Radar Systems for "Sense and Avoid" on UAV

Operating Frequency and Tradeoffs

Stéphane KEMKEMIAN, Myriam NOUVEL-FIANI
Radar Technical Directorate
THALES Aerospace Division
F-78852 – Elancourt CEDEX - FRANCE
stephane.kemkemian@fr.thalesgroup.com
myriam.nouvel@fr.thalesgroup.com

Pascal CORNIC[1], Patrick Le BIHAN[1], P. GARREC[2]
[1]Radar Technical Directorate [2]Mission Airborne Systems
THALES Aerospace Division
[1]F-29000 – Brest CEDEX – FRANCE
[2]F-33000 – Pessac CEDEX – FRANCE
pascal.cornic, patrick.lebihan@fr.thalesgroup.com
patrick.garrec@fr.thalesgroup.com

***Abstract*—Up to now, UAV are widely used, but only in special conditions, both in space and time, which leads to the notion of "segregated airspace". Sense and Avoid systems must be installed on board the UAV to allow their insertion in the general air traffic. Such systems will include cooperative and non-cooperative sensors for reliability. The radar is likely the most useful non-cooperative sensors because it is an "all-weather" sensor and it provides, by essence, accurate ranging and closing speed. The paper discusses solutions in three radar bands: S, X and Ka bands. For each of them, one or two solutions are presented and the pros and cons are discussed. It will be seen that X band is an interesting solution to be pursued.**

Keywords: UAV, Sense and Avoid, Segregated Air Space, Radar, Electronic Scanning, Digital Beam Forming, Space coding.

I. INTRODUCTION

UAV are widely used, mainly for military surveillance purpose. Indeed, these platforms are light, easily and quickly deployable. They can approach closely the area of interest without endangering an aircrew or a costly platform.

For surveillance purposes, these unmanned aircrafts usually carry electro-optical or radar payloads (SAR imagery and Moving Target Indicator). In the near future, some combat functions and related sensors will also be onboard unmanned aircrafts.

Up to now, UAV are employed in crisis or war times. They do not need to be inserted in the general aviation traffic as in peace time. For training purposes, the UAV are flown in special areas called "segregated areas", which are especially attributed for UAV deployment in a limited space area and in a limited time slot.

Moreover, there are emerging applications of UAV for security purpose, for example:

- Border and coastal surveillance;
- Anti-terrorist surveillance;
- Fire or pollution surveillance (forests, seas).

Such operations will be possibly permanent, both in time and space. So, a segregated airspace limitation will be no longer acceptable and the UAV will have to be inserted in the general air traffic without any disturbance to other aircrafts.

To realize this insertion, UAV will have to be fitted with "Sense and Avoid" systems. Such automatic systems have to act as "human pilots" onboard. The reliability, in term of failure, ability to detect hazards and to take right decisions, is of prime importance.

UAV, in general air traffic, must follow the air rules (both VFR and IFR rules). They must also have the same behavior than any other manned aircraft. In particular, they must not hazard other aircrafts with inappropriate reactions.

The main tasks to be carried out by a Sense and Avoid system are:

- In "normal" conditions, the traffic separation both in horizontal and vertical planes. This task is especially mandatory in the VFR domain.
- In "emergency" conditions, the collision avoidance with other aircrafts.
- And, it is advisable to provide additional weather and terrain avoidance functions.

In this paper we study radar solutions for Sense and Avoid systems, corresponding to three radar bands:

1. In "low" radar band, in S-band around 3 GHz;
2. In the "classical" airborne radar band, in X-band around 10 GHz;
3. And in millimeter wavelength region, in Ka-band around 35 GHz.

The pros and cons related to these three solutions are developed hereafter. Moreover, frequencies regulations have to be taken into account but are not addressed in this paper.

II. SYSTEM REQUIREMENTS

At this time, there is no formal regulation about such systems. Nevertheless, some preliminary hypotheses are generally admitted:

A. Reliability:

The reliability of such a system is of prime importance; the system shall merge both cooperative and non cooperative sensors:

- The discussion on the cooperative sensors is beyond the scope of this paper. Only a general example is given. Such a cooperative sensor can be a Traffic Collision Avoidance System (T-CAS). A T-CAS system provides firstly "traffic advisories" then takes "resolutions advisories" according to the hazard level of the track conflict between aircrafts (A/C).
- Non cooperative sensors shall have the same field of view than a pilot in a cockpit, which is to say about **±110° in azimuth** and about **±15° in elevation** (relative to the aircraft). This coverage corresponds to the "see and avoid" task that does a "manned" crew.

The fusion of data coming from cooperative and non-cooperative sensors is not discussed here as it is also beyond the scope of this paper.

B. Two main tasks:

The system shall carry out **two main tasks**:

1. The traffic insertion and separation: Air navigation is mainly based on vertical and lateral separations:
   - Vertical spacing greater than **500 ft** (150 m);
   - Horizontal spacing greater than **0.5 NM** (925 m).
2. The collision avoidance: A safety cylindrical area with a radius of 500 ft (150 m) is defined around each A/C. A collision or a quasi collision (air-miss) occurs if an A/C enters in the safety area of another one.
   - The maneuver related to the collision avoidance is an emergency one. In normal operation, if the traffic insertion function has properly worked and all surrounding aircrafts have followed the air regulations, no emergency maneuver would occur.
   - This emergency maneuver is carried out at "short" range: we do not need detection at very long range in this case.

   In the emergency case, the maneuver decision is automatic. In "normal" case, the maneuver can be either done automatically by transferring the tracks data to the UAV autopilot system or a proposal of maneuver can be sent to the Ground Control Surveillance, which takes the decision to do it or not.

C. Advance warning time requirements:

- About **20 seconds of advance warning**.
- The warning time of 20s is a trade-off allowing both a repositioning maneuver, which is compatible with the UAV maneuverability, and an exhibition of a normal "manned" behavior to the other aircrafts.

D. Concerning the non cooperative sensors:

- The non-cooperative sensors have to provide at least **similar measurements to those provided by a "human" pilot**:
  - Angular position;
  - Range;
  - Relative closing velocity estimation.
- To provide sufficient redundancy, it is preferable having two non cooperative sensors, based on different physical signatures of the environment (*e.g.* optical and radar signatures). In normal use, information coming from both of them is merged. In case of a failure of one of them, a "nominal" safety must be provided by the remaining one.

The purpose of this paper is to deal with only one non cooperative sensor, namely the radar.

III. Radar Sensor Requirements

A. Functional requirements

These system requirements can be translated in "Radar minimal requirements":

- An **angular coverage equivalent to the field of view of a pilot in a cockpit**: ±110° in azimuth and ±15° in elevation (section II.A). Thus, the corresponding solid angle to be monitored is about **2 sr**.
- **Angular tracking accuracy** allowing the computation of a realistic flight path that guarantees sufficient spacing when crossing other aircrafts (the spacing requirements are given in section II.B.)
- A revisit time in tracking mode smaller than **2 seconds**. (To ensure a proper target tracking.)
- About 20 seconds of advance warning (section II.C). **This requirement is not expressed in terms of range, but in terms of time for advance warning**. In other words, the required range is proportional to the closing velocity.
- The Radar Cross Section of a target is **> 1 sqm**.

B. Physical aspects

Ideally the system should be flexible in term of installation on various platforms. At this step, we consider two main classes of platforms:

- The fixed wings platforms (*cf.* Figure 1.);
- The Vertical Take Off and Landing (VTOL) platforms (VTUAV, *cf.* Figure 2.).

The weight, cooling, electrical consumption and aerodynamic disturbance of the Sense and Avoid system must be limited. Moreover, these features must be shared with the "useful" payload (*e.g.* reconnaissance sensors for a reconnaissance UAV).

Figure 1. Example of fixed wing UAV (Watchkeeper 450, [1])

Figure 2. Example of rotary wings VTUAV

IV. OPERATING FREQUENCY CONSIDERATIONS

A. *Power budget considerations & scanning issues*

During the search phase, it can be demonstrated that the received SNR, after coherent processing, is proportional to:

$$SNR \propto \frac{P_{AVG} T_{REV} A_R \sigma}{\Omega . R^4} > \text{Threshold}\ "T" \quad (1)$$

Where: P_{AVG} is the average transmitted power, T_{REV} is the revisit time (< 2s) and σ is the target R.C.S. (> 1 sqm and assumed frequency independent). The maximum detection range is R and Ω is the whole radar coverage (2 sr). A_R is the R.F. antenna surface on receive. In order to detect the target with a given probability, the *SNR* must be greater than a given threshold "*T*" to ensure a proper false alarm rate.

The equation (1) is valid whatever the scanning method is: mechanical, sequential Electronic Scanning (E-Scan) or by using Digital Beam Forming (DBF). It does not directly depend on the antenna gain on transmit. In other words, this condition is universal, provided that antenna gain on transmit (coherent spatial gain) can be exchanged against coherent gain along time (Doppler processing) on receive. The condition (1) can be rewritten in:

$$P_{AVG} A_R > T' \quad (2)$$

A good balance has to be found between the transmitted power (consumption, cost, cooling...) and the antenna surface on receive (size, weight, angular accuracy…). An antenna size of about **5 or 6 dm²** is a good trade-off between installation constraints and efficiency (gain and angular resolution).

The digital forming of simultaneous and numerous beams on receive allows a longer integration time than what could be permitted with a sequential scanning (whatever is, mechanical or electronic.) Thus, for higher radar bands, the DBF technique is the only one that allows a realistic Doppler processing by providing sufficient dwell time on target and sufficient Doppler resolution as shown in table I.

TABLE I. SCANNING ISSUES WITH "SEQUENTIAL SCANNING METHODS"

Total coverage 2 sr. in 2 seconds and A_R = 5 dm²			
Band	**S (3 GHz)**	**X (10 GHz)**	**Ka (35 GHz)**
Receive gain	18 dB	28 dB	39 dB
Beam width	0.2 sr	0.02 sr	1.6 10^{-3} sr
Beams number	> 10	> 100	> 1250
Dwell time	< 200 ms	< 20 ms	**< 1.6 ms**
Scanning rate	**> 150°/s**	**> 500°/s**	**> 1700°/s**

A full mechanical scanning could only be conceived in S-band. However, a rotation rate of more 150°/s on two axes does not seem very suited for a high reliability system.

The conclusion of table I is that **E-Scan or DBF is mandatory for such a system, at least on one axis** (vertical or/and horizontal).

V. RADAR SYSTEMS SOLUTIONS

A. *S-band solution*

The main interest of this solution relies on the possibility to have a flat DBF antenna system with a few number of receive only elements and one or some wide coverage transmit only elements. For instance a receive surface of 5 to 6 dm² can be filled with only 20 to 24 modules (with a λ/2 mesh).

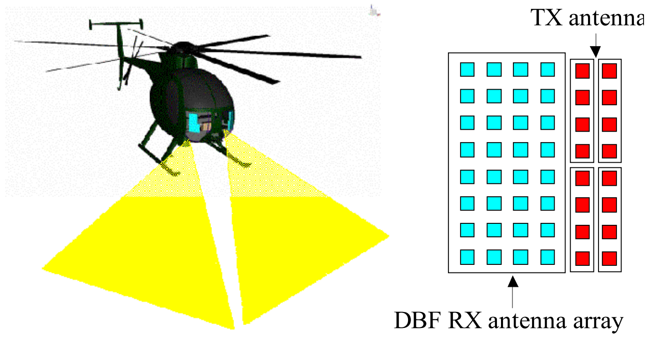

Figure 3. S-band system on a VTUAV

Such a system can be applied directly on the airframe of the UAV without a significant external extra volume. Nevertheless, the coverage of a flat panel (E-Scan or DBF) is limited to about ±60°: two panels are needed to cover ±110°.

In the example in Figure 3. both DBF on reception and E-Scan on transmission are used[1]. The interest of using both of these scanning methods is to improve the performance in tracking mode. Indeed, the DBF only is very interesting in the search phase, but less in tracking a target because the radiated power cannot be steered in the target direction. Moreover, this method avoids issues with very long coherent integration times. A low cost but convenient discreet E-Scan can be achieved by using PIN-diodes phase switches at low R.F. level.

[1] THALES patented system.

1) *Advantages:*

A non ambiguous waveform is feasible, both in range and velocity, which simplifies the waveform design and the dynamic range requirements (no range ambiguity on target).

2) *Disadvantages:*

They are related to the low directivity of the antenna system due to the low operating frequency. Two consequences occur:

1. With classical Doppler filtering, bad detection on slow moving targets at ranges beyond the UAV ground altitude (strong ground clutter return). However, a Space-Time DBF processing can mitigate this issue.

2. The second one is the bad angular accuracy due to the limited size of the antenna system that can be installed.

B. *Ka-band solution*

In the one hand, a full mechanical scanning solution is not possible (for the coverage and advance warning which are required.) On the other hand a full 2D DBF like in S-band case leads to a very large number of receive modules and a prohibitive cost. A trade-off is to mix mechanical rotation in azimuth and DBF in elevation. In this case, the antenna is constituted of about twenty receive only sub-arrays vertically disposed. Each sub-array has a vertical directivity of some tens of degrees: this configuration avoids grating lobes within the coverage domain while having the minimum of receive channels. The transmit sub-array has the same coverage than each receive sub-array. It is fed by a Power Amplifier system (PA) excited by a single Wave Form Generator (WFG).

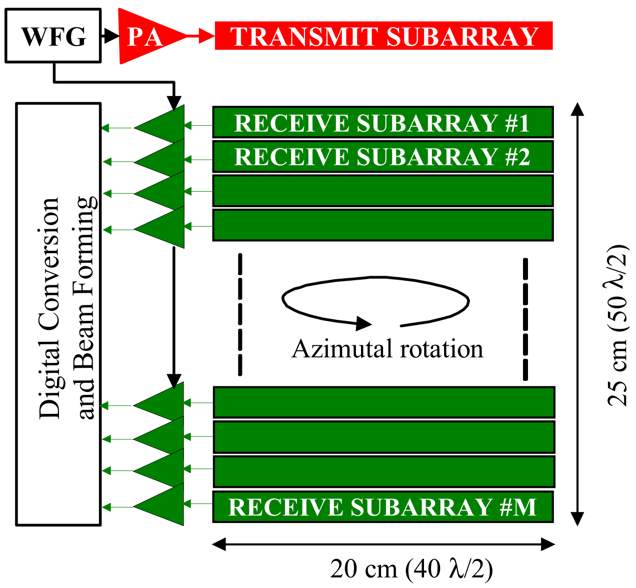

Figure 4. Possible Ka-band antenna system

1) *Advantages:*

Such a solution leads to narrow beams after DBF and easily meets the requirement in term of angular accuracy for target location and angular selectivity against ground clutter.

2) *Disadvantages:*

They are mainly at the level of the large number of receiver channels, which may lead to a costly design, especially in this millimeter band.

C. *X-band solutions*

1) *First X-band solution*

This first X band solution is similar to the Ka one. The azimuth scanning is also provided by mechanical rotation and the vertical scanning can be done either by DBF only or by using a 1D Active Electronic Scanning + DBF solution such as in Figure 5. As previously, each of the six sub-arrays has a vertical directivity of some tens of degrees.

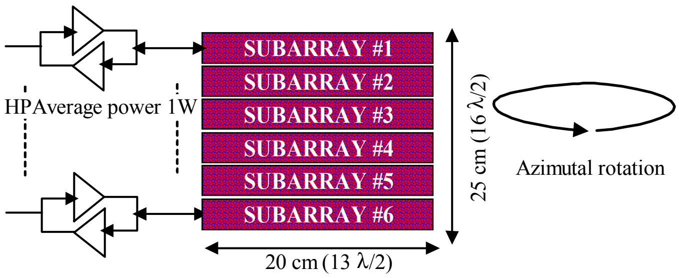

Figure 5. Possible X-band antenna system

In a basic configuration, only 6 T/R modules are needed. In a more complex solution, each of the six sub-arrays has two channels on receive (12 channels for the whole system) to provide accurate mono-pulse measurements in azimuth. Another interest is that mono-pulse solution allows 2D Space Time Processing, which enhances the detection on slow moving targets against the ground clutter.

a) *Advantages:*

This solution in the X-band is a good tradeoff between the angular accuracy and the number of receive channels. A waveform with few range/Doppler ambiguities is feasible and easies the implementation of a Space-Time processing for enhancing the slow moving targets detection.

The technologies developed at large scale for the new AESA X-band radars (radars for fighter or for long range surveillance) can be reused (in this case, pulsed waveforms with a duty cycle equal or lower than 10-15% are a suitable solution.)

A solution in X-band takes sense with the future Multi Function Radars (MFR) on board fighters. These MFR will carry out, not only the “radar” functions, but also some cooperative functions with other R.F. devices onboard or outboard. For instance, a data-link function between the UAV and the MFR or the ground based ATOL (Automatic Take-Off and Landing) beacons in the X-band is conceivable.

b) *Disadvantages:*

As the Ka-band solution, this solution needs a mechanical rotation on azimuth and an extra volume outside the UAV.

Such a system uses the same R.F. band than most of airborne radars on board fighters. On the one hand, disturbing interferences may occur but, on the other hand, cooperative functions are feasible as discussed previously.

The angular accuracy is lower than in Ka-band but remains compatible with the localization requirements and clutter rejection issues.

2) *Second X-band solution*[2]

This second X-band solution is a fully static one. A transposition in X-band of the S-band solution (see Figure 3.) is not very interesting. Indeed, the equation (2) states, for a given average power, that the surface of the receive antenna must remain the same. In the S-band solution, about 20 to 24 modules are needed. In X-band, the same concept leads to about 200 modules: this is likely a costly design.

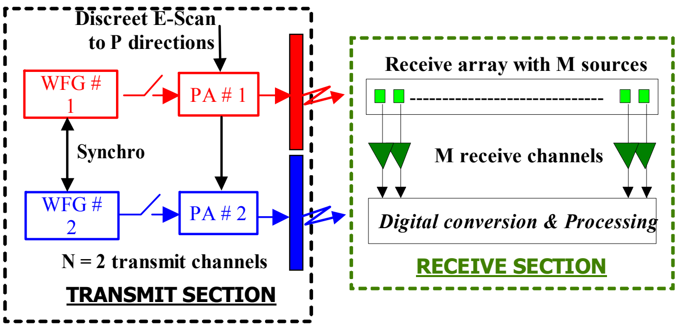

Figure 6. Second X-band solution (fully static)

The proposed concept utilizes two separate antenna systems, one for transmission, and the other for reception. **Both are perpendicular linear arrays** (Figure 6.):

a) *Receive section:*

The receive section is built around a horizontal linear array used on a DBF basis. After beam forming, **it provides accurate targets locations in azimuth**. The array is sized to have the highest gain as possible respect to the available space onboard while statically covering the elevation domain (±15°). Each receive array element is non directive in azimuth.

b) *Transmit section:*

The transmit system uses both vertically E-Scan and space coding on transmit. The transmit array is non directive in the azimuth plane but it is directive in the elevation plane and coverts a fraction of the total elevation domain (±15°):

1. The **E-Scan performs the elevation scanning** within the search domain.
2. The space-coding performs a so-called “mono-pulse at transmit” system and **provides accurate targets locations in elevation**.

In this example, the **E-Scan is carried out only to a few number P of directions,** thus can be implemented by using low cost technologies.

Two orthogonal signals (one “red” signal and one “blue” signal in Figure 6.) are applied to each half of the transmit antenna by using two synchronized WFG. Theses signals are then separated on receive channels, thanks to their orthogonal properties, and the differential phase allows retrieving the elevation of a target. Such a system is a particular application of the general coherent MIMO radar concept [2]. This special space coding, which merges both colored transmission and “classical” E-Scan, is interesting from a cost saving point of view. Indeed, a full space coding, having the same angular resolution and the same coverage, would need a lot of costly WFG: here, only two WFG are needed.

For each half antenna, the E-Scan is done with PIN diodes phase switches between the WFG and the set of parallelized Power Amplifiers which feeds each half antenna.

c) *Advantages:*

This solution has the advantage of systems operating in higher frequency bands: Ku, Ka, etc. (high angular accuracy for a limited antenna size) without having the disadvantage of needing a large number of T/R modules (cost). Indeed, such a system, in terms of directivity, is equivalent to another one with a non directive transmit antenna and a rectangular receive antenna whose shape would be the convolution of those of the two perpendicular (T/R) antennas [2], [3].

Another advantage is that transmit and receive functions do not need to be collocated. So, the full integration of such a static system within the airframe is possible.

d) *Disadvantages:*

The receive antenna surface is obviously lower than in the previous examples (S-band, Ka-band and 1st X-band solution). For a given detection range, a greater average power is needed. Therefore, we will see at the next section how to deal with that.

The linear array on reception has a maximal horizontal coverage of about ±60°. As for the DBF S-band solution (section A), two systems are needed to cover the whole required domain.

VI. WAVEFORM AND PROCESSING ISSUES

A. *Collision path detection*

Whatever the solution is and whatever the frequency band will be, we are finally interested in detecting only the collision path targets (in the collision avoidance operation) or the quasi-colliding ones (in the traffic separation function).

1) *Collision condition*

The “true” collision condition is summarized in the Figure 7. At time t_0, the UAV is at $P(t_0)$ and the intruder is at $I(t_0)$.

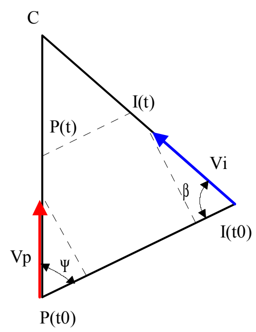

Figure 7. Collision case

2 The second X-band solution is protected by several THALES patents.

Necessary collision condition: ***(PI)*** must be included in the plane generated by the two velocity vectors $\vec{Vp}$ and $\vec{Vi}$.

Sufficient condition: the necessary condition fulfilled, by using the Thales' theorem, the collision condition is:

$$Vp.\sin\psi = Vi.\sin\beta \tag{3}$$

If, *Vp*, *Vi* and β are constant, this condition leads to:

$$\frac{d\psi}{dr} = 0, \quad \frac{dV_{RR}}{dr} \quad or \quad \frac{d\psi}{dt} = 0, \quad \frac{dV_{RR}}{dt} = 0 \tag{4}$$

2) Quasi-Collision condition

The quasi collision case corresponds to the traffic separation function (or the emergency avoidance maneuver at short range). This condition consists in testing that the absolute value of the derivative is lower than a threshold, which depends on the range and the safety area radius.

B. Consequence on waveforms

1) Waveforms suited for colliding targets

A so-called "processing matched to the collision or quasi-collision target path" is used. In particular, long coherent integration times after beam forming are used in order to:

- Enhances the sensitivity on "interesting" targets;
- Reduces or even prevents the detection of targets with fast angular rates (non-colliding targets) to avoid the processing of useless tracks.

2) Waveform suited for a constant warning time

As it was seen in the section III, a Sense and Avoid radar works on a constant advance warning basis on hazardous targets. That means:

- **A long detection range on a fast closing target** (for instance at least 8 km on a target closing a 400 m/s). But such detection can be easily achieved by using a non Doppler ambiguous waveform, which will detect the target on a thermal noise background.
- **A short detection range on a slow closing target** (for instance 2 km on a target closing a 100 m/s). Turned in terms of radar energy budget, this ratio is $1:4^4 = 1:256$. In the one hand, **the slow target needs 23 dB less, in terms of energy budget, than the fast one**. On the other hand, the slow one can be in the clutter Doppler region, where its detection is more difficult, and waveform and processing suited for that are required.

a) Example of a waveform for fast target

In the case of the second X-band solution, we need a greater transmitted power than in the other solutions, due to a lower R.F. receiving antenna surface than in other solutions, but a non Doppler-ambiguous waveform is particularly well suited. These two requirements can be fulfilled with a continuous waveform (CW) and a long coherent integration time, provided there is a sufficient decoupling between transmit and receive sections.

A convenient transmitted power in a CW mode can be obtained by using about a ten of "Commercial off the shelf" parallelized Power Amplifiers (PA) with a peak power of about one or two Watts.

The space coding required in the second X-band solution can be easily carried out by using two orthogonal sinusoidal signals spaced with at least the Doppler extent of the processed signals (some tens of kHz).

Another interest of this waveform is the narrow spectrum occupancy compared to a high peak power pulsed one.

b) Example of a waveform for slow target

At the opposite of the previous waveform, we are here interested in reducing the unavoidable ground clutter disturbance. So a pulsed non range-ambiguous waveform is well suited. The shorter detection range required on slow targets can easily deal with a low peak power system.

The space coding is achieved by using, for instance, two pseudo random ($0/\pi$) orthogonal codes, which serve also as pulse compression codes.

c) Management of the two waveforms

Since the required sensitivities for both waveforms are very different (23 dB) an adequate time sharing is applied to maximize the time share dedicated to the long range waveform while preserving a fine Doppler resolution for both waveforms.

VII. CONCLUSION

Three candidate radar bands for Sense and Avoid radar were analyzed. For each of them, the required angular coverage implies *de facto* the use of DBF, at least on one axis to avoid unrealistic scanning rates.

The X band solution is a promising solution in terms of performances, cost and installation ease.

Two solutions were presented in X-band, the second one, which merges DBF, E-Scan and Space coding is interesting because it is a static solution, which provides a good angular accuracy and can be integrated within the UAV airframe without extra volumes.

REFERENCES

[1] http://www.thalesgroup.com/Press_Releases/090813_Aerospace_Watchkeeper_major_flight_trials/

[2] Le Chevalier, F, "Space-time transmission and coding for airborne radars", Radar Science and Technology, vol. 6, n° 6, December 2008 (journal of CIE)

[3] Roulston, J, "The Post-War Development of Fighter Radar in Europe – A British Perspective", RADAR'08, Adelaide, Australia, September 2008.