Early Warning Against Stealth Aircraft, Missiles and Unmanned Aerial Vehicles

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Konstantinos Zikidis
Hellenic Air Force

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Abstract Since the 2nd World War and during the Cold War, the air defense radar has proven to be the main surveillance sensor, where each radar would cover a radius of more than 200 nautical miles. Apart from the electronic warfare, the emergence of stealth or low observable technology, the evolution of ballistic and cruise missiles, as well as the democratization of UAVs (Unmanned Air Vehicles) or drones, have contested the capabilities of the typical surveillance radar. All these targets are difficult to detect, because they exhibit low RCS (Radar Cross Section), potentially flying at the upper or lower limits of the radar coverage or outside the expected velocity range (being either too slow, e.g. some UAVs, or too fast, like ballistic missiles). This chapter begins with the estimation of the RCS of various potential targets, as a function of the radar frequency band. In this way, the expected detection range against a set of targets can be calculated, for any given radar. Secondly, different radar types are considered, such as low frequency band radars or passive / multistatic radars, examining the respective advantages and disadvantages. Finally, some issues are discussed concerning the "kill chain" against difficult-to-detect targets, in an effort to defend efficiently the air space.

Keywords: Radar, RCS – Radar Cross Section, Stealth, Low Observable, Ballistic Missiles, Cruise Missiles, UAV – Unmanned Air Vehicles, Drones, Low Frequency Band Radar, Passive Radar, Multistatic Radar, Kill Chain.

1. Introduction

The invention of the radar system cannot be attributed to a single person or state. It is rather an evolution, pursued by many nations concurrently and sometimes antagonistically, before and after the 2nd World War. Development of radar systems culminated during the Cold War. The radar theory is now well established and a number of classic books are available, such as [1, 2, 3], while the radar has been considered as the primary sensor against aerial targets, for more than half a century.

Konstantinos C. Zikidis

Department of Aeronautical Sciences, Hellenic Air Force Academy, Dekelia Air Base, Greece

e-mail: kzikidis@cs.ntua.gr

Along with the radar, electronic warfare systems have also been evolving, exhibiting various features to counter radar operation [4, 5]. Today a typical jet fighter is equipped with a self protection system, including a Radar Warning Receiver (RWR), a multi channel jammer system, sometimes called ECM System (from the older term *Electronic CounterMeasure*), as well as passive decoys (chaff and flare dispenser system) or even active towed decoys. Most jammers today include DRFM (Digital Radio Frequency Memory) capability, while more advanced counter-measure systems employ cross-eye jamming [6] or active cancellation techniques [7]. Of course, electronic warfare systems are not limited to aircraft but equip also ships, tanks or ground-based systems.

Since the late '70s, a new technology appeared, gradually taking over the military world, even though it took more than a decade to come out: low observable or stealth. Following the "Have Blue" project, whose two prototypes proved the possibility to construct a stealth airplane (even though both crashed), the US began development of the F-117 Nighthawk and soon after the Advanced Technology Bomber (ATB) program, which eventually led to the stealth bomber B-2 Spirit. At the same time, they also decided to modify the B-1A to the B-1B Lancer, exchanging some of its high performance capabilities for the reduction of its radar signature. Since the end of the '80s, when the first stealth aircraft were revealed to the public, the reduction of the Radar Cross Section (RCS) has become the primary requirement for any military asset [8, 9].

Apart from jet fighters/bombers (either stealth or not), UAVs or Unmanned Aerial Vehicles, commonly (but not properly) called drones, have exhibited considerable advances during the last decades [10, 11]. Military UAVs are now amassing far more flight hours than manned fighter aircraft, while the Predator family UAVs (i.e., the MQ-1 Predator, MQ-9 Reaper and MQ-1C Gray Eagle) have accumulated until 2016 more than 4 million flight hours, according to their manufacturer. Such UAVs exhibit low RCS, while they may also fly too slow or too low, preventing some radars from detecting them. Even worse, the limits between a UAV and a loitering munition, e.g., the IAI Harpy and Harop, are rather obscure. Therefore, UAVs can be a quite hard-to-detect target, while armed UAVs (UCAV – Unmanned Combat Aerial Vehicle) and loitering munitions may pose a real threat to a radar system. On the other hand, a saturation attack by decoy UAVs, acting as jet fighters, would oblige fire control radars to switch on transmission (betraying their position and becoming vulnerable to anti-radiation missiles, as was the case in the 1991 Gulf War air campaign) or even trigger the launch of expensive surface-to-air missiles against low cost drones.

Cruise missiles can be considered as a similar threat for a radar, since they usually fly a few feet above the ground, but they feature better capabilities (speed, warhead, precision), while they also exhibit small RCS. On the other hand, ballistic missiles pose a substantially different threat, by flying very high in their apex phase and very fast during the final phase. Only a few radars have ballistic missile defense capabilities. Even in that case, combining speed with decoy deployment and maneuvering renders a ballistic missile difficult to intercept. In the case of a MIRV missile, featuring a payload of *Multiple Independently Targetable Reentry Vehicles*, it is rather impossible to avoid suffering damage.

All these technologies, i.e., electronic jamming, stealth, UAV/UCAV/etc and cruise/ballistic missiles, challenge the capabilities of radar systems. In an effort to ensure the surveillance of a given air space, the following steps will be considered:

1. First, the RCS estimation for various targets is attempted. Apart from open source RCS values, an approach based on computer simulation will be followed for the F-16 and the F-35 jet fighters, as well as for the DF-15 short-range ballistic missile, as case studies. More specifically, a 3D model will be constructed for each of these targets. Then the POFACETS code, a MATLAB application based on the Physical Optics method, will be employed to predict the RCS of these targets, in certain radar frequency bands. This approach has been proposed in [12, 13].
2. Secondly, the expected detection range for a typical ground radar will be estimated against various threats. In this way, the significance of stealth technology will be proven.
3. Different radar types will be examined, such as low frequency and passive radars, complementing each other, in order to cover the air space.
4. The chapter will conclude with an analysis of the "kill chain" against stealth threats and how not to break it, taking into account also operational issues.

2. RCS Estimation Of Various Targets

The RCS (Radar Cross Section) of a target can be defined as the projected area of a virtual metal sphere which would scatter the same radiation power as the target does [8]. The RCS is usually represented by the symbol σ and expressed in square meters (m^2) or in dBsm (decibel with respect to 1 square meter). It depends on the actual size, the shape and the reflectivity of the target (i.e., on the coating). Taking into account the radar equation, the range at which a radar detects a target is proportional to the 4th root of the target's RCS, as shown below.

The RCS exhibits significant fluctuations and can be considered as a stochastic function of the relevant position and aspect of the target with respect to the radar. A mean value can be computed for the front sector of a target, which could be used to calculate the maximum detection range of this "incoming" target for a certain radar set.

The RCS of any military asset is supposed to be classified. However, mean frontal RCS values for various targets have appeared in the open literature, either from measurements in suitable test ranges or from theoretical estimation with the help of computational electromagnetics, or even from unofficial leaks. In Table X.1, a comprehensive RCS list for several targets is depicted, based on [9] and the references therein. It is noted that most of these values are given "as is", since there is no official claim or statement.

Table X.1 RCS values for various targets. These values are just indicative, presumably referring to the frontal aspect (head on) RCS of an aircraft in clean configuration (without external loads, such as fuel tanks, missiles etc), in the X-band (8-12 GHz) [9]

Target	**RCS (m^2)**
Navy cruiser (length 200m)	14000
B-52 Stratofortress	100 – 125
C-130 Hercules	80
F-15 Eagle	10 – 25
Su-27 Flanker	10 – 15
F-4 Phantom	6 – 10
Mig-29 Fulcrum	3 – 5
F-16A	5
F-18C/D Hornet	1 – 3
Mirage 2000	1 – 2
F-16C (with reduced RCS)	1.2
T-38 Talon	1
B-1B Lancer	0.75 – 1
Sukhoi FGFA prototype (derivative of PAK FA for India)	0.5
Tomahawk TLAM	0.5
Exocet, Harpoon	0.1
Eurofighter Typhoon	0.1 class
F-18E/F Super Hornet	0.1 class
F-16IN Super Viper (proposed to India for the MMRCA)	0.1 class
Rafale	0.1 class
B-2 Spirit	0.1 or less
F-117A Nighthawk	0.025 or less
bird	0.01
F-35 Lightning II	0.0015 – 0.005
F-22 Raptor	0.0001 – 0.0005
insect	0.00001

Trying to examine the RCS for some representative targets and its dependence on the radar frequency, an approach based on computational electromagnetics was followed. The term “computational electromagnetics” refers typically to computationally efficient approximations to Maxwell's equations in order to obtain real life results, since it is quite difficult to obtain closed form solutions in real world problems, unless the related physical objects are very simple.

Concerning the issue of RCS prediction of a physical object of known shape, there are various methods, such as the Method of Moments, the Finite Difference Method, Geometrical Optics and Physical Optics. The last one, the Physical Optics (PO) method, yields good results at higher frequency bands (closer to the optical region), in the specular direction, by approximating the induced surface currents. The PO currents are integrated over the illuminated portions of the target to obtain the scattered far field, while setting the current to zero over the shadowed portions. Despite some certain shortcomings, the simplicity of the PO method ensures low computational overhead [14, 15].

The POFACETS 4.1 code is a MATLAB application, developed by the US Naval Postgraduate School, implementing the PO method for predicting the RCS of complex objects. The program models any arbitrary target by dividing it to many small triangular facets and the scattered field of each facet is computed as if it were isolated and other facets were not present. Multiple reflections, edge diffraction and surface waves are not taken into account. Shadowing is included by considering a facet to be completely illuminated or completely shadowed by the incident wave. The PO method is used to calculate the induced currents on each facet. The scattered field is computed using the radiation integrals [16].

Apparently, in order to employ the POFACETS code, it is necessary to have a 3D model of the target. Taking into account that reliable blueprints or CAD files cannot be available for any military asset, except maybe for very old ones, a 3D model of the target has to be created. The procedure used for that purpose is described in [12, 13] and in a few words is as follows:

- Preprocessing of 2D images or still images from videos of the object, by converting them to drawings, using software such as GIMP.
- Estimation of the overall dimensions of the object.
- Construction of a properly scaled 3D model, based upon the above-mentioned drawings and dimensions, with the use of suitable software, e.g., AUTODESK 3ds Max or Blender 3D suite.
- Fine-tuning of the 3D model, based on photos/videos.
- Running simulations with the POFACETS code, which imports .stl files and converts them to .m files, to be processed by MATLAB. The imported 3D models are considered to be *Perfect Electric Conductors*. The monostatic RCS is computed, where the transmitter and the receiver are co-located, as is the case for most radar systems.

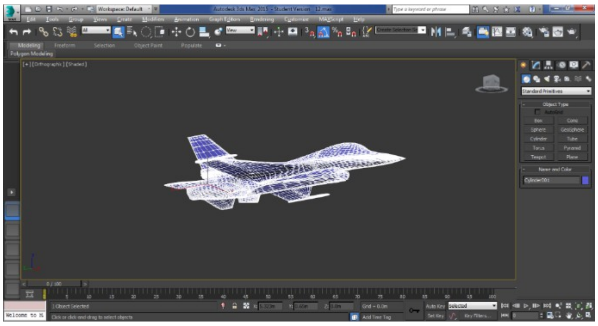

Fig. X.1 The F-16C model, with the radar nose cone, created with the help of AUTODESK 3ds MAX software [13]

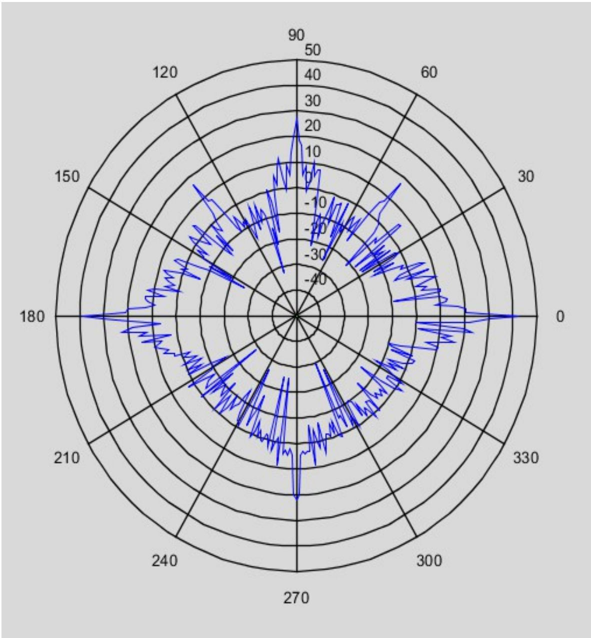

Fig. X.2 RCS polar plot for the F-16C model, at the same level, at 10 GHz (the aircraft nose is pointing at 90°) [13]

RCS of the Lockheed Martin F-16C

Following the procedure analytically described in [13] and briefly mentioned above, the 3D model of an F-16C is depicted in Figure X.1. The aircraft is depicted with its radar nose cone but in the computer simulation the model used was without the cone, which is more or less transparent for the radar. The RCS of the F-16 model was computed for a radar transmitting at 10 GHz (X-band), like a typical fire control radar. The RCS pattern shown in Fig. X.2 corresponds to the polar plot of the F-16 RCS, seen at the same level (θ=90° and φ ranging from 0° to 360°). The mean frontal RCS, averaged from -30° to +30° in azimuth (in steps of

1°) and from -15° to +15° in elevation (in steps of 5°) is -2.8 dBsm (that is 0.525 m²).

According to Table X.1, the mean RCS of the F-16C is reported to be 1.2 m², while the RCS of the F-16IN proposed in the frame of the recent MMRCA competition in India is in the 0.1 m² class, featuring an AESA radar and possibly other RCS reduction treatments as well. Therefore, the above-mentioned result (based on an F-16 model with AESA radar) is quite reasonable, falling between these two RCS values. If further RCS reduction measures had been taken into account, such as the application of the HAVE GLASS program, the RCS would be even smaller, approaching the reported F-16IN RCS value.

RCS of the Lockheed Martin F-35

For the F-35, a similar approach was followed and two models were created, one with and one without the radar nose cone [13]. The model with the nose cone is depicted in Figure X.3. However, the model without the nose cone was imported to the POFACETS code and the resulting RCS polar plot, seen from 10° below, is depicted in Figure X.4. It is noted that the use of radar-absorbent material (RAM) coating, which would further decrease the RCS, has not been taken into account.

The mean overall RCS and the mean front sector RCS (averaged from -30° to +30° in azimuth, in steps of 1°, and from -15° to +15° in elevation, in steps of 5°) were calculated in various frequency bands, from VHF to Ku-band. The results are shown in Figure X.5. Obviously, the RCS of the F-35 is not so small at lower frequency bands.

The F-35 features advanced RAM (called "fiber mat" [17, 18]), which is more durable and requires less maintenance, with respect to coatings of older stealth aircraft, according to Lockheed Martin. The F-35 RAM has been reported to make use of carbon nanotubes (CNT) technology, absorbing electromagnetic waves over a wide range of frequencies [18]. Therefore, the actual RCS values are expected to be lower than the ones obtained by the POFACETS code.

RAM coatings are frequency selective, i.e., they provide higher attenuation at specific frequency bands, for example at the X-band or above. At lower frequency bands, RAM coatings are less effective. Trying to emulate the use of RAM, an attenuation in the class of 10 dB is considered, at least concerning X-band and higher frequency bands.

As seen in Figure X.5, the mean RCS at 10 GHz (without the use of RAM) for the front sector is -10.1 dBsm. With the use of RAM, the RCS would be further reduced to the class of -20 dBsm, which corresponds to 0.01 m², confirming that the F-35 exhibits a really low RCS. This value is higher than but quite close to (within 3 dB) the RCS values appearing in various sources, which estimate the front sector RCS of the F-35 from 0.0015 to 0.005 m² [9].

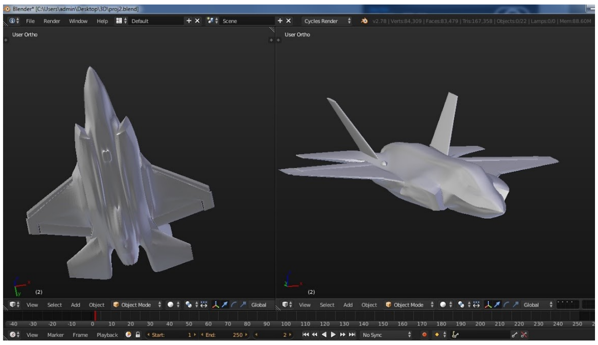

Fig. X.3 The F-35A model with the radar nose cone, created with the help of Blender 3D suite [13]

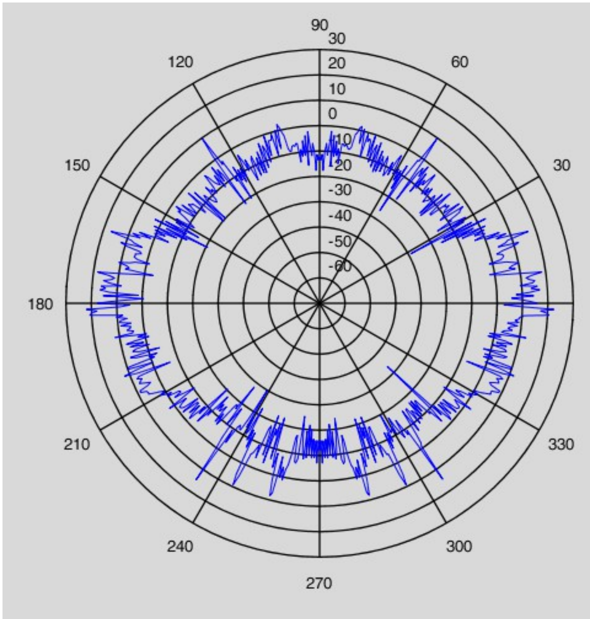

Fig. X.4 RCS polar plot for the F-35A model, at 10 GHz, seen from below (depression angle 10°). RCS is relatively small in a wide sector in the front, apart from the peaks produced by the leading edges of the wings (approximately at 35° off-axis), attaining higher values at the sides (due to the wings and the fuselage) [13]

RCS of the Dong-Feng 15 (DF-15) Missile

The DF-15 is a Chinese short-range ballistic missile, in three variants (A, B and C). The 3D model of the DF-15C was created in CATIA v5 and is depicted in Figure X.6. Importing the model to POFACETS, the RCS diagram at 10 GHZ is shown in Figure X.7. Averaging the frontal RCS in a similar manner as before, the result at 10 GHz is at the class of -17 dBsm. By subtracting 10 dB, in order to emulate the use of RAM, the RCS becomes -27 dBsm, i.e., 0.002 m². At 150 MHz, the average head-on RCS reaches -13 dBsm (0.05 m²). In the VHF-band, RAM is rather ineffective, without any significant RCS reduction.

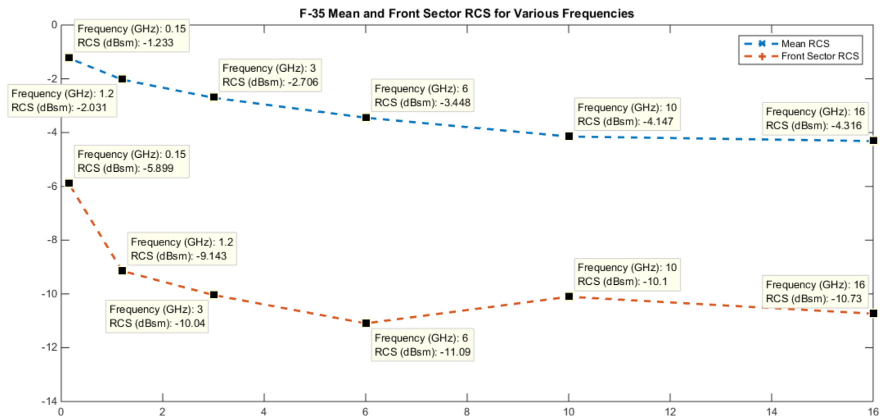

Fig. X.5 The mean overall RCS (upper curve) and the mean front sector RCS (lower curve) of the F-35 model versus frequency. It is clear that the F-35 RCS is not so small at lower frequency bands. In this graph, the use of Radar Absorbent Material (RAM) is not taken into account. RAM would further reduce the RCS, especially at higher frequency bands (S-band and above) [13]

The RCS of the DF-15 missile has been reported to be 0.002 m^2 in the X-band and 0.6 m^2 in the VHF-band [19]. In the X-band, the above mentioned result coincides with the reported RCS. At VHF, the computed RCS is higher than the one at 10 GHz but not exactly as the one reported in [19]. However, it is quite close, proving that the proposed approach yields reasonable results, as well as that the RCS of some stealth targets is considerably higher at lower frequency bands.

RCS vs Detection Range

Considering the RCS values of Table X.1, as well as the above-mentioned revised F-35 RCS values with the help of POFACETS, it is possible to make a diagram of the RCS for various targets. Furthermore, with the radar equation in mind, knowing the detection range of a radar for a certain target with known RCS, it is possible to calculate the respective detection range for any target.

More precisely, the fundamental form of the radar equation is as follows [1]:

$$R_{max} = \sqrt[4]{\frac{P_t G A_e \sigma}{(4\pi)^2 S_{min}}}$$

where R_{max} is the maximum detection range, P_t the transmission power, G and A_e the gain and the effective area of the transmitting and receiving antennae (which coincide in the usual monostatic radar), σ is the target RCS and S_{min} the minimum detectable signal. Therefore, for a given radar set, where P_t, G, A_e and S_{min} are fixed, R_{max} is proportional to the 4th root of σ : $R_{max} \propto \sqrt[4]{\sigma}$.

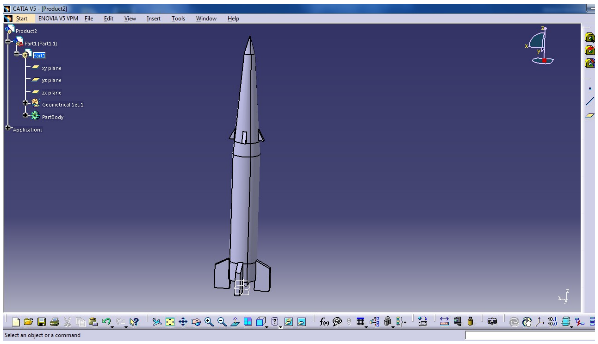

Fig. X.6 The DF-15C model in CATIA v5 CAD suite[13]

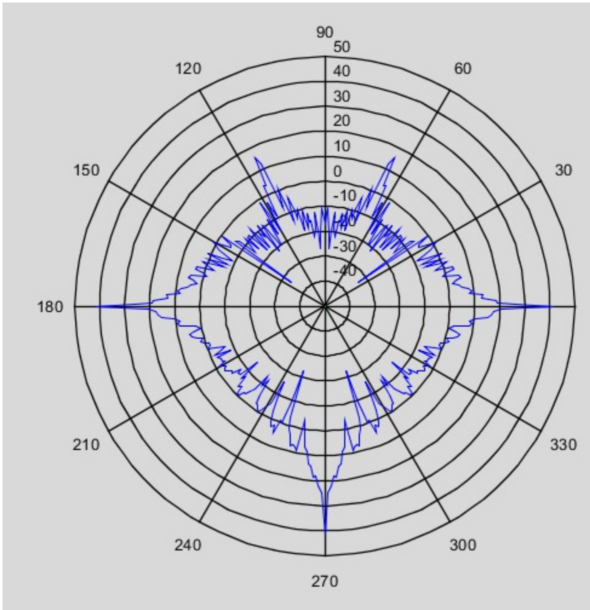

Fig. X.7 RCS diagram for the DF-15C missile, at the same level, at 10 GHz [13]

So, if a radar can detect a standard target with an RCS of 1 m² at $\hat{R}$, a target of σ m² will be detected at $R_{max} = \hat{R}\sqrt[4]{\sigma}$. For example, the Raytheon HR-3000 (HADR) S-band air defense radar can detect a 1 m² RCS target at 320 km or 173 nautical miles [9]. Assuming that the RCS values of Table X.1 are valid for the S-band, a range vs RCS curve can be drawn, indicating also the various targets.

Instead of the "range vs RCS", an inverse "RCS vs range" curve is proposed, offering also a graphical representation of the detection range for each target. So, in Figure X.8 there is an RCS vs detection range curve for the HR-3000 radar. In this way, the range at which that radar can detect a target is shown in linear scale, starting from the left axis. Trying to depict the RCS of the various targets of Table X.1, the gray rectangles shown in Figure X.8 are created, due to the uncertainty (min and max RCS estimated values, corresponding to different detection ranges).

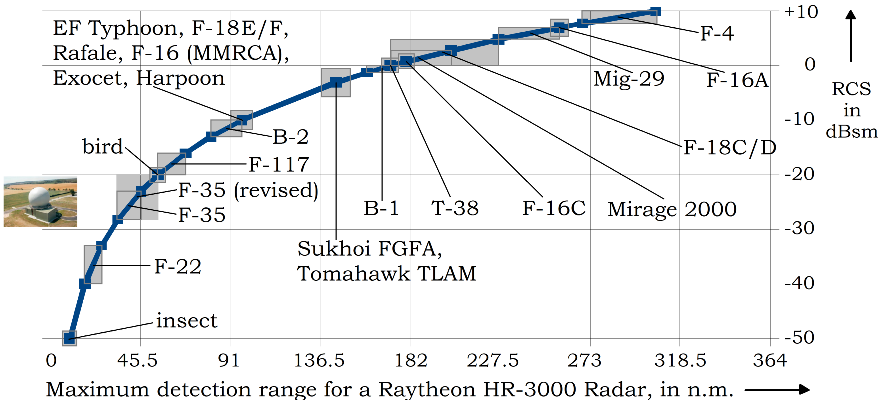

Fig. X.8 RCS (in dBsm) of various targets versus the respective detection range (in nautical miles) for the HR-3000 S-band air defense radar. Each target is depicted with a gray rectangle, the size of which depends on the estimation uncertainty of its RCS. It should be noted that the RCS values of the targets are only indicative, since they correspond to a different radar band, i.e., the X-band [9]. In any case, the significance of low observable is obvious: while legacy fighters are picked up at more than 200 n.m. and modern jets (with RCS≈0.1 m²) at 100 n.m., stealth aircraft are detected at close ranges (<65 n.m.)

It is noted that the HR-3000 operates in the S-band, while the values of Table X.1 correspond to the X-band (a graph showing the IEEE radar bands is shown in Figure X.9). So, the RCS values in Figure X.8 are only indicative. Especially for the F-35, its RCS in the S-Band is approximately -10 dBsm or 0.1 m² (without RAM), according to Figure X.5. Taking into account that RAM is not as efficient at lower frequencies, an attenuation of 10 dB in the S-band would not be realistic. Assuming that the attenuation in the S-band is half as that in the X-band (i.e., 3 dB lower), the application of RAM would further reduce the RCS by 7 dB. Therefore, a more reasonable prediction of the F-35 RCS in the S-band would be -17 dBsm (that is 0.02 m²). Such a target would be detected at more or less 65 nautical miles (n.m.) by an HR-3000 radar (and not at 40-50 n.m., as indicated in Figure X.8).

3. Detecting difficult-to-detect threats

The above computer simulation analysis proves what has been known for long: *stealth threats are not so stealth at lower frequencies*. In other words, the basic principles of RCS reduction, i.e., purpose shaping and special radar absorbent coating, are less efficient at lower frequency bands [19]. So, stealth airplanes or missiles are optimized for higher frequencies, from the S-band and above. Anyway, most dangers (i.e., fire control radars) are in these frequency bands.

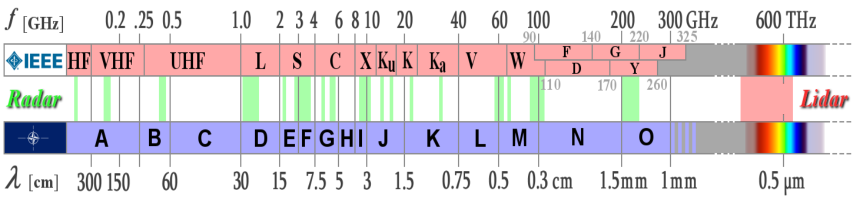

Fig. X.9 IEEE and NATO radar frequency bands, with respective wavelengths [20]

Indeed, ground-based air defense system radars may emit in the S-band (for search) and in C or X-band (for tracking / fire control). Aircraft fire control radars operate in the X-band, while missile radar seekers may operate in the X or Ku-band. At lower frequency bands, there are mostly surveillance radars, which do not pose an imminent danger. A notable exception would be the Soviet-era radars used as search radars in anti-aircraft batteries, such as the P-18 which helped downing one F-117 during the war in Yugoslavia.

On the other hand, wide-band stealth is rather impossible or at least not cost effective. At lower frequencies, major aircraft parts, such as wings, horizontal and vertical tails, fall into the resonance or Mie scattering region, as their principal dimension becomes comparable with or a multiple of the radar wavelength. In this way, the primary effect of purpose shaping, which is to avoid scattering the incoming radiation back to the transmitting radar, is degraded. This is more evident on smaller planes, while large planes such as the B-2 stealth bomber are more "immune" to this phenomenon, namely they conserve their low observable characteristics even at low frequencies. This explains why the B-2 is a "flying wing": if it had any horizontal or vertical tails, it would enter more easily the resonance region, possibly increasing RCS, if illuminated by low frequency radiation [19]. Furthermore, RAM is inherently narrow-band and cannot be efficient at lower bands. In other words, much more thick coatings would be required in order to efficiently protect the skin at lower frequencies, increasing weight and cost prohibitively [18].

Low Frequency Band Radars

According to the above rationale, *low frequency band radars* seem to be a promising approach against stealth threats, including ballistic missiles. Such radars operate at frequencies in the L-band (1.2-1.4 GHz) or lower. Practically, apart from the L-band, low frequency radars operate in the UHF-band (~0.5 GHz) and VHF-band (~150 MHz). In this category, over-the-horizon radars operating in the HF-band should also be mentioned, based on either the surface wave principle or on tropospheric scattering.

Frequency and wavelength have an inverse relationship, so lower frequency means longer wavelength. This, in turn, would imply larger antenna, excessive volume and weight and limited transportability. Such a radar would be a perfect target on its own. Furthermore, low frequency radars are susceptible to clutter and cannot provide the necessary accuracy for fire control [21]. They are employed mostly for early warning, cueing higher frequency (and thus more accurate) radars to the direction of the target, increasing their probability of detection. Finally, the electromagnetic spectrum is quite congested at V/UHF, making difficult the allocation of unused frequencies for radar operation. For all these reasons, VHF/UHF radars have long been considered as obsolete in most Western countries and have been replaced by L and S-band radars.

However, having realized the significance of lower frequency bands, many countries (especially Eastern ones) have employed modern digital electronics technology to overcome some of the performance limitations inherent in V/UHF and other similar radar. With the progress of active electronically scanned array (AESA) antennae and improvements to computers and signal processing, lower-band radars have become more accurate and their range has increased [22]. Mobile low freq. radar systems have also been presented, which, despite their size, could be folded, getting ready to be transported in a few minutes.

Besides, low freq. radars cannot be detected or jammed by most aircraft self-protection systems, except for specialized wide-band ESM (Electronic Support Measures) and low band jammers, features not common to jet fighters. Especially V/UHF radars cannot be engaged by anti-radar missiles, such as the Raytheon AGM-88 High-speed Anti-Radiation Missile (HARM), or loitering munitions, such as the IAI Harpy. Therefore, low freq. radars offer some critical advantages, in addition to increased detection ranges against difficult-to-detect targets, including ballistic missiles, since quite a few of modern radars exhibit also ballistic missile defense capabilities.

A notable example of a complete radar system is the 55Zh6M Nebo-M mobile multi-band radar complex, developed by the Russian Nizhny-Novgorod Research Institute of Radio Engineering (NNIIRT), which was the first to present a VHF AESA system. Nebo-M includes three truck-mounted AESA radar systems: the VHF RLM-M, the RLM-D in the L-band and the S/X-band RLM-S, as shown in Figure X.10. All three radars operate simultaneously, connected to a ground control vehicle, which performs data fusion. In this way, a target would be detected first by the VHF radar, which would cue the RLM-D. This in turn would cue the RLM-S, which could use a "stop and stare" technique, increasing the dwell time and thus the probability of detection, offering a weapon-quality track [22].

Recent examples of low freq. radars include the Thales SMART-L EWC (Early Warning Capability, featuring the latest GaN AESA technology), the IAI-ELTA UHF-band AESA ELM-2090U family, the CETC JY-27A Skywatch-V, as well as the HF IAI-ELTA ELM-2270 EZ GUARD coastal surveillance system, which is able to detect also low flying aircraft. Other examples can be found in [9, 21, 22].

Fig. X.10 The Nebo-M radar complex, comprising 3 radars in different bands (metric, deca-metric and centimetric, in terms of wavelength, or VHF, L and S/X, in terms of frequency) and a control station, performing sensor fusion [19, 23]

Considering the example of the Alenia-Marconi L-band S743D Martello 3D surveillance radar, a detection range of 200 n.m. against a standard target of 1 m^2 can be assumed, taking into account a brochure claiming "long range detection of small, fast targets at distances beyond 200nm". In the L-band, the F-35 RCS has been predicted to be in the -9 dBsm class, without RAM (see Fig. X.5). Emulating the use of RAM and following a similar approach as previously, the attenuation in the L-band can be estimated to be 3 dB lower than the one in S-band (7 dB), that is 4 dB. In this way, the F-35 RCS is -13 dBsm or 0.05 m^2. Such a target would be detected by a S743D at approximately 95 n.m. Compared to the S-band HR-3000, the L-band S743D offers almost 50% more detection range against the F-35. Taking into account the RCS increase at lower frequencies and the narrow-band nature of RAM, equivalent V/UHF radars are expected to exhibit even longer detection range against the F-35, exceeding 100 n.m. Please note that this value is still small, compared to the detection range of typical targets (with RCS > 1 m^2), which exceeds 200 n.m.

Even if a range of 100 n.m. would be acceptable for early warning and fire control radar cueing, it should be noted that all above-mentioned range values pertain to electromagnetically clear conditions. If the environment is congested by strong electronic warfare transmissions (by specialized low band jammers), detection performance is degraded.

Taking into account the above, modern 3D AESA low frequency band radars with advanced digital processing and ECCM (Electronic Counter-Counter Measures) capabilities should be considered as the basic building block of an integrated air defense system, capable of countering difficult-to-detect targets, such as stealth aircraft, ballistic missiles, as well as cruise missiles and UAVs, depending on the radar coverage. Such radar network should be dense enough, keeping in mind a detection radius of less than 100 n.m. and sufficient radar overlap, as well as sensor redundancy. Mobility is also a key issue, for enhanced survivability: a fixed radar is a known target, with limited lifetime in time of war.

Passive Coherent Location (PCL) Radars

A network of low frequency radars as discussed above would sufficiently cover the given airspace against all kinds of threats, at least from a certain altitude and above, depending on the radar horizon. However, a very low-flying aircraft, cruise missile or UAV, exploiting coverage gaps due to ground obstacles (mountains, hills, islands, etc) and remaining as long as possible in the radar shadow, could deceive the air defense system and approach dangerously close to an asset before being detected. One solution to this problem, albeit an expensive one, would be a very dense radar grid. Another idea would be the use of a different kind of sensor, to act as a gap filler.

In this context, a viable approach would be the use of *passive radars*. The operation of passive radars, also known as Passive Coherent Location (PCL) radars or Passive Bistatic radars, is based on the exploitation of existing transmissions. At all times, there are various transmissions (e.g., FM radio, DAB, analog/digital TV, HDTV, GSM, 3G), covering significant parts of the lower airspace. A passive radar comprises a "reference" antenna, directly receiving the broadcast of a station, and a "target" antenna, searching for a potential target. In case of a target being present, the signal from the station will be possibly received also by the "target" antenna, shifted in time (due to the longer distance covered to and from the target), shifted in frequency (due to the doppler effect, since the target is moving), and of course at a considerably lower power level (due to the longer distance and the scattering on the target). Therefore, if a signal similar to the direct signal of the "reference" antenna is received by the target antenna, there is a potential target, as shown in Figure X.11. Comparing the two signals and taking into account the relevant geometry (directions of antennae and relative position of the station), the position of the target can be calculated [24, 25].

Passive radars offer some certain advantages in the modern warfare, such as the following:

1. They provide covert detection and tracking.
2. They cannot be detected by aircraft self-protection systems or even more dedicated ESM (Electronic Support Measures) systems, they cannot be easily jammed, and they cannot be targeted by anti-radiation weapons (such as the AGM-88 HARM and the IAI Harpy).
3. They involve lower budgetary requirements, both for procurement and for operation (e.g., there is no transmission, so there is no need for expensive electron tubes and associated circuitry).
4. They typically involve transmissions in V/UHF, so they fall into the category of low frequency band radars, with the relevant anti-stealth capabilities, as explained in the previous sections.
5. Furthermore, no license is required for their operation, as would be the case for active radars in congested environments, such as at the vicinity of an airport.

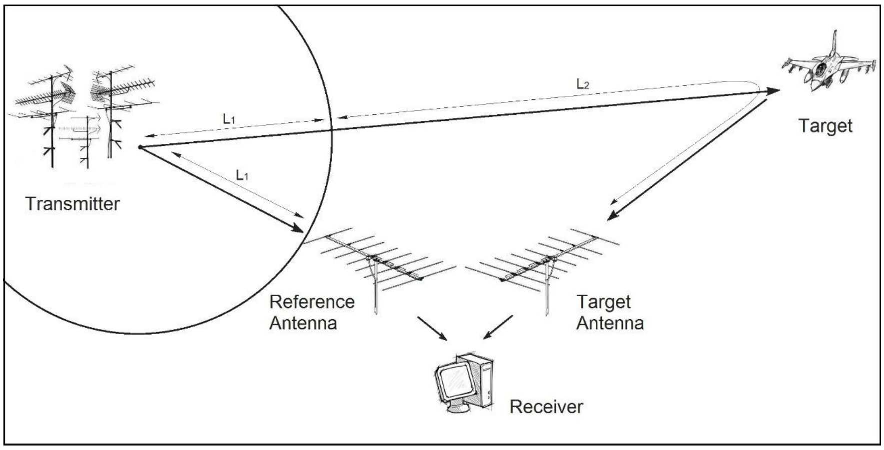

Fig. X.11 The principle of operation of the passive radar: measuring the difference of the time of arrival of the "direct" signal from a station and the same signal after having being scattered on the target [25]

On the other hand, they present some drawbacks, such as the dependence on the geometry and on signals not optimized for radar use, the increased computational requirements, the inability to detect anything at higher altitudes (since there is practically no broadcast above 10000-15000 feet), and the difficulty to provide 3D tracking (many PCL radars are 2D).

Despite the various shortcomings, it seems that many countries are developing PCL radars, even if they may not admit to do so. There have been examples of PCL systems which were once announced, promoted for some time and subsequently disappeared. Notable examples are the Silent Sentry 2 by Lockheed Martin [26] and CELLDAR by BAE Systems and Roke Manor Research [27], in the US and UK, respectively. The only relatively mature passive radar is the Homeland Alerter 100 by the French Thales Air Systems [28]. More recently, a passive radar was proposed in Germany by Airbus Defence and Space (ex Cassidian), as well as the Italian AULOS Passive Covert Location Radar by Selex Sistemi Integratti. Now, the emergence of low-cost Software Defined Radios (SDR), as well as the abundance of cheap computers, have allowed the implementation of PCL systems, not only by radar manufacturers, but also by non-governmental agents, such as enthusiasts and students in electrical engineering.

The unique capabilities offered by the PCL approach in the context of the modern battlefield, especially against stealth and low flying threats, in combination with the covert operation and the low cost, make them a viable candidate for the gap filler role, in order to cover the lower tier of the airspace, depending of course on the availability of the existing transmissions.

The combination of a passive radar system with one or more dedicated transmitters, emitting a suitable, powerful signal, would transform the passive radar to a bistatic/multistatic system. In this way, issues like the coverage at higher altitudes or at areas without sufficient existing transmissions (e.g., over the open sea) could be mitigated. The transmitted signal could be disguised with a modulated content, like music. Even if the dedicated transmitters cease to emit (due to enemy attack or sabotage), the system would fall back on pure passive mode. At the present time, there are not so many multistatic radar systems available. However, such systems exhibit some serious advantages, including the backup passive mode, and should be investigated more thoroughly.

Finally, the category of ESM radars should also be mentioned, that is passive sensors/radiolocators which measure the time difference of arrival (TDOA) of pulses at three or four sites, in order to accurately detect and track aircraft exploiting their own emissions. Systems of this category require some kind of transmission from the target, such as IFF/SSR, TACAN/DME, radar or even jamming signals. If an intruder attacks silently, he cannot be detected by such a system. However, ESM radars offer an accurate and low cost means of surveillance, at least for everyday operations. This principle has been used in the frame of civil air traffic control, exploiting ADS-B transmissions, known with the term *multilateration*. In the defense context, if a potential intruder is aware of the existence of such sensors, he would have to apply even more stringent EMCON (emission control), imposing a further restriction to his activities. The most well known example is the family of the Czech Vera-NG. There is also a number of eastern systems, such as Kolchuga-M, VEGA 85V6-A and DWL002 [25].

4. Unbreaking the Kill-Chain

According to common practice, the "kill chain" from the point of view of the defender against an intruder comprises the following steps:

1. Detection (usually by a long range surveillance radar),
2. Identification (e.g., with the use of IFF/SSR),
3. Tracking (with a fire control radar, either ground-based or air-borne),
4. Weapon/Asset Selection (e.g., ground-based air defense or jet fighter),
5. Engagement (fire the selected weapon),
6. Assessment (evaluate the results of the attack).

Detection is the first step towards any reaction against an intruder. That is why the discussion in the previous sections is focused mainly on the detection of enemy threats. Assuming now that a suitable radar network has detected a target and that this target has been identified as hostile (e.g., by failing to respond to IFF Mode 4/5 interrogation), the next step requires tracking by a radar which should be able to provide a weapon-quality track, operating typically in the C, X or Ku-band.

Using the F-35 as a case study, according to Figure X.5 and the relevant analysis, its RCS is very small in higher frequency bands, at the order of 0,01 m² or even less. Therefore, there is a high probability that even if an F-35 could be detected by lower frequency surveillance radars, it would not be detected by fire control radars, operating at higher frequencies. This is more probable in the case of aircraft fire control radars, where volume, weight and power limitations, impose restrictions on the radar power – aperture product. The situation is even worse concerning missile radars. More analytically:

a. According to open source info, the Northrop Grumman AN/APG-68(V)9 mechanically scanned array radar, equipping recent blocks of F-16 jets, can detect a standard target of 1 m² RCS approximately at 38 n.m. [13]. This radar would not perform well against the F-35, which exhibits an RCS of about 0.01 m² in the X-band, allowing an F-16 to detect it as close as 12 n.m. In other words, an F-16 would get inside the air-to-air missile envelope of the F-35 before picking it up.

b. Concerning the F-35 radar, the AN/APG-81, by Northrop Grumman as well, open sources cite 150 km (that is 81 n.m.) against a 1 m² RCS target. Solving for 0.01 m², it seems that an F-35 can pick up another F-35 at a range of a little more than 25 n.m. Even if this distance is more than double the previously mentioned range of the F-16, still it is small, allowing the pilot to gain only a limited perception of the tactical situation against stealth threats.

A list of various radars and their estimated detection ranges against the F-35 can be found in [9] (with the F-35 RCS assumed to be equal to 0.0015 m², according to an unofficial USAF "leak").

This issue has been known as "breaking of the kill chain" [22]: even if a stealth target, such as the F-35, is detected by surveillance radars, the track may not be possible to be handed over to jet fighter radars in order to intercept it. Moreover, even if a fighter achieves a missile launch against such a target, the missile may not "see" the target when it goes active. This applies to ground-based air defenses, as well.

In order to "unbreak" the kill chain, the following issues should be considered:

- AESA radars offer unique advantages compared to older, mechanically scanned array (MSA) radars. Perhaps the more obvious advantage is longer detection range (almost twice the range compared to MSA radars). However, it should be noted that as the beam reaches high off-boresight angles, the maximum detection range, as well as the accuracy, are degraded considerably. This issue does not affect MSA radars.
- Apart from the radar, almost all jet fighters now employ InfraRed Search & Track (IRST) systems. These are passive sensors which offer serious advantages, such as longer detection range and much better angular resolution with respect to the radar, while they cannot be jammed easily. On the other hand, they cannot measure distance accurately enough and their performance depends on the weather conditions. Newer generation IRST systems are advertised to exhibit anti-stealth capabilities [22].
- As shown above, the fighter aircraft radar is simply inadequate to provide effective situational awareness against stealth threats. Therefore, the "big picture" should be transferred from the Air Control System, via tactical

data link (e.g., Link16) to the fighter aircraft. In this way, fighters would be aware of the all-around tactical situation, even without turning their radars on, preventing also the intruder from locating and identifying them on his RWR display.

- Furthermore, fighters should have the ability to engage a track transferred via data link, even if it is not confirmed by their own radar, possibly firing a missile in Lock-On After Launch (LOAL) mode. This implies lower Pk (kill probability), since the track supplied via data link is of lower quality with respect to the aircraft radar track. However, this is better than waiting forever to get a radar track.
- The same applies to ground-based air defense systems, which they should also be networked, receiving tracks from the Air Control System and engaging them automatically, even without confirming the targets with their own radars.
- It is clear that no single sensor is able to cope with a stealth threat effectively. Different kind of sensors should be employed, covering multiple frequency bands, from HF and VHF to optical, and their readings should be correlated and fused.
- Netcentric warfare principles should be applied: information from every available sensor should be used, identified, fused and transferred to the shooter or even to the missile, in order to engage the target [29].

5. Conclusions

The air threat today is not limited to conventional, fast flying jet fighters and bombers. In the modern air battle, one can find stealth fighter aircraft, ballistic and cruise missiles, UAVs (Unmanned Air Vehicles) flying at various flight profiles, as well as heavily loaded fighters/bombers, with advanced avionics for discrete and accurate air-to-air and air-to-ground targeting. Furthermore, all these threats feature more or less reduced radar and infrared signatures. Legacy air defense radars may find it rather difficult to provide early warning against such threats, especially under strong electronic warfare transmissions.

In this context, using the Lockheed Martin F-35 stealth fighter as a case study, it was proven that low frequency band radars (i.e., L-band or lower bands) offer some significant advantages, especially radars operating in the V/UHF-band. Therefore, modern low frequency band AESA radars, with advanced digital processing, ECCM and ballistic missile defense capabilities can be used as a building block in an integrated air defense system. These radars offer detection ranges of the order of 100 nautical miles against targets, such as the F-35.

In order to fill gaps in the radar coverage, passive radars are proposed, which exploit existing transmissions (e.g., FM, TV, mobile telephony), providing coverage at low to medium altitudes. Furthermore, since they do not emit on their own, they cannot be detected and threatened by anti-radiation weapons.

Finally, some aspects of maintaining the "kill chain" were discussed, pointing out the importance of multi-band sensors, data fusion, tactical data links and network-centric warfare.

Survival against today's air threats requires a suitable adaptation at all levels, a wide transformation of assets, an evolution of capabilities, in fact a transition to a new era. Failure to comply with these requirements would result to limited situational awareness and could lead to loss of assets without any prior warning.

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