FMCW Radar for the Sense Function of Sense & Avoid Systems onboard UAVs

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***Abstract*—Rockwell Collins France (RCF) radar department is currently developing, in close collaboration with TNO in The Hague, The Netherlands, a Frequency Modulated Continuous Wave (FMCW) radar sensor dedicated to Obstacle Warning function and potentially to air traffic detection. The sensor combines flood light illumination and digital beam forming to accommodate demanding detection and coverage requirements. Performances have been evaluated in flight tests and results prove that such a radar sensor is a good candidate for the Sense Function of Sense & Avoid Systems onboard UAV.**

Keywords - UAVs; Sense and Avoid; FMCW radar sensor; Digital Beam Forming

I. INTRODUCTION

Civilian and government-operated Unmanned Air Vehicules (UAVs) are nowadays only authorized to operate in segregated airspace. The main challenge of the next coming years is to allow them operate alongside other manned aircraft in civil integrated airspace. This challenge requires innovative technology development and system demonstrations for UAVs to be considered fully airworthy and for the right regulatory framework to be in place for this integration. Above all, robotic aircraft and their operators will need to demonstrate a high level of operational robustness and the ability to "sense and avoid" other air traffic. Various solutions have been considered, including visual and acoustic solutions [1].[2], while of course a radar-based solution has the advantages of long range, instantaneous range and velocity measurement and weather and light conditions independence. Several studies and programs have already demonstrated the strengths of radar based solutions [1].[3][1].[3]. Existing radar systems, as in [1].[3] are typically scanning radar systems, mechanical and/or electronic, where a single beam is scanned to cover the required field-of-view. In this case, time-on-target and update rate are conflicting requirements. A superior technology is based on Digital Beam Forming, replacing the single beam scanning by multiple simultaneous beams [1].[3].

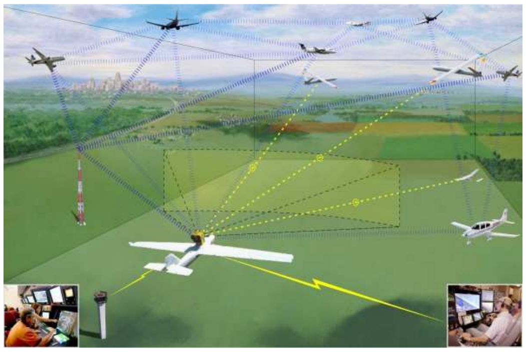

Fig. 1 Artist concept shows unpiloted aircraft in complex airspace. (NASA)

In this challenging context, Rockwell Collins France (RCF) radar department, in close collaboration with TNO in The Hague, The Netherlands, is developing a FMCW radar sensor candidate for the Sense Function of Sense & Avoid Systems onboard UAVs.

Due to its operational context, the sensor has to operate in adverse weather conditions, and has to conciliate two apparently mutually exclusive constraints:

- Cover a wide field of view with a high refresh rate, the field of view required is in the order of magnitude of 100° horizontal x 40° vertical
- Detect small traffic targets, typically a Cessna, at sufficient range for collision detection and avoidance.

This second constraint imposes a high coherent observation time on target, which seems contradictory with the first constraint of high refresh rate, using a scanning antenna.
Long range detection is also a challenge for FMCW sensors which are known to be limited in term of sensitivity by their transmit leakage into the receiver.

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The radar sensor(*) that has been developed by RCF and TNO at X band combines state of the art FMCW technology and Digital Beal Forming (DBF) for complying to the two above mentioned constraints. Figure 2 shows a photo of the FMCW radar sensor mounted on a helicopter during a Flight test campaign. The hardware design is based on prior experience in building compact multichannel FMCW radars sensors for various applications [1].[4].

(*): This radar sensor architecture is protected by several TNO and joint TNO/RCF Patents

II. RADAR MAIN FEATURES

A. FMCW Transmit / Receive

The transmitter transmits a continuous wave modulated in frequency (FMCW Frequency Modulated Continuous Wave). For minimizing the transmit leakage into the receiver, the spectral purity of the transmitter has been enhanced by an “offset-frequency” phase-locked loop principle. In addition, the transmit antenna is separated from the receive antenna to ensure sufficient isolation between transmit and receive. The receiver is of homodyne type, while a Single Side Band receiver has been realized in order to achieve 3 dB lower noise than a simpler Double Side Band receiver. The receiver design is small enough in size to allow a half-wavelength spaced horizontal array of receivers. Vertically spaced arrays allow elevation angle estimation.

Fig. 2 FMCW radar system mounted on a helicopter.

The transmitter employs a flexible waveform generator that allows adaptation of waveform parameters (sweep length, repetition frequency, bandwidth) to the application. This FMCW radar technology allows achieving remarkable performances in terms of range and radial speed resolutions.

Moreover, for a required detection range, it necessitates a much lower transmitted peak power than classical pulse radar technology for achieving the same Signal to Noise Ratio (SNR).

B. Flood illumination / Digital Beam Forming

The radar sensor transmitter “illuminates” the whole field of view of interest with a wide-beam transmit antenna.

The receiver is composed of an antenna array, with associated receive channels so that each element of the receive array is individually digitized. The spatial mapping of targets echoes is obtained through digital beam forming processing of the received data. This digital beam forming allows creating simultaneously all the narrow receive beams covering the complete field of view of interest. This is schematically depicted in the figure below.

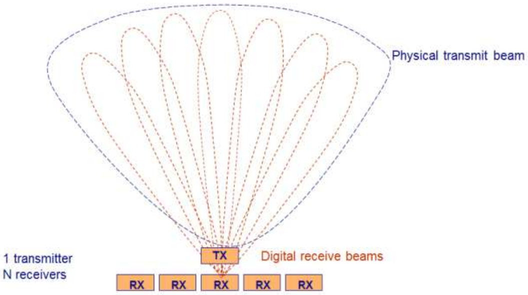

Fig. 3 Flood illumination / Digital Beam Forming.

This process ensures at the same time:

- A long observation time on targets over the whole required coverage, which provides a high radial velocity resolution and increases the probability of small target detection,
- A high refresh rate for surveillance of the required whole field of view.

III. THE FLIGHT TEST CAMPAIGN

A. Overview

Rockwell Collins has conducted a flight test campaign to evaluate the potential and performance of this FMCW radar sensor for UAS “Sense & Avoid” applications. The main objective was to demonstrate the detection capability of FMCW radar in terms of maximum detection range.

Fig. 4 View of the target from the carrier platform during a chase from behind.

B. Test scenarios

Specific flight phases relative to traffic detection have been performed: chase from behind, head-on approach, 45° approach, 90° approach, at a speed of approximately 90 kts for each platform.

- **Carrier platform** = Eurocopter AS350
- **Target** = Cessna 172 (considered as a representative object of interest for an air traffic detection application)

Fig. 5 Flight test campaign carrier platform and target

C. Radar prototype limitations

The radar prototype used during the Flight test experimentation was developed for different applications and had the following limitations for Traffic Sensing:

- **Reduced transmitter Field of View**
  The lack of transmit power was compensated by increasing the transmit antenna gain through a limited transmit field of view.
- **Reduced instrumented range**
  The analog bandwidth and sample rate of the receivers are limited to a maximum instrumented range of 10 km.

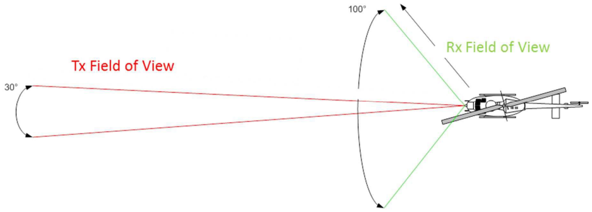

Fig. 6 Radar prototype with a limited Tx field of view.

D. Radar processing

Raw radar data were recorded during the flight scenarios and processed off-line. In order to maximize the SNR of the target and thus the detection range, the following processing steps are applied.

- **Digital beam forming**
  Digital beam forming is performed in azimuth and elevation to survey the entire field of view simultaneously with multiple receive beams.
- **Coherent integration over a long time interval**
  The optimum observation time for coherent integration has been determined from the data collected during the flight trials. As the Radar Cross Section of any complex object much larger than the radar wavelength will exhibit strong fluctuations as a function of aspect angle, the RCS of a moving object will fluctuate, leading to loss of coherence after a short time. Hence integrating coherently over more than a few tenths of seconds, has no benefit as demonstrated by Figure 7. Incoherent and binary integration can be used to further increase detection probability and reduce false alarm rate.

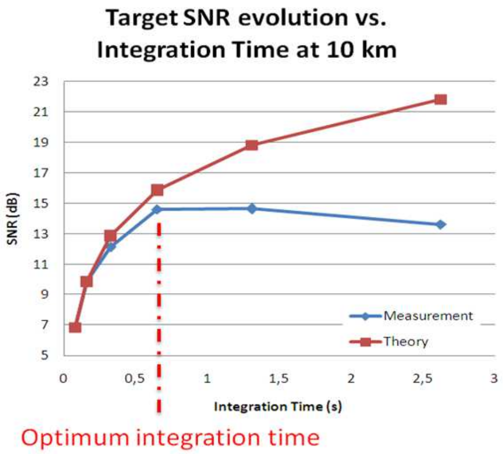

Fig. 7 Target SNR evolution versus coherent integration time.

- **Range migration compensation**
  Range migration of the target echo during the coherent integration interval is compensated to ensure that the target echo remains in the same range cell. In the experiment, GPS information from both platforms was available so that range migration before detection could be performed on the basis of known relative velocity. As the range processing already involves an FFT transformation of the received sweeps, a progressive range shift by a fractional number of cells can be easily implemented by appropriate phase shifts prior to the FFT. In the more practical case of unknown target speed, there are several options to deal with this, such as detection in a few predefined speed ranges or implementing a separate detection mode using CW without modulation.
- **CFAR detection**
  An adaptive detection threshold is used in all beams and Doppler filters to maintain a Constant False Alarm Rate (CFAR). Subsequently, detections are clustered and the range, azimuth, elevation and radial speed are estimated.

- **Target tracking**
  To confirm the presence of a target, multiple beams are digitally formed around the target bearing in order to further enhance its SNR and angular designation accuracy, see Figure 8. Typically, 9 beams are formed in azimuth (+/- 4° around the GPS target azimuth) and 6 beams in elevation (+/- 3° around the GPS relative target elevation). Finally, a tracking algorithm was implemented in order to ease target localization in radar signal through automatic track initialization.

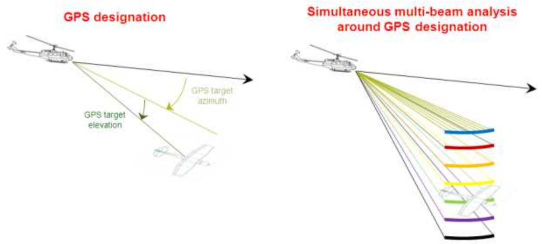

Fig. 8 : Multibeam analysis of targets.

Although the maximum detection ranges are obtained when detecting in thermal noise, strategies for detection in the clutter have also been explored. In fact, for practical implementation, the following modifications are foreseen:

- **CW waveform**
  It consists in implementing a CW waveform with a fixed frequency in which the radar does not measure range but only detects the presence of objects based on speed (Doppler shift). As Doppler shifts can be low, this requires that the radar sensor has low noise properties quite close to the carrier frequency. The CW mode is combined with a track mode based on an FMCW waveform for accurate range and speed measurements. The SRF of this mode will be selected in such a way that the target is not masked by surface clutter.

- **Staggered SRF**
  With a single SRF, the Doppler shift of ground clutter can coincide with the (aliased) Doppler shift of a flying obstacle; hence the ground clutter creates some blind velocities. These can be overcome by varying the SRF, so that blind zones at one SRF are covered by other SRF values.

- **Vertically spaced array**
  An additional option is to employ vertically spaced arrays not only to measure elevation, but also to suppress ground clutter on the basis of its vertical angle separation. This option needs an adaptive algorithm such as Space-Time Adaptive Processing (STAP) and is more complex than the staggered SRF option. It is expected that the latter option will generally suffice.

E. Test results – Operational ranges

Fig. 9 Chase from behind flight phase and tracking outputs

The evaluation of prototype performances in terms of maximum detection range has been limited by several constraints:

- Prototype field of view (mostly penalizing 45° and 90° approach)
- Waveform maximum instrumented range
- Flight phase configuration (d. AC/HC when radar signal recording started)

Therefore, we introduced the notion of "observed detection range" which is the maximum range achieved in the flight test configuration.

TABLE I. FLIGHT TEST CAMPAIGN - DETECTION RANGE RESULTS

Approach	Observed detection range	Post-analysis observations
Chase from behind	2.3 km (1.2 NM) (HC 120kts – AC 90kts = 2m30s before collision)	Maximum observable detection range was limited by flight phase configuration. Indeed, flight phase and recording started when d.AC/HC was already 2.3km. Target was detected and tracked over the whole flight phase.
Head-on approach	10 km (5.4 NM) (HC 90kts – AC 90kts = 1m47s before collision)	Target first detected at 10 km, confirmed by automatic tracking at 8.2 km
45° approach	5 km (2.7 NM) (HC 90kts – AC 90kts = 0m58s before collision)	Maximum observable detection range was limited by the maximum instrumented range (5 km)of the waveform configured for this flight phase. Target was detected and tracked over the whole flight phase.
90° approach	3 km (1.6 NM) (HC 120kts – AC 80kts = 0m45s before collision)	Maximum observable detection range was limited by prototype field of view. Target was detected and tracked over the whole flight phase.

Note that the notion of “observed detection range” does not define the actual prototype maximum detection range, which could be obtained assuming the limitations of section III.C are overstepped. Although it could not be evaluated for all flight phase configuration, this prototype maximum detection range can be extrapolated based on RCS measurements that have been collected from the various flight phases and related to target aspect angle (see Fig. 10).

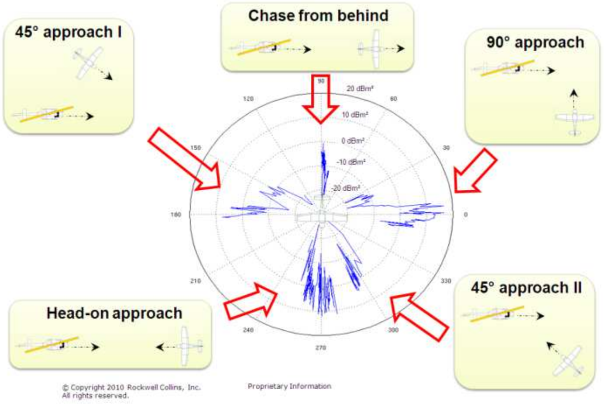

Fig. 10 Observed RCS of cooperative target collected during each flight phase

Based on these collected data, Table II indicates the prototype extrapolated performances in terms of maximum detection range, depending on the approach configuration.

TABLE II. EXTRAPOLATED PROTOTYPE MAXIMUM DETECTION RANGE

Approach configuration	**Extrapolated maximum detection range**
Chase from behind	Up to 6km (3.2 NM) (HC 120kts – AC 90kts => 6m28s before collision)
Head-on approach	Up to 12km (6.5 NM) (HC 90kts – AC 90kts => 2m09s before collision)
45° approach	Up to 8km (4.3 NM) (HC 90kts – AC 90kts => 1m33s before collision)
90° approach	Up to 17km (9.2 NM) (HC 120kts – AC 80kts => approx. 3m56s before collision)

F. Measured SNR – Head-on approach

Fig.11 shows observed SNR (Signal to Noise Ratio) evolution over range during the head-on approach which provided the maximum observed detection range.

As we can see on this curve, first detections occurred at 10km (5.4 NM) and tracking enabled to lock on the target a little further than 8km (4.3 NM).

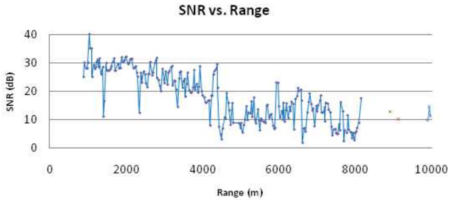

Fig. 11 Measured SNR over range during head-on approach

IV. CONCLUSION

Flight tests results have confirmed the expected detection range performance of the radar prototype. They thus provide a very promising indication for the feasibility of a FMCW radar based sensor as part of a practical “Sense and Avoid” system. These results represent a first validation of the technology choices that were jointly proposed by Rockwell Collins France and TNO to answer the demanding requirements of this airborne application. Especially, the digital beam forming concept associated with flood light illumination allows combining wide angle coverage, high velocity resolution, and high refresh rate. The proposed approach thus offers a distinct advantage over conventional scanning radar solutions. Although the flight tests were done at X-band, the need for a low volume and weight solution along with good performances in adverse weather may lead to a final solution using a higher frequency band.

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