

Radar Sensors for Wind & Wake-Vortex Monitoring on Airport : First results of SESAR P12.2.2 XP0 trials campaign at Paris CDG Airport

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1. Introduction

On airports, runway is the limiting factor for the overall throughput, and more especially the fixed ICAO wake turbulence separation minima, that are over conservative as they do not take into account wind conditions. These hazardous flows usually dissipate quickly because of decay due to air turbulence or transport by cross-wind. However, due to safety reasons, most airports assume a worst-case scenario and use conservative separations, which means the interval between aircraft taking off or landing often amounts to several minutes. However, with the aid of accurate wind data and precise measurements of wake vortex by Radar sensors, more efficient intervals can be set, particularly when weather conditions are stable. Depending on traffic volume, these adjustments can generate capacity gains, which have major commercial benefits. This paper will present European SESAR P12.2.2 project that develops a verified wake turbulence system according to related operational concept improvements in order to, punctually or permanently, reduce landing and departure wake turbulence separations and, therefore, to increase the runway throughput in such a way that it safely absorbs arrival demand peaks and reduces departure delays. This global objective will be achieved by means of Radar sensors to deliver in real time position and strength of the wake vortices and to assess wind conditions including ambient air turbulence by EDR. This paper will present the Radar component of sensors trials campaign, performed at CDG Airport in Spring 2011, providing results of statistical analyses of two UHF wind Profilers Radars and one X-band Wake-Vortex Monitoring Radar data collection, respectively benchmarked with Sodar/Lidar Profiler and 3D Wake-Vortex Monitoring Lidar. The main results were convincing in terms of wake vortex detection. Most of wake vortices were detected in both critical areas. Results show that Radar and Lidar are complementary depending on weather conditions: X-band Radar performances are optimal under rainy conditions when Lidar performances are optimal in dry air. For wind, the overall availability of UHF Wind Profiler Radars data as a function of the height above the surface will be presented (the percentage of the time that reflectivity was sufficient to make a measurement and that the atmosphere was sufficiently homogeneous and stable). The statistical comparison between 2 UHF profilers (and with Sodar/Lidar Profilers) will be based on histograms of interpolated data availability, wind velocity and direction profiles in specific periods, calculation of bias, standard deviation and correlation for wind velocity and direction by altitude. Using combinations of sensors, models and real measurements, and thanks to some improved sensors already planned within the project (X-band E-scanning radar), it should be possible to reach operational needs for the Wake-Vortex Advisory system.

2. Rational for wake-vortex hazards mitigation on Airport

Wake vortices are a natural by-product of lift generated by aircraft and can be considered as two horizontal tornados trailing after the aircraft, and their encounter is the main cause of loss of control by Pilots. A trailing aircraft exposed to the wake vortex turbulence of a lead aircraft can experience an induced roll moment/bank angle that is not easily corrected by the pilot or the autopilot. Most recent accidents are referenced in: November 12, 2001 - AA Flight 587 crashed shortly after takeoff from John F. Kennedy Airport, due to pilot error in the presence of wake-turbulence from a Boeing 747; November 4, 2008 - Mexican Government LearJet 45 with Secretary of the Interior, flying behind a Boeing 767-300 and above a heavy helicopter, crashed before turning for final approach at Mexico City Airport.

reasons for loss of control

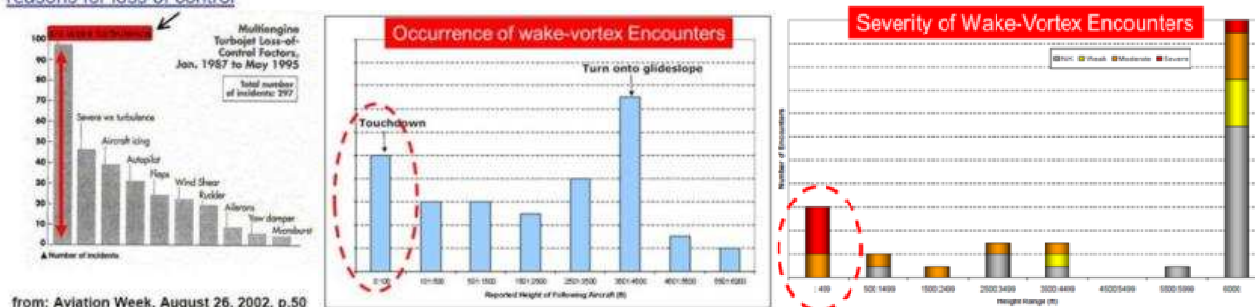


Fig. 1 (at left) Statistics for loss of control causes, (at right) Occurrence/severity of Wake-Vortex encounters

To characterize Critical Area of Wake-Vortex Encounter, we can use results of NATS enquiry that has shown that highest occurrences of wake-vortex encounters are at the touchdown (behind 100 feet in altitude) and at turn onto glideslope (between 3500 -4500 feet in altitude). But, severe wake-vortex encounters mainly occur less than 500 feet in altitude, and should be monitored in this critical area with an associated Alert System defined as a Safety net.

As given by in statistics of figure 1, main occurrence and severity of wake-vortex encounters are concentrated at low altitude. We can also observe that impact of wake-vortex encounter is more critical at low altitude due to roll angle, due to flying command limits, more especially during final approach and Initial Climb phases.

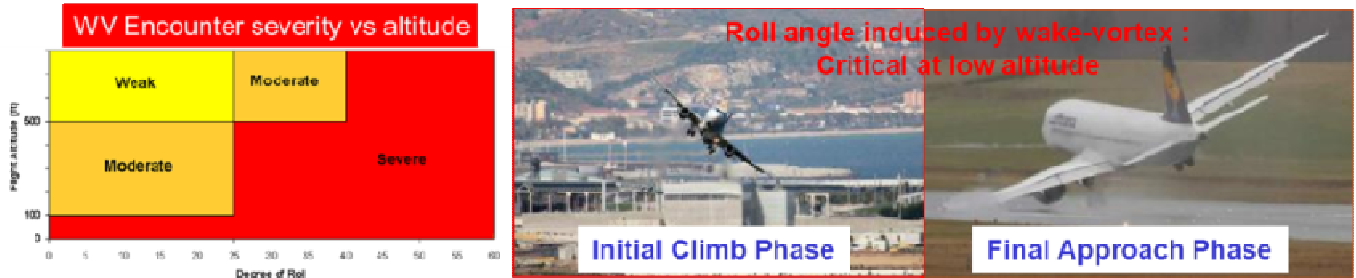


Fig. 2 (at left) Wake-Vortex Encounter Severity versus altitude indexed by roll angle , (at right) critical phases of wake-vortex encounters at low altitude during Initial Clim or Final Approach

As it has been previously underlined, critical area of wake-vortex encounter is localized at low altitude. But these area are also characterized by complex behavior of Wake-Vortex Hazards due to Ground Effect:

- *Wake vortex behavior differs significantly depending on altitude:* in high altitude, out of ground effect, wake vortex behavior is affected by the wind, but remains stable and predictable by “Wake-Vortex Predictor”. At low Altitude, Ground effect can lead to unexpected wake vortex behavior. These phenomena are very difficult to predict and to model.
- *In Ground Effect, Wake Vortices Behaviors are driven by very instable causes:* rebound of vortices on the ground, strength enforcement of 1 Vortex due to low level wind-shear induced by airport infrastructure, generation of secondary vortices, and decay of wake-vortex due to low altitude atmosphere stratification.



Fig. 3 Wake-Vortex in ground effect (vortex rebound, vortex enforcement by wind-shear, secondary vortex generation)

Because of high severity of Wake-Vortex Encounter at low altitude where wake-vortex have also complex behavior due to ground effect, it is very important and requested to monitor wake-vortex by sensors in all weather conditions.

3. SESAR P12.2.2 XP0 Sensors Trials Campaign

Two configurations relative to the North runways of Paris CDG Airport (i.e. 09L/27R and 09R/27L) were used to benchmark the Wake Vortex and Weather sensors at Paris CDG Airport.

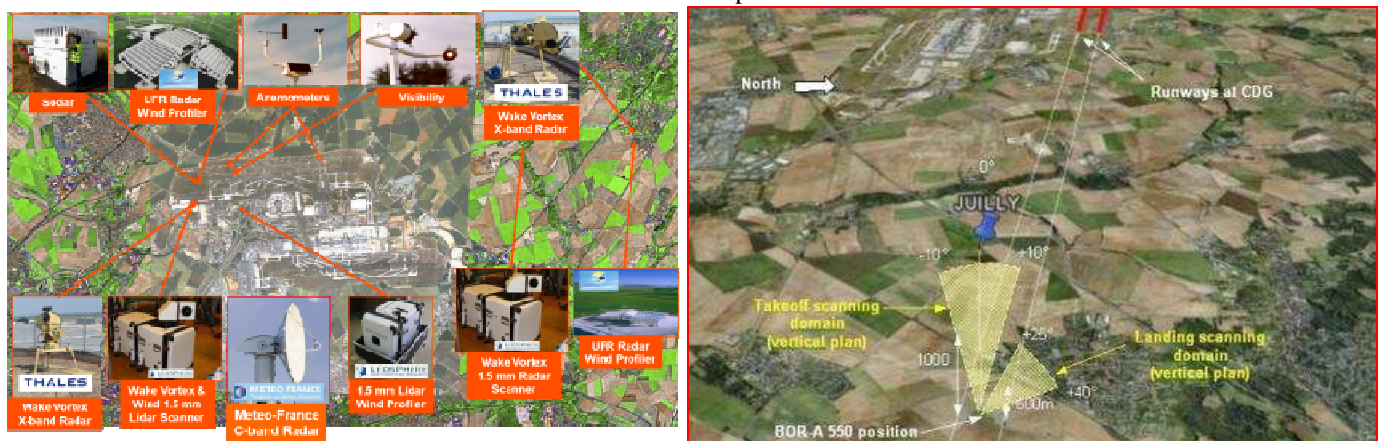


Fig. 4 (at left) Sensors deployment on Paris CDG Airport for SESAR P12.2.2, (at right) Wake-Vortex X-band Radar at Juilly under the glide with vertical scanning

The Weather sensors benchmarked during sensors assessment campaign (XP0) were: One UHF wind profiler (PCL1300 of DEGREANE deployed under the glide), One UHF wind profiler (PCL1300 of METEO FRANCE deployed at CDG Airport), One SODAR PCS 2000 (METEK) (SODAR of METEO FRANCE still operational in CDG), One LIDAR wind profiler (WINDCUBE-70 of LEOSPHERE), Two Anemometers (of METEO FRANCE still operational in CDG). The Wake Vortex sensors benchmarked during sensors assessment campaign (XP0) were: One X band RADAR (BOR-A 550 of THALES), One LIDAR (WINDCUBE 200S of LEOSPHERE).

4. X-band Wake-Vortex Radar Detection in Rainy Weather

In the plane orthogonal to the glide axis, during the rainy weather condition, 34 aircrafts have crossed the scanning plane of the radar: 13 aircrafts taking-off: 4 heavy (B777, A340, A330, B767), 9 medium (B737, A319, MD80, EMB190); 21 aircrafts landing: 9 heavy (B777, MD11, A330), 12 medium (B737, A320, A321, B717, EMB170).

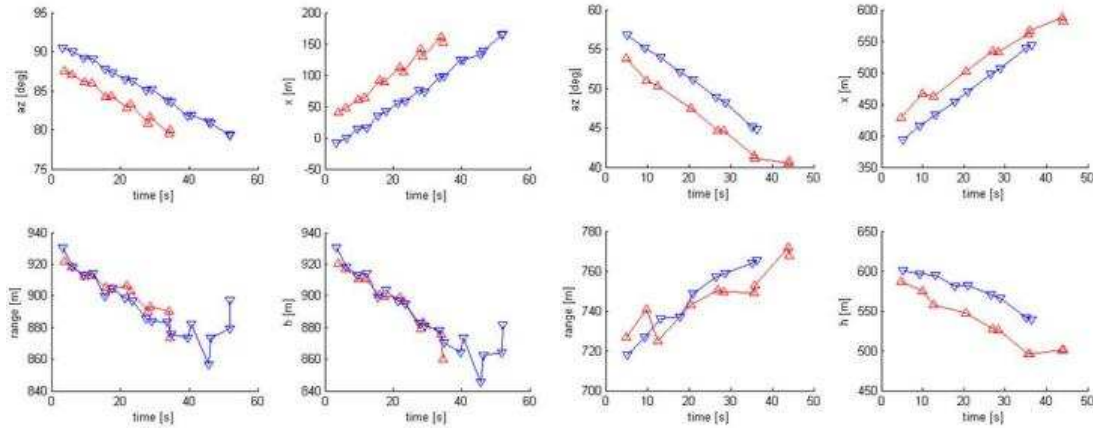


Fig. 5 X-band Radar tracking of: A340 during take-off (on the left), B777 during landing (on the right)

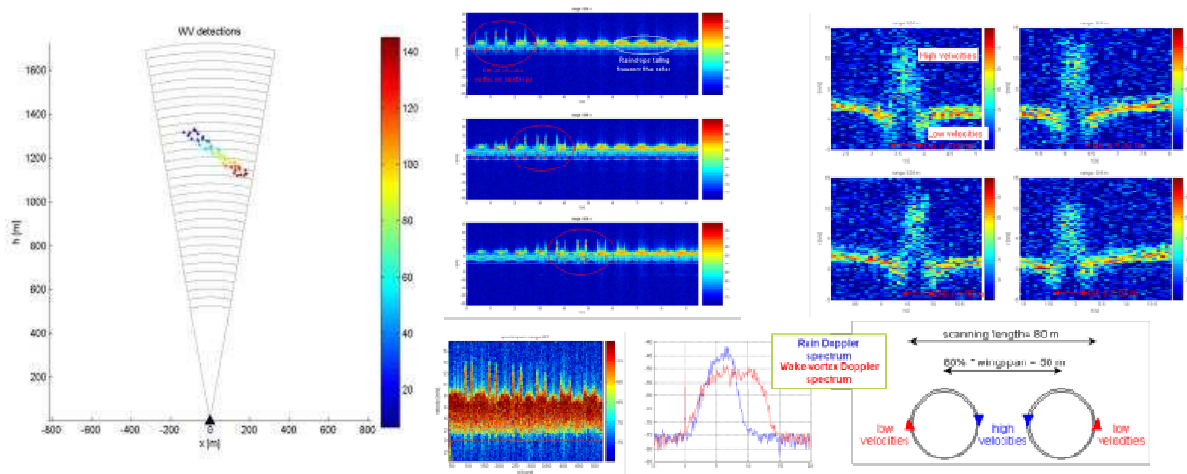


Fig. 6 X-band Radar tracking of wake-vortices in rainy weather: (at left) tracking versus time, (at right) Doppler spectrum

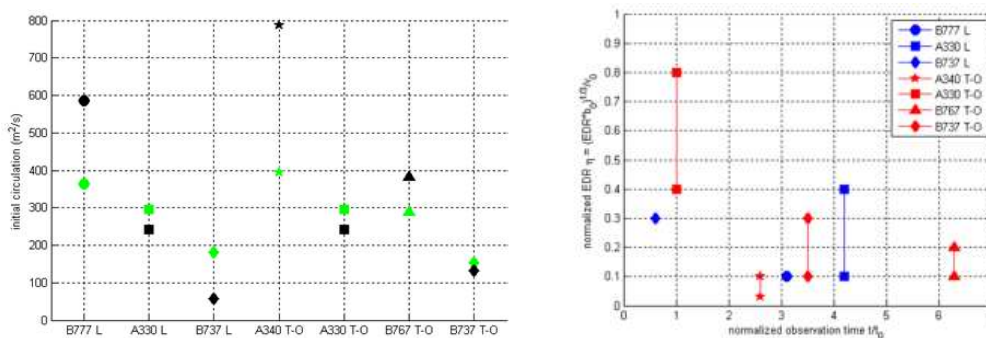


Fig. 7 (at left) Initial circulation versus aircraft configuration (in black : $\Gamma_0 = \frac{Mg}{\rho T \cdot b_0}$, in green, $\Gamma_0 = 2\pi b_0 v_0$ in black), (at right) Normalized EDR (Eddy Dissipation Rate) versus normalized observation time (L: Landing, T-O: Take-Off)

In rain, the BOR-A X-band radar was able to detect wake vortices for all of them, via the Doppler analysis of the raindrops. The observation time of the wake vortices varies from a few seconds up to 250 s. This time seems to be limited by two factors: when the rain rate is too low, it is more difficult to detect raindrops and then wake vortices; in most configurations, vortices are lost when they go out of the radar scan (in range or angle) after some time.

4.1 Synthesis of wake-vortex Radar data exploitation

The X-band RADAR has successfully detected wake vortices generated by aircraft of categories HEAVY and MEDIUM in rainy conditions. The BOR-A X-band RADAR has detected wake vortices up to 1350 m above the instrument. Due to the less favorable weather conditions for Doppler-RADAR measurements in combination with the limited power budget of the BOR-A, wake vortices could only be detected during rain. Wake vortices were detected merely because of scattering on raindrops and the variation of relative dielectric constant within the vortices. The X-band RADAR was able to distinguish the two vortices in some cases. However its angular resolution limits its capabilities to provide accurate vortex core positions. For future campaigns, the new X-band RADAR will be designed with a narrower beam width to investigate this issue. Detection in dry air requires a higher power budget than the power which could be used in XP0. This point offers room for improvement and will be assessed during future measurement campaigns, especially in XP1 (power budget increase by 10, beam width divided by 2). The ability of the wake vortex sensors to detect aged vortices depends on:

- the time the vortices stay within the area where the sensor is scanning and thus on the dimension of scanning sector and crosswind,
- rapid vortex decay (e.g. due to strong atmospheric turbulence) would also result in shorter vortex detection times,
- other parameters like wind shear and atmospheric stability (they are also assumed to affect wake vortex decay and transportation, but are not included in this study).

With the X-band RADAR, wake vortices could be observed up to a maximum of 250 s after the airplane (wake vortices could be observed in relation to the crosswind, which transported the vortices more or less quickly out of the scanning domain). The relationship between EDR and wake vortex decay could not be finally analyzed. For the time being, algorithm to compute wake vortex circulation from a Doppler effect on raindrops is not yet available, but will be developed based on Multi-physic simulation: an algorithm of inversion should be developed and calibrated on Wake-Vortex simulation based Fluid mechanical model coupled with Electromagnetic model.

4.2 Recommendation on Wake-Vortex Radar sensor based on XP0 trials results

The main results were convincing in terms of wake vortex detection. Most of wake vortices were detected in both critical areas with detection ranges that have been demonstrated to be over the detection needs. Wake vortex was detected as long as it was in the sensor scanning domain, except for some cases where detection algorithms must be tuned.

For Radar sensor deployment, two principal sensor position options can be distinguished: under the flight path which allows the two vortices to be separated due to the angular resolution. However it requires a large scan angle when the vortex is close to the sensor, sideways, with a vertical scan perpendicular to the corridor axis. This setup is well suited to track vortices down to the ground. The two vortices could be separated due to the range resolution. Both concepts have their specific strengths and weaknesses. The optimum geometry should be chosen depending on the selected operational concept. Radar has more restrictive limits with respect to small scan angles in order to avoid ground clutter, but this shortcoming can possibly be compensated because of the RADAR's longer range.

Thanks to XP0 results, it has been demonstrated that, in high altitudes, wake vortex behavior, being affected only by the wind, is predictable. Out of ground effect, wake vortex predictors will be able to compute wake vortex behavior based on theoretical models. They need as input an accurate wind speed and direction. In these areas, no wake vortex monitoring sensor is recommended. On the opposite, close to the ground, where wake vortex behavior is affected by IGE (In Ground Effect) and low wind shear that can lead to unexpected wake vortex behavior like complex rebounds and enforcements that cannot be accurately predicted and modeled, a wake vortex monitoring is mandatory. Sensors scanning domain must be large enough to cover both landing & take-off. The best sensors position is demonstrated to be sideways, few hundred meters upstream from the touch down area.

Results show that Radar and Lidar are complementary depending on weather conditions: X-band Radar performances are optimal under rainy conditions and Lidar performances are optimal in dry air. In consequence, for wake vortex monitoring the recommendation is to deploy an X band Radar (electronic scanning) coupled with a 1.5 μ m Lidar, monitoring in a collaborative way as meta-sensor, both located perpendicularly to the runways, a few hundred meters upstream from the touch down area.

Nevertheless, some improvements have to be done on these sensors to reach the performances needed by an operational system. Update rate needed to scan the Wake-Vortex 3D volume should be around 10 s. This capacity is already available for

Lidar, but should be developed for Radar by electronic scanning. Both Lidar and Radar have evaluated the circulation of Wake-Vortex, but this part needs further algorithm development to be able to assess accurate initial circulation and decay.

A gap in data availability has been observed in particular weather conditions, after a raindrop when air has been cleaned from aerosols. Thus, the Radar power budget must be increased in order for it to detect wake vortices in the whole domain where Lidar data are not available. These developments were already planned within the project. Thus, the campaign results confirm the theoretical analysis.

A new multifunction X-band Radar (wake-vortex, weather, traffic) with Electronic scanning capability will be deployed in September/October 2012 at Paris CDG Airport for XP1 trials campaign of SESAR P12.2.2 project, for simultaneously monitor Wake-Vortex close to the runways and assess Wind in the glide and around the airport.



Fig. 8 (at left) Radar Sensors deployment at XP1 Trials campaign scheduled in Sept. 2012, (at right) new Multi-Function (wake-vortex, weather, traffic) Electronic scanning X-band Radar for XP1 trials at CDG airport

5. SESAR P12.2.2 XP0 Wind Sensors Trials

For wind, the overall availability of UHF Wind Profiler Radars data as a function of the height above the surface are presented (the percentage of the time that reflectivity was sufficient to make a measurement and that the atmosphere was sufficiently homogeneous and stable). The statistical comparison between 2 UHF profilers (and with Sodar/Lidar Profilers) have been based on histograms of interpolated data availability, wind velocity and direction profiles in specific periods, calculation of bias, standard deviation and correlation for wind velocity and direction by altitude.

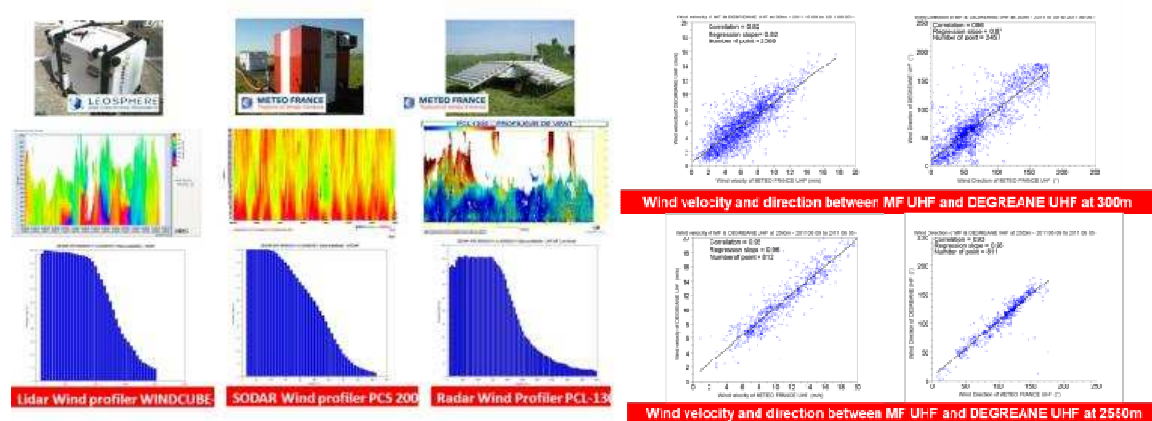


Fig. 9 (at left) histograms of availability according to altitude, (at right) correlation of wind measurements

The ranges that could be covered by the various weather sensors are summarized in the table:

Sensor	Minimum range	Maximum range % availability	
		90%	10%
LIDAR wind prof.	100m	950m	1950m
SODAR	20m	150m	370m
Anemometers	10m	10m	10m
UHF wind profiler	170m	1600m	3950m

The wind field was performed using data that were provided every 10 minutes. For safety critical aviation applications however, update intervals around 1 minute are foreseen at least for the most critical parameters. The Eddy Dissipation Rate, EDR, needed for Wake-Vortex Predictor is still a subject of research: EDR retrieval algorithms derived from Radar or Lidar wind profile measurements are under study. EDR Retrieval algorithm is already available for the UHF wind profiler.

Regarding the X band Radar, a rationalization could be done by using a multifunction Radar, able to monitor both wind and wake vortices. As the scanning domains are different, this RADAR should be an electronic scanning one. This kind of Radar will be used for the following phases of the project.

For weather monitoring, the recommendation is to deploy two sets of sensors. One located under the glide interception point, including an UHF wind profiler and a 1.5 μ m Lidar wind profiler, the other one located close to the runways and composed by an anemometers field, a high power 3D X Band Radar and a 3D 1.5 μ m Lidar scanner.

For wake vortex tracking and predicting, weather data are critical. The following parameters are mandatory for the system: Wind field (u, v and w components), EDR (Eddy Dissipation Rate), Temperature vertical profile. Wake vortex tracking and predicting need accurate data in the defined critical areas, requiring direct measurements. EDR is a parameter which can be computed from wind measurements coming from different sensors or provided by weather forecast models.

6. Conclusion of XP0 Trials campaign

XP0 confirmed the feasibility of a prototype based on existing sensor technologies. Using combinations of sensors, models and real measurements, and thanks to some improved sensors already planned within the project (e.g. more powerful Radar), It should be possible to reach current operational needs. Considering the state of the art on sensor technology, and the needs for operational monitoring of Wake Vortices, it is recommended that further developments on sensor technology focus on the performance of the selected technologies on a long-term basis, which will allow verification of the overall reliability of the sensors and their maintenance needs, evaluation of the opportunity for upgrading or replacement of some sensors with current R&D sub-systems. For future, wake vortex decision support system performances should take advantage of technology progress on sensors and associated algorithms. Technologies study (Low Cost 2D Electronic scanning Radar Antenna and high power laser source Lidar) and Radar/Lidar simulators/algorithms upgrades (Wind/EDR monitoring in Clear Air), validated by trials on Munich and Toulouse airports, will be conducted by THALES and 12 other European partners in FP7 Call 5 study UFO (*UltraFast wind sensOrs for wake-vortex hazards mitigation*).

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