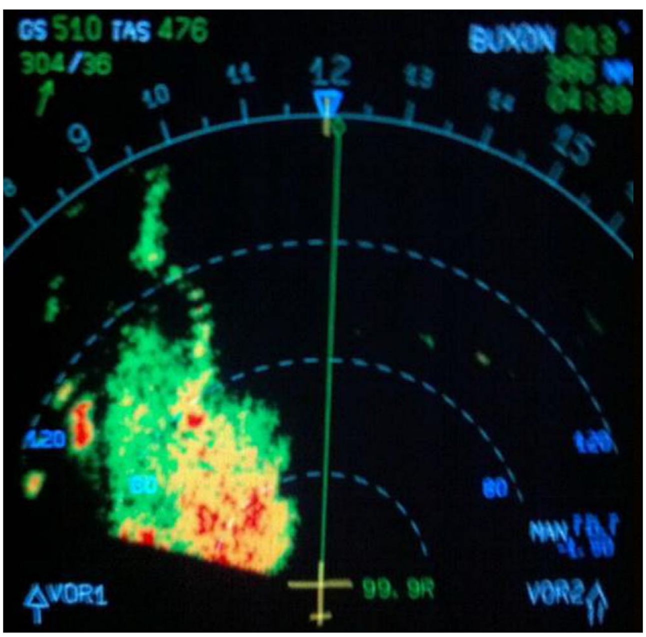

Fig. 17 Photograph of the onboard radar display on 4 February 2013 at 03:54 UTC.

onboard radar had not detected this gap due to its limited range. However, the captain also saw from the Cb-TRAM overview that there was another gap coming up that was also not observed by the onboard radar. He decided to take this opportunity, planned the safest route according to Cb-TRAM, and flew it tactically by looking at the onboard radar, i.e., he verified with the onboard radar that the route was as safe as Cb-TRAM had predicted it. Indeed, the gap between the thunder cells could be confirmed with the onboard radar when they turned the aircraft by 90 deg to the left. The area of thunderstorms could safely be passed, and the flight to Frankfurt could be continued.

In total, the aircraft flew a deviation of 300 n miles (Fig. 19, line with triangles), and the circumnavigation of the thunderstorms reduced the fuel reserve by 3.0 tons. If the aircraft had continued the course of 120 deg just a few more minutes, a stopover in Paris would have been necessary for refueling. In a postanalysis, the captain calculated that they could have saved more than 2 tons of fuel if they had uploaded Cb-TRAM a few minutes earlier and had seen and flown the first gap, which was closer to their original course (flight route along waypoints ORARO–TASIL).

V. Discussion

The cases presented in this study demonstrate that Cb-TRAM is a valuable tool to provide pilots an overview of the current thunderstorm situation and its development in the next hour beyond the onboard radar range. However, Cb-TRAM can never replace the use of onboard radars. There is always a latency of about 7 min between the observation by satellite and the Cb-TRAM data availability and display in the cockpit, which is partly due to the transmission of the satellite data down to Earth to the Cb-TRAM operation center (about 5 min) and the Cb-TRAM processing time (about 2 min). Because thunderstorms are quickly developing phenomena, the details of the thunderstorm situation might change within this period. In contrast, the onboard weather radar reflects the current observation immediately in front of the aircraft. Therefore, the primary information for tactical maneuvers (i.e., seconds up to minutes ahead) must still be the onboard radar, whereas Cb-TRAM is suitable for the strategic planning of the flight route 10–60 min ahead. The Lufthansa flight described in Sec. IV is an example of how pilots can use the combined information from the onboard radar and Cb-TRAM. Cb-TRAM provides the overview of the situation; thus, it can act as a pathfinder, which is then verified with the onboard radar for the tactical flight maneuvers.

The information provided by Cb-TRAM is not only useful when uplinked into the cockpit but also when available at the ground. For instance, flight dispatchers, flight followers, and air traffic controllers can use the Cb-TRAM information in weather displays on the ground to advise pilots en route via ACARS or voice regarding appropriate avoidance maneuvers, if the planned flight route crosses areas with thunderstorm activity. Moreover, if Cb-TRAM information was available to all aviation stakeholders on the ground and in the air, the common situational awareness of thunderstorm impacts in the near future could facilitate the discussion about mitigation strategies. This can potentially reduce the workload of the decision makers and support collaborative decision making (CDM) in the manner of the SESAR (Europe), NextGen (United States), and CARATS (Japan) programs.

Note that the onboard radar observes other aspects of a thunder cell than Cb-TRAM. Cb-TRAM detects the thunderclouds as seen from space; i.e., it marks areas with towering clouds that quickly grow with time and have a texture exceeding a critical threshold. In these areas, heavy turbulence, icing, lightning, and heavy rain (or even hail) can be expected. In contrast, the onboard radar detects only the precipitation of the thunderclouds. For this reason, the most intense precipitation cores (as indicated by red colors in the onboard radar display in Fig. 17) indicating heavy rain and hail cover much smaller areas than the Cb-TRAM objects, which also include other hazardous features. Thus, Cb-TRAM helps the pilot to not only keep a safe

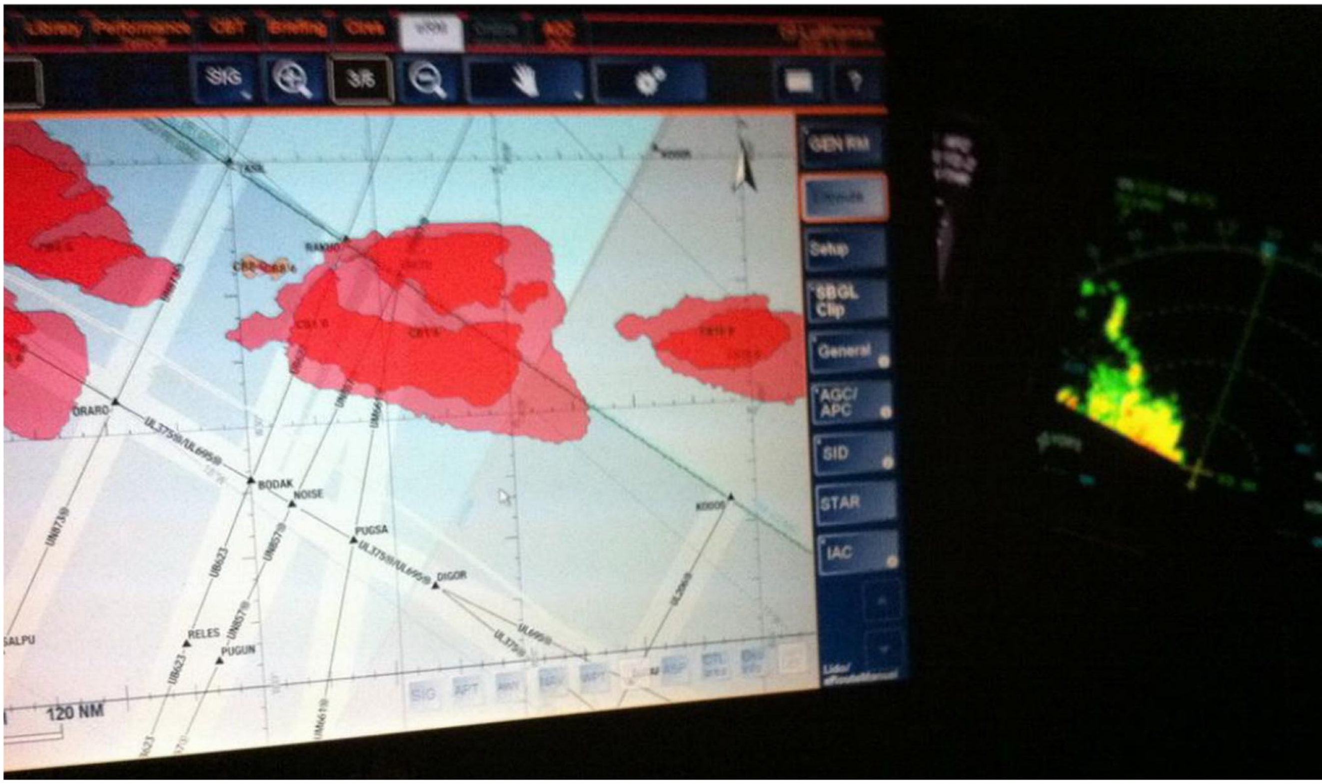

Fig. 18 Photograph of the EFB with Cb-TRAM data at 03:30 UTC and the onboard radar display at 03:56 UTC.

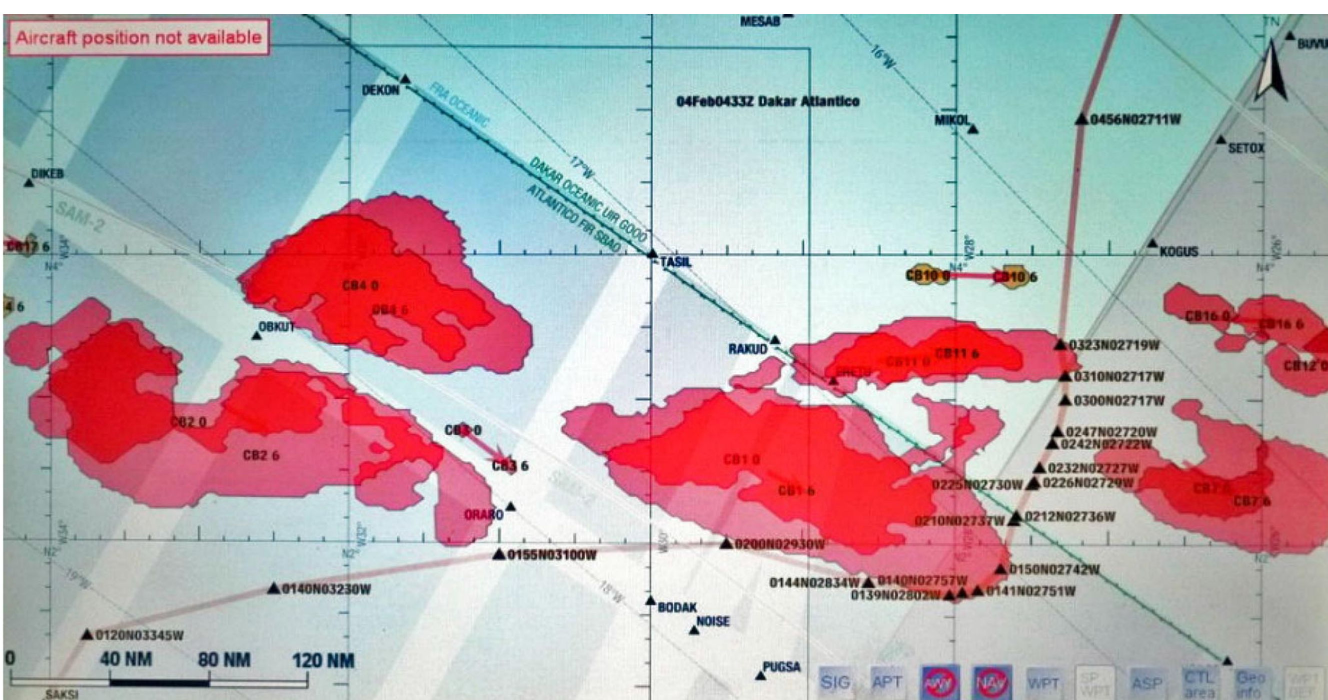

Fig. 19 Photograph of the EFB with Cb-TRAM data in the eRM from 4 February 2013 at 04:15 UTC.

distance to the heavy precipitation cores but also to the other hazards related to a thunderstorm.

The present study presents only a few cases illuminating the potential, the accuracy, and the merit of Cb-TRAM. Fortunately, the Lufthansa flight from Rio de Janeiro to Frankfurt described in Sec. IV was equipped with an in-service aircraft for a global observing system (IAGOS) measurement instrument that measured different meteorological parameters like temperature, water vapor, and ice particle number concentrations. These measurements provided further evidence that the flown route was safe with regard to thunderstorm-related hazards. The IAGOS database covers a large number of flights and offers the opportunity for an ongoing study to systematically proof the validity of Cb-TRAM [30].

VI. Conclusions

Cb-TRAM is an algorithm for the detection, tracking, and forecasting of thunderstorms up to 1 h (called nowcasting) based on geostationary satellite data. In contrast to numerical weather forecasts, which can only give a rough estimate on when and where thunderstorms might occur, Cb-TRAM provides an overview on when and where thunderstorms are currently occurring and how they will develop in the near future. This is an ideal prerequisite for the use of Cb-TRAM in the cockpit of aircraft because it enables strategic flight planning 1 h ahead instead of just minutes ahead based on the out-of-window view and the limited range of the onboard radar. In close cooperation with pilots from Lufthansa and DLR flight experiments, Cb-TRAM has been validated by comparing it to onboard observations, both in postflight analyses and in real time. From this comparison, the following conclusions can be drawn:

1) The Cb-TRAM detections and nowcasts are in good agreement with the onboard radar images; i.e., Cb-TRAM enhances the situational awareness of the flight crew and allows for strategic flight route planning.

2) In contrast to the onboard radar, Cb-TRAM provides a much broader picture of the thunderstorm situation around the aircraft and on the flight route ahead; i.e., the pilot can avoid the tactical searching for gaps between the thunder cells and plan and adjust the flight route well in advance without stress.

3) The improved situational awareness results in a foresighted strategic planning and helps to increase flight safety: turbulence, icing, hail and lightning encounters, and eventually aircraft incidents and accidents can be better avoided.

4) The foresighted strategic planning enables cost-efficient flying: smarter flight routes lead to fuel savings, reduced delays, less holding patterns, and less deviations to alternates.

5) To enable the uplink of data from ground stations to the aircraft, different technologies can be used and combined, if possible, depending on whether the aircraft is on the ground (cell-phone IP) or in the air (FlyNet IP or ACARS when feasible).

6) With modern datalink technologies and strong compressible data formats, resulting in a few kilobytes of data per up-link, an uplink of Cb-TRAM data into the cockpit of an aircraft is feasible close to real time.

It is evident from the current study that Cb-TRAM would add even larger value to aviation safety and efficiency, if it was available on a global scale. Currently, work is in progress to extend Cb-TRAM to Cb-global, with the goal to provide real-time thunderstorm information for all flight routes worldwide [31].

Acknowledgments

This study was supported by the Deutsches Zentrum für Luft- und Raumfahrt (DLR) Projekt Wetter und Fliegen (2008–2011) and the DLR's Vorhaben Wetter-Optimierter Luftverkehr. We are grateful to Erik Kretschmer of the Karlsruher Institut für Technologie for being the person in charge of the gimballed limb observer for radiance imaging of the atmosphere (GLORIA) measurement instrument and for enabling the uplink of cumulonimbus tracking and monitoring Cb-TRAM images via the Iridium link in GLORIA.

References

[1] Tafferner, A., Forster, C., Hagen, M., Hauf, T., Lunnon, B., Mirza, A., Guillou, Y., and Zinner, T., "Improved Thunderstorm Weather Information for Pilots Through Ground and Satellite Based Observing Systems," *American Meteorological Society* [Online Proceedings], Jan. 2010, Paper 161186, https://ams.confex.com/ams/90annual/webprogram/Paper161186.html [retrieved 18 Jan. 2010].

[2] Tafferner, A., and Forster, C., "Weather Nowcasting and Short Term Forecasting," *Atmospheric Physics*, edited by Schumann, U., Springer–Verlag, Berlin, 2012, pp. 363–380.
doi:10.1007/978-3-642-30183-4

[3] National Center of Atmospheric Research, "Turbulence Research and Development," Research Applications Laboratory Annual Report 2006 (online), http://www.ral.ucar.edu/lar/2006/priorities/4.23.php [cited 28 Feb. 2017].

[4] Campbell, S., Ishutkina, M., and McPartland, M., "Benefits Analysis of Ground-Sourced Convective Weather Alerting in the Cockpit," *15th AIAA Aviation Technology, Integration, and Operations Conference*, AIAA Paper 2015-3396, June 2015.
doi:10.2514/6.2015-3396

[5] "Performance Review Report 2010: An Assessment of Air Traffic Management in Europe During the Calendar Year 2010," EUROCONTROL Performance Review Commission Final Report, Brussels, Belgium, 2011.

[6] Evans, J., and Ducot, E., "The Integrated Terminal Weather System (ITWS)," *Lincoln Laboratory Journal*, Vol. 7, No. 2, 1994, pp. 449–474.

[7] Mueller, C., Saxen, T., Roberts, R., Wilson, J., Betancourt, T., Dettling, S., Oien, N., and Yee, J., "NCAR Auto-Nowcast System," *Weather Forecast*, Vol. 18, No. 4, 2003, pp. 545–561.
doi:10.1175/1520-0434(2003)018<0545:NAS>2.0.CO;2

[8] Tafferner, A., Forster, C., Hagen, M., Keil, C., Zinner, T., and Volkert, H., "Development and Propagation of Severe Thunderstorms in the Upper Danube Catchment Area: Towards an Integrated Nowcasting and Forecasting System Using Real-Time Data and High-Resolution Simulations," *Meteorology and Atmospheric Physics*, Vol. 101, No. 3, 2008, pp. 211–227.
doi:10.1007/s00703-008-0322-7

[9] Forster, C., and Tafferner, A., "An Integrated User-Oriented Weather Forecast System for Air Traffic Using Real-Time Observations and Model Data," *CEAS 2009 European Air & Space Conference, Royal Aeronautical Society Conference Proceedings* [CD-ROM], Oct. 2009.

[10] Dixon, M., and Wiener, G., "TITAN: Thunderstorm Identification, Tracking, Analysis, and Nowcasting—A Radar-Based Methodology," *Journal of Atmospheric and Oceanic Technology*, Vol. 10, No. 6, 1993, pp. 785–797.
doi:10.1175/1520-0426(1993)010<0785:TTITAA>2.0.CO;2

[11] Pierce, C. E., Hardaker, P. J., Collier, C. G., and Hagget, C. M., "GANDOLF: A System for Generating Automated Nowcasts of Convective Precipitation," *Meteorological Applications*, Vol. 7, No. 4, 2000, pp. 341–360.
doi:10.1017/S135048270000164X

[12] Lang, P., Plörer, O., Munier, H., and Riedl, J., "KONRAD ein Operationelles Verfahren zur Analyse von Gewitterzellen und Deren Zugbahnen, Basierend auf Wetterradarprodukten," Deutschen Wetterdienstes Rept. 222, Offenbach, Germany, 2003.

[13] Kober, K., and Tafferner, A., "Tracking and Nowcasting of Convective Cells Using Remote Sensing Data from Radar and Satellite," *Meteorologische Zeitschrift*, Vol. 1, No. 18, 2009, pp. 75–84.

[14] Mecikalski, J. R., and Bedka, K.-M., "Forecasting Convective Initiation by Monitoring the Evolution of Moving Convection in Daytime GOES Imagery," *Monthly Weather Review*, Vol. 134, No. 1, 2006, pp. 49–78.
doi:10.1175/MWR3062.1

[15] Walker, J. R., MacKenzie, W. M., Mecikalski, J. R., and Jewett, C. P., "An Enhanced Geostationary Satellite-Based Convective Initiation Algorithm for 0–2 Hour Nowcasting with Object Tracking," *Journal of Applied Meteorology and Climatology*, Vol. 51, No. 11, 2012, pp. 1931–1949.
doi:10.1175/JAMC-D-11-0246.1

[16] World Meteorological Organization, "Developing Support for National Meteorological and Hydrological Services in Satellite Data, Products and Training," *RA II Pilot Project Newsletter*, Vol. 3, No. 3, July 2012, http://www.wmo.int/pages/prog/sat/documents/RA-2-PP_Newsletter-Vol3-N3.pdf [retrieved 28 Feb. 2017].

[17] Stich, D., "Convection Initiation—Detection and Nowcasting with Multiple Data Sources," Ph.D. Dissertation, LMU München, Fakultät für Physik, 2013, p. 141.

[18] Carvalho, L., and Jones, C., "A Satellite Method to Identify Structural Properties of Mesoscale Convective Systems Based on the Maximum Spatial Correlation Tracking Technique (MASCOTTE)," *Journal of Applied Meteorology*, Vol. 40, No. 10, 2001, pp. 1683–1701.
doi:10.1175/1520-0450(2001)040<1683:ASMTIS>2.0.CO;2

[19] Mosher, F. R., "Detection of Deep Convection Around the Globe," *Preprints 10th Conference Aviation, Range, Aerospace Meteorology*, American Meteorological Soc., Boston, MA, 2002, pp. 289–292.

[20] Vila, D. A., Machado, L. A. T., Laurent, H., and Velasco, I., "Forecast and Tracking the Evolution of Cloud Clusters (ForTraCC) Using Satellite Infrared Imagery: Methodology and Validation," *Weather and Forecasting*, Vol. 23, No. 2, 2008, pp. 233–245.
doi:10.1175/2007WAF2006121.1

[21] Morel, C., and Sénési, S., "A Climatology of Mesoscale Convective Systems over Europe Using Satellite Infrared Imagery, I: Methodology," *Quarterly Journal of the Royal Meteorological Society*, Vol. 128, No. 584, 2002, pp. 1953–1971.
doi:10.1256/003590002320603485

[22] Guillou, Y., "Algorithm Theoretical Basis Document for 'Rapid Development Thunderstorms' (RDT-PGE11 v2.2)," SAF/NWC/

CDOP/MFT/SCI/ATBD/11, No. 2, Rev. 2, 2010, http://www.eumetrain.org/data/2/274/media/flash/SAF-NWC-CDOP-MFT-SCI-ATBD-11_v2.2.pdf [retrieved 28 Feb. 2017].

[23] Zinner, T., Mannstein, H., and Tafferner, A., "Cb-TRAM: Tracking and Monitoring Severe Convection from Onset over Rapid Development to Mature Phase Using Multichannel Meteosat-8 SEVIRI Data," *Meteorology and Atmospheric Physics*, Vol. 101, Nos. 3–4, 2008, pp. 191–210. doi:10.1007/s00703-008-0290-y

[24] Zinner, T., Forster, C., de Coning, E., and Betz, H.-D., "Validation of the Meteosat Storm Detection and Nowcasting System Cb-TRAM with Lightning Network Data—Europe and South Africa," *Atmospheric Measurement Techniques*, Vol. 6, No. 6, 2013, pp. 1567–1583. doi:10.5194/amt-6-1567-2013

[25] Lindholm, T., Kessinger, C., Blackburn, G., and Gaydos, A., "Weather Technology in the Cockpit, Transoceanic Human-Over-The-Loop Demonstration," *Journal of Air Traffic Control*, Vol. 55, No. 1, 2013, pp. 18–21.

[26] Lunnon, R. W., Hauf, T., Gerz, T., and Josse, P., "FLYSAFE-Meteorological Hazard Nowcasting Driven by the Needs of the Pilot," *American Meteorological Society* [Online Proceedings], Aug.–Sept. 2009, Paper 103462, https:/ams.confex.com/ams/pdfpapers/103462.pdf [retrieved 28 Feb. 2017].

[27] Kessinger, C., Frazier, E., Blackburn, G., Lindholm, T., and Rehak, N., "A Demonstration to Validate the Minimum Weather Services for Oceanic and Remote Airspace," *American Meteorological Society* [Online Proceedings], Jan. 2015, Paper 268598, https://ams.confex.com/ams/95Annual/webprogram/Paper268598.html [retrieved 28 Feb. 2017].

[28] Kessinger, C., Blackburn, G., Rehak, N., Ritter, A., Milczewski, K., Sievers, K., Wolf, D., Olivo, J., and McParland, T., "Demonstration of a Convective Weather Product into the Flight Deck," *American Meteorological Society* [Online Proceedings], 2015, Paper 269015, https://ams.confex.com/ams/95Annual/webprogram/Paper269015.html [retrieved 28 Feb. 2017].

[29] Mirza, A., Pagé, C., and Geindre, S., "FLYSAFE—An Approach to Flight Safety—Using GML/XML Objects to Define Hazardous Volumes Space for Aviation," *American Meteorological Society* [Online Proceedings], New Orleans, 2008, Paper 134030, https://ams.confex.com/ams/pdfpapers/134030.pdf [retrieved 28 Feb. 2017].

[30] Stich, D., Forster, C., Tafferner, A., Saueressig, G., Beswick, K., and Petzold, A., "Validation of the Satellite-Based Thunderstorm Detection and Nowcasting System Cb-Global with IAGOS Onboard Measurements," *Journal of Applied Meteorology and Climatology* (to be published).

[31] Stich, D., Forster, C., Tafferner, A., Koehler, M., Soelch, I., and Gerz, T., "Information on Thunderstorm Initiation, Nowcast and Forecast for Aviation Safety and Efficiency," *1st ECATS Conference*, 2013, http://www.ecats-network.eu/events/past-events/conference/presentations.

J. Krozel
Associate Editor