MAGIC ATOLS: MICROWAVE AND GPS INTEGRATED COOPERATIVE AUTOMATIC TAKE-OFF AND LANDING SYSTEM

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Abstract

When avionic solution developed for UAVs can bring benefit for civil aviation safety. Measuring at grazing angles with an RF System is a problem which is a show stopper for many systems. ILS and even MLS are subjects to this problem and try to survive it. Instead of struggling against the physical problem, MAGIC ATOLS turns it into its profit. With such an approach, , the conventional expensive ILS system can be replaced by state of the art, easy to install robust equipments. The availability of affordable sensors providing measurements in bad weather conditions will enhance the safety during those critical phases. Some runways are not equipped with CAT III ILS mainly due to the life cycle cost of such systems. Thanks to a new spatial sampling algorithm, Magic ATOLS will permit a democratization of the NAVAIDS (Navigational Aid System Aids), allowing more and more runways to be equipped and thus contributing to the safety enhancement of the take-off and landing phases.

1 Introduction

For any aircraft, a well-known motto is "Landing is not an option". The take-off and landing are safety critical maneuvers, mainly in bad weather condition, when the visibility is reduced. With the increasing endurance of the new UAVs, more than six hours can elapse between launching the system and recovery. The meteorological conditions can thus change and the landing system has to cope with the maximum constraints to allow a safe operation. The landing operation is even more difficult when there is no pilot in the aircraft and when the aircraft is remotely controlled[1]. Landing an UAV requires a highly demanding human reaction time for an ultra specialised operator and an intensive training. Moreover it is not "all weather conditions" as it depends on the visibility during the safety critical manoeuvre. For UAS, manual landing must be abandoned, as 50% of UAV's losses have occurred during manual take-off or landing phase. This manual solution is no more possible as a certified system in compliance with the USAR code (STANAG 4671) precludes the use of manual landing.

The GPS solution is used for a lot of UAV systems although this solution is not CAT III certified. GBAS GPS (Ground-Based Augmentation System) is not yet CAT III certified, mainly due to the availability and integrity restrictions. The possible addition of Galileo services will improve the overall confidence level but will need to be proven and certified. Although commonly used in the UAV world, its single use is legally prohibited for the critical operational phases.

The laser solution is sometime employed for UAVs although it has a strong limitation in heavy rain, fog and snow. Moreover the laser beam being narrow by nature, a methodical sweeping of the detection envelope by a large number of scans is necessary to detect a target, thus increasing the research duration. It has to be highlighted that an accurate positioning of the beams in relative with the runway is compulsory. In case of multiple targets, target confusion is always possible as the tagging of

[1] This is even more complex due to the « mirror » effect, all commands are inversed compared to a normal aircraft.

the pencil beam which is returned by the reflector carried by the airplane is not possible.

Another known solution is based on millimetric wave systems, that are also very directional thus needing a searching phase to pick-up the relevant target. These systems are also demanding an absolute calibration toward the runway to provide the localisation coordinates in the runway's geodesic reference. Those systems have actuators to mechanically steer the parabolic dish antenna toward the target. In case of multiple targets, those systems reach quickly their limits, as they need to share the time and rapidly jump from one target to another, with the risk of a poor tracking or even a confusion between targets. Moreover, due to atmospheric losses in high frequency band they have to operate as transponders, one way being achieved by the ground system transmitter, and a transponder onboard the aircraft answering at another frequency. In case of failure of the onboard transponder, the system is no more operating, since it is single failure dependant.

Furthermore they are costly and difficult to handle.

On civilian airports the landing is performed with the help of ILS (Instrument Landing System). Permanently installed and adapted on each airport, those systems require maintenance and periodic manual calibration and are sensible to multi-path effects. In addition they are expensive and thus not always available on all airways. They require both an equipped airfield and a modified aircraft. Besides, they are not usable for take-offs.

On military applications, in addition to the ILS systems, PAR (precision approach radars) are used for deployment. Those systems have to cope with the physical problem of multi-path propagation, and thus are remaining huge and heavy.

A radar based solution provides the great advantage of improving the safety as the integrity of the system is easier to assess.

The radar sensors are particularly well fitted to operate in bad weather conditions. The principles are known and admitted for en route control.

The radar systems have to measure the incoming aircraft position with a great accuracy at grazing angles. Those conditions imply a lot of constraints on the radar design and architecture, as the multi-path effect has to be eliminated. The multi-paths attenuate and degrade the radar echo, making detection more difficult and elevation measurement quite impossible at very low grazing angles. Facing this issue, the sole common immediate solution is to narrow the pencil beam to exclude from the reception antenna the signal reflected on the ground. Generally, it leads to huge antenna size and the inherent constraints on the actuators for moving the aerial. The search and lock phase is also rendered critical as the aircraft can sometime escape from this narrow beam and in that case a new search phase has to be initiate at short distance.

For the UAV application, Thales designers were forced to improve the existing systems and to find a solution to fix the multi-path effect which was the limiting phenomenon for miniaturising the radar sensor. It was compulsory to set up a dedicated system, easily deployed, easy to handle, small, light, without calibration needs and requiring no specific skill for the operators. Another constraint to cope with was that take-off and landings have to be routinely performed in all weather conditions.

The even more demanding challenge of rotary wings UAVs deck landing onboard frigate in severe sea state conditions was also clearly dependent of this miniaturisation.

The English KISS motto: "Keep It Simple and Stupid" was plagiarized in "Keep It Simple and Smart" the French KISS.

An explanation of the process used to turn the physical problems into advantage is depicted in the following paper. Field measured values and operational results will be unveiled. The status of the various technical improvements will be detailed.

2 Existing field constraints: CONOPS

The system is constituted by the following elements:

- A ground radar, placed in edge of runway, making the location of the aircraft both in distance and in angle simultaneously on the RADAR skin echo and on the continuous wave signal emitted by a beacon embarked on the drone.
- A beacon embarked aboard the aircraft, which supplies to the radar, by its emission, a punctual position reference
- A ground beacon installed on the runway edge in the neighbourhood of the touch point with a predetermined position with regard to the radar. This beacon allows to refine the location of the drone, the measurement of the angular position of the drone being made by ecartometry technique by the radar in differential between the position of the embarked beacon or the echo of skin, and the position of the ground beacon. Figure 1 represents the installation concept the system aside the runway.

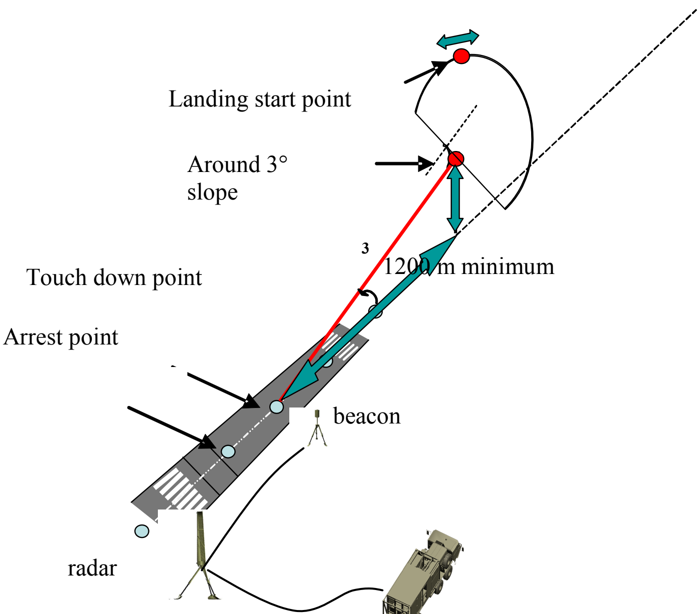


Figure 1: install[illegible]ncept

The whole system is managed by means of a ground station, which transmits to the drone through the system data link the positions coordinates measured by the radar. Optionally, it could also beneficiate from a direct dedicated link between the ground radar and the embarked beacon, to duplicate the transmission.

The radar has a wide and fixed beam, which allows an instantaneous detection in the whole coverage domain, without necessity of scanning the space to find one or several targets.

It works in X-band, and relies on low-cost technologies and architectures:

- Simultaneous Emission / Reception in homodyne mode
- Printed circuit antennae
- Low level solid state transmission
- Direct Digital Synthesis (DDS)

Due to the small size and light weight of the system, an installation on the runway size is always possible.

3 Characteristics of the radar

3.1 Functional capacities

During the approach phase, the drone penetrates into the radar antenna lobe. It is first detected and identified through the detection of the beacon fixed frequency transmitted signal. This detection occurs at a range greater than 10 km.. Before this phase, the UAV is still using its own navigation system to reach the landing area.
After beacon detection and from a 5 km range from the ground radar, the radar acquisition starts

As long as the the approach phase is going on, the requirements on the angular measurement accuracy become more and more stringent, reaching up to one milli radian during the final approach. At the same time, the range accuracy is requested to be better than one meter.. The speed measurement accuracy is of 0.1m/s.

These requirements have to be achieved within a minimum refresh rate of 20Hz and in accordance with a maximum latency time of 100ms

3.2 RADAR Wave forms

The radar operates in continuous mode (CW) and simultaneous emission and reception.
The waveform includes two interleaved sequences:

- The first sequence is assigned to the "active" mode. During this sequence, the radar emits in the UAV direction, detects it, estimates its position and its speed from the skin echo. The wave form used during this phase is FMCW. (Frequency Modulated Continuous Wave)
- The second sequence corresponds to the "passive" mode .During this sequence, the radar listens successively the signals issued by the embarked beacon and the ground beacon then deducts the UAV position in regard to the touch down point. During this sequence, the radar Local Oscillator is automatically tuned to the beacons frequencies.

So, the radar has two independent channels which supply the position of the drone in a redundant way. The safety is improved thanks to this redundancy. The integrity is ensured by the permanent measurement of the known position of the ground beacon.

3.3 Elevation angular measurement

The angular measurement domain is valid up to 15 ° in elevation. The signal processing is split in two areas:

- at grazing angles, typically from 0° to 5°dedicated and adapted to ground reflections interferometer techniques are used. This signal processing applies in particular to a standard glide slope (3 °) and in any cases during the final approach, where the location accuracy must be maximum.
- At higher angles, typically from 5° to 15°: Digital Beam Forming processing is performed. This signal processing applies in particular during constant altitude flights.

Both signal processing methods are applied at the same moment to the signal received from the embarked beacon and to the skin echo, which confers to the system a strong operating safety.

3.4 Grazing Angles signal processing

3.4.1 The problematic of the reflection on the ground

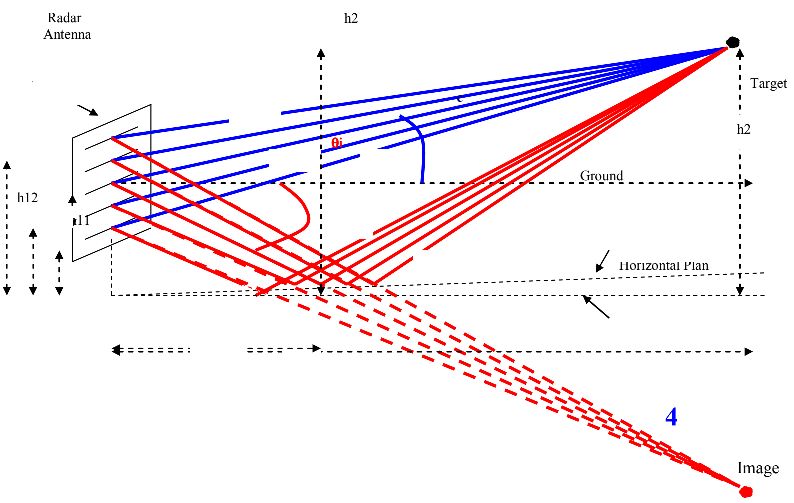
The problem of the reflections on the ground is well known from radar people.

The consequences of these reflections on the radar performances are the following:

- Deterioration of the signal detection as the signal reflected by the ground can be in phase opposition with the direct signal
- Location in elevation deterioration as the coherent combination of direct and reflected signals is creating phase and amplitude aberrations on the receiving antenna

Such a configuration is depicted in figure 2

These deteriorations can be critical for the surface-to-air tracking radars for the detection and during the tracking of targets at very low-altitude.



The figure 3 below represents an example of elevation measurement disturbance due to the multi path effects in a standard radar signal processing along the range.

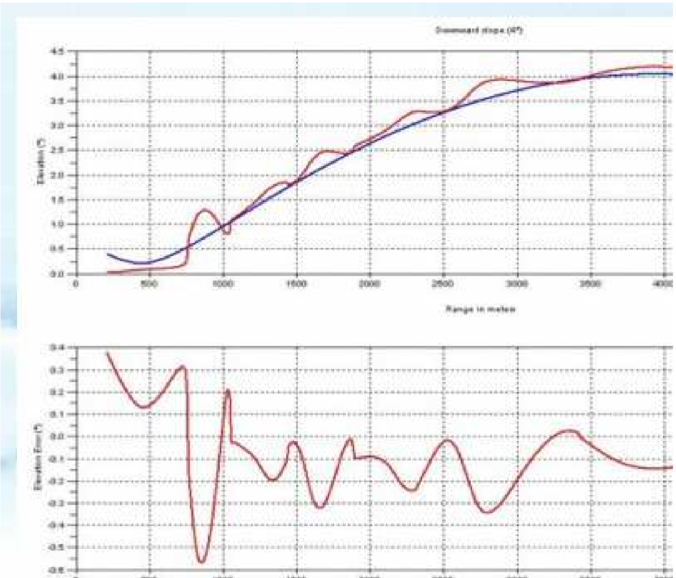


Figure 3 Measurement distortions in classical radar

The common solutions usually implemented to cope with those reflection problems consist in filtering at the antenna level the signals reflected by the ground.

This is made by minimizing the contribution of these reflected signals thanks to an appropriate tilt and to an increased directivity of the radar beam.

This method requires antennas very directive and steered in a very precise way. Unfortunately, the reduction of the beam width directly increases the size of the antenna. However, the antenna dimensions are very pejorative, as the actuators have to be build in consequence, their implementation on the runway side are also difficult or even prohibited for practical and safety reasons.

These antennas have to be also associated to complex processing, as high resolution adaptive processing. These processing require heavy computing resources and are sensitive to the hypotheses made on the propagation model, in particular regarding the coherence or not of the reflected signal with the direct signal, which made those signal processing methods difficult to implement and not robust.

3.4.2 MAGIC ATOLS grazing angle signal processing

The basic idea is to use the ground reflection instead of trying to struggle against it. The choice is made to favour those reflections.

1. By using a wide beam antenna in elevation to cover the ground reflected signals.
2. By using the horizontal polarisation to get a high reflection coefficient, constant in amplitude and phase in a wide domain.

The goal is then to measure the differential angle between the target and its reflected image, instead of trying straight forward to measure the target elevation angle.

The resultant signal constituted by the direct signal and the ground reflected image creates interferences waves which generate distance dependant amplitude modulation of the transmitted and received signals. This modulation perturbed the RF transmission as depicted in the figure 4

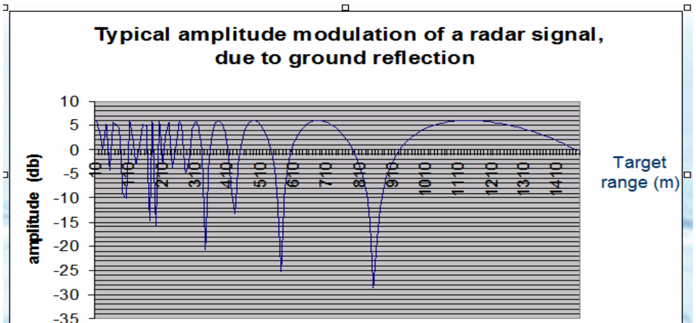


Figure 4

This modulation is also detectable on a radar antenna, assuming that a spatial sampling is performed on the vertical axis, issued from independent sub arrays. This is achievable with a patch array antenna using N independent channels, spread on the vertical dimension as highlighted in the figure 5 and 6.

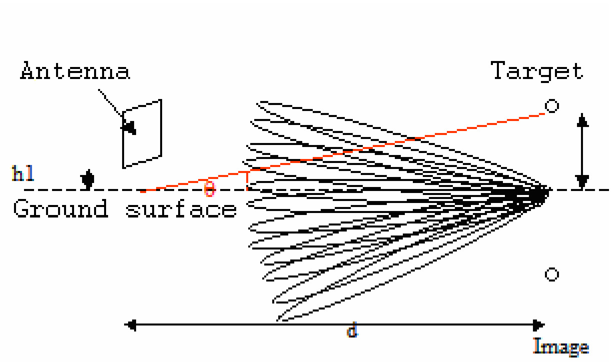


Figure 5 Recombined signal received on the antenna

ρ is the ground reflection amplitude coefficient (ρ#1 in H polarisation)

λ is the signal wave length

d is the distance between the radar and the target

φ is the phase depending on the reflection plan

θ is the elevation angle between the radar and the target.

The figure 7 below represents the modulated signal sampled on the antenna height and the result of the correlation with the set of replicas.

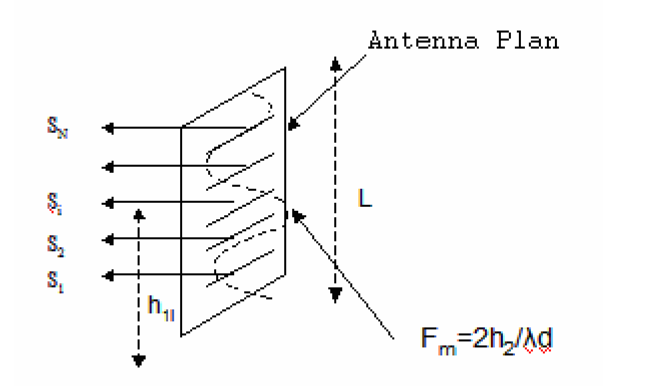


Figure 6 Shape of the received recombined signal on antenna surface.

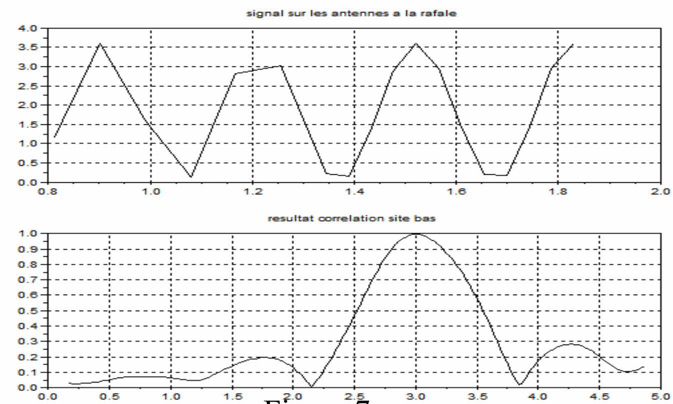


Figure 7

The frequency modulation measurement Fm, on the height of the antenna gives the direct value of the elevation angle of the target $\theta=h_2/d$

This estimation is performed in correlating the received signal in comparison to a set of possible replicas, where the modulation signal on the antenna can be described by the following:

With $1+\rho^2-2\rho\cos((4\pi h_{1i}h_2/\lambda d)+\varphi)=1+\rho^2-2\rho\cos((2\pi h_{1i}/\lambda).2\theta+\varphi)$

If the signal amplitude is received on the sub array ranked i

h_{1i} is the height of the concerned sub array phase centre related to the reflection plan.

h_2 is the height of the target related to the reflection plan

For an antenna of len … rrelation resolution can be wri … λ/2L

The optimal measurement accuracy can be expressed in relation to the signal over noise ratio S/N:

$\sigma\theta$ # $\Delta\theta/(2.5(2\ S/N)^{1/2})$

As an example, for an antenna height of L=1.2m and a signal over noise ratio S/N of 20 db, the measured accuracy σθ is better than 1 mrd.

3.5 Antenna architecture

The antenna is based on 4 sub arrays for the transmit function, with an aperture of 10° in elevation and 20° in azimuth; and at the reception a lacunary array of 24 elements with the aperture of 20° per 20° arranged in two identical columns of 12 sub arrays.

The antenna is rear tilted of 5° in the vertical plan, providing a global aperture of -5° to +15° in elevation.

In order to optimise the balance of transmitted power, the optimised transmit antenna is selected in accordance with the interference figure measured on the reception antenna.

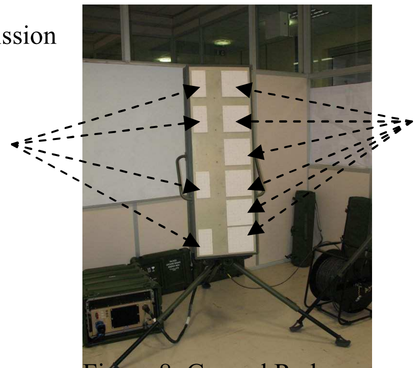


Figure 8: Ground Radar

Each sub arr… ted digital receiver includ… front end filtering process: range compression in the radar active mode and band pass filter in beacon reception mode.

The complete processing tasks perform Digital Beam Forming, Doppler processing, detection, 3D location on a dedicated processing board. This board is also in charge of the complete tracking and data processing tasks.

The ground radar architecture is depicted in figure 9.

Thanks to number of reception channels, the equipment is to ensure a safe operation, even in case of some channel failures. The build in test, operated toward the ground beacon ensure the complete system integrity. Thus the radar positioning and alignment is not critical as it is self controlled by the continuous measurements and an incorrect vertical alignment is auto corrected. A misalignment of 2° is absorbed by the system self calibration.

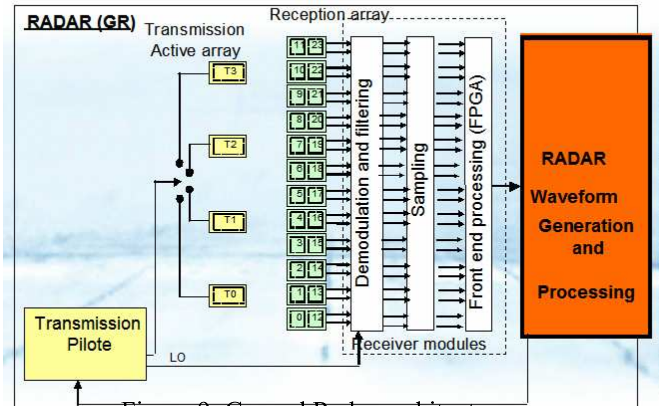


Figure 9: Ground Radar architecture

4 Field experiments: Obtained results

The following curves in figure 10 are highlighting the trajectory estimation results of an approach followed by a touch and go at a range of 400 m from the radar.

In blue the DGPS measurement (1 point per seconde).

In violet the trajectory measured by the radar (20 points per seconde)

Those curves show a good correlation between the DGPS and the the radar data, with the advantage of a better radar dynamic response thanks to the higher refresh rate.

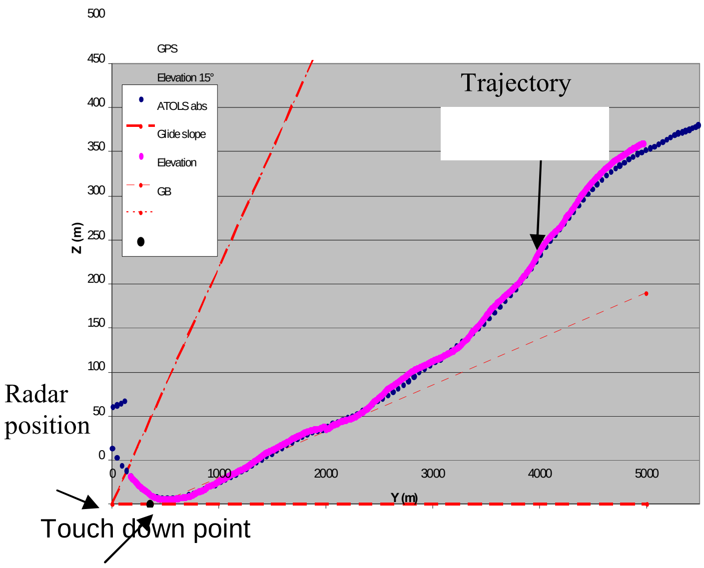


Figure10: Elevation measurement: height versus range

The exhaustive measurement sets, performed in a great number of conditions and on various airfields have demonstrated the capability of the MAGIC ATOLS to accurately locate an UAV and to track the trajectory with the required accuracy of 1mrad, even at few meters above the ground.

5 Integration into civilian application

MAGIC ATOLS is now in flight validated and in operation on of the major European UAV system. To turn this system into a manned aircraft, various solutions are possible.

- The simplest one is to use the radar as a PAR (Precision Approach Radar). With no beacon installed onboard the aircraft, a synthetic voice can be rooted on a dedicated radio channel, providing adequate information for the landing. This solution mimic the deck landing used on board aircraft carriers.
- A medium solution is the adjunction of the embarked beacon, which can be either integrated or just plugged behind the windscreen, fed by an internal battery or by Aircraft power supply. This solution allows a hand-check between the radar and the embarked beacon, as the onboard allocated frequency can be controlled. The feed back of the measurements can be either by radio as depicted in the previous point or by display on the standby instrument.
- A fully integrated solution can also be proposed, with the information straight forward modulated by the radar waveform and received and decoded by the beacon. Of course a coupling with the automatic pilot can be proposed as it has successfully be proven by the Automatic Landing already performed.

6 Conclusion

The field proven MAGIC ATOLS can now be safely employed on civilian application for navigation aids on small runways. This will considerably enhance the safety, mainly on non ILS equipped airports. Unfortunately recent events have proven that relying only on pilots feelings was not sufficient to ensure a safe landing in bad weather conditions.

The unequalled performances on grazing angles measurement have permitted to minimize the size, weight and power of the automatic landing function. A special attention was made to preserve a complete redundancy on the measurements, either in the number of channels involved or in the kind of measurement performed on two different signals, the embarked beacon and the skin effect. The integrity is ensured by the online measurement of the ground beacon, seen by the system as a known reference.

This newly developed system, initially designed for UAVs applications can be advantageously reconfigured to perform ILS like services. The main characteristics of this system are rendering it ideally well fitted for mobile application but also for an easy installation and handling.

MAGIC ATOLS by using RF signals is an all weather condition system.

- The accuracy is more than needed for the landing and the accuracy improves coherently when range decreases.
- The integrity is ensured by a continuous integrated measurement of the external beacon and a complete monitoring of the internal redundant channels. A comparison is performed between the results obtained between the radar channels and the beacons channels.
- The low latency is obtained by the intrinsic radar measurement speed which precludes the filtering needs requested with the other sensors.
- The reliability is obtained by the duplication of channels, either in transmission or in reception and by an orthogonal measurement of the radar and beacon signals.
- The continuity is ensured by the capability of the system to self detect the failure and to reconfigure the system in real time. The system provides the

measurement standard deviation and the likelihood level ensuring also an external appraisal. The landing can be achieved in acceptable safety conditions even during possible degraded states.

- The availability of the system is high thanks to all the efforts of having a fix, with no mechanical steering, system including redundancies.

The opportunity of getting a low cost, easy to handle NAVAIDS, flight validated is now open for civilian application.

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