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Low Observable Principles, Stealth Aircraft and Anti-Stealth Technologies

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Abstract

During the last decades, stealth technology has proven to be one of the most effective approaches as far as the endeavor to hide from radar systems is concerned. Especially for military aircraft, "stealth" or "low observable" technology has become ubiquitous: all new aircraft types are designed taking into account low observable principles and techniques, while existing jet fighters are considered for modification in order to reduce their radar signature. Low radar signature for a target means that it is detected and tracked at a shorter distance from a radar.

However, low observable does not mean no observable, i.e., complete disappearance from the radar screens. Furthermore, stealthiness comes at a price. Apart from the development cost, stealth aircraft have higher flyaway cost and important maintenance costs, while they have significant operational limitations due to the specific aircraft shape imposed and materials used, and also due to the limited fuel and weapons, which have to be carried internally. Any pylon, tank, missile or pod carried externally increases the radar signature.

Having realized the capabilities of stealth aircraft, many countries have been developing anti-stealth technologies. The following systems have been reported to be potential counter-stealth approaches: passive / multistatic radars, very low frequency radars, over-the-horizon radars and sensitive IR sensor systems. It is commonly

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accepted that the U.S. exhibit an important advantage on the stealth domain, while Russia and China are leading the anti-stealth effort, followed by other countries.

This paper will begin by a brief history of the development of stealth aircraft and a short presentation of the most important stealth fighters of today. It will continue by exploring the basic concepts of low observable principles, mainly reduction of RCS – Radar Cross Section. Focusing on the F-35 stealth aircraft, there will be an attempt to calculate the expected detection ranges for a number of representative radar systems, taking into account an open-source estimation of the F-35 fuselage RCS. Finally, there will be a brief presentation of systems which are reported to have anti-stealth capabilities. Considering all such anti-stealth proposals, it will become evident that no system alone seems to be capable of providing adequate protection: a suitable combination of radar, sensors, weapon systems, tactical data links, as well as tactics, should be employed to effectively counter stealth threats.

Keywords: Stealth aircraft, low observable, RCS, passive radars, multistatic radars, VHF radars, IR sensors, IR Search and Track.

Introduction – Historical background of stealth aircraft

Man has always tried to evade the enemy by keeping his profile or “signature” low. In the past, that meant to take care and hide from the eyes of the enemy, i.e., to take into account the optical region. From the time of appearance and development of the radar systems, the meaning of hiding expanded also to other parts of the electromagnetic spectrum. Today, all military equipment take into account low observable principles (l.o.), trying to be discreet at all aspects, reducing acoustic, radio, radar and infrared emissions, as well as in the optical region, trying to blend into the surrounding environment.

Historically, the first attempt towards the construction of an aircraft with l.o. characteristics is considered to be the German Horten Ho-229, built a little before the end of WWII. That aircraft, which never saw operational action, is said to incorporate some special graphite paint absorbing radar waves. Its special “flying wing” shape is supposed to have inspired Northrop to design later the B-2 stealth bomber.

Until the '70s, among the aircraft types which exhibited, intentionally or not, l.o. characteristics, one would include the British Avro Vulcan and two planes by Lockheed, the U-2 Dragon Lady and most notably the impressive, Mach 3+, SR-71 Blackbird. Despite the efforts mainly of the U.S., none of these aircraft was really difficult to detect by radar.

In the meantime, during the '60s, the Russian physicist Petr Ufimtsev studied the scattering of electromagnetic waves and formulated what is known today as the Physical Theory of Diffraction [1]. His work was not considered by the U.S.S.R. as classified and was published. The main conclusion of his work (although it may have not been explicitly stated) was that radar return is related to the edge configuration of an object, not its size. U.S. engineers came across Ufimtsev's work and realized that he had set the foundations of finite analysis of radar reflections [2]. The advances in computer technology during the '70s allowed the performance of computer simulations using concepts of Ufimtsev's work, while also allowed the design of fly-by-wire systems, which would be essential for the control of aircraft not optimized from the aerodynamic point of view. Following all these, after the 1975 static model project *Hopeless Diamond*, Lockheed constructed two aircraft demonstrators, under the code name *Have Blue*. Although both planes were lost during flight testing, the program was deemed successful, proving the concept of a stealth fighter aircraft.

Figure 1. The Lockheed F-117A Nighthawk stealth ground attack aircraft. First flight in 1981, revealed to public in 1988, took part in all major conflicts and was retired in 2008. In the first Gulf war, it flew 1300 sorties, undetected and unharmed. It is true that if an F-117A was spotted during flight testing at Groom Lake (or *Area 51*, as it is most commonly known), in the '80s, it would be hard to realize that it is just a new jet fighter...Photo: public domain, en.wikipedia.org

After the positive results of the *Have Blue* project, the U.S. awarded in 1978 a contract to Lockheed to develop the F-117A. First flight was in 1981 and initial operational capability was achieved in 1983. In total, 64 F-117s have been built. All this series of projects were “black”, until late 1988, when the F-117A was revealed to public. Since then, it saw operational action in almost every conflict of the U.S. Until its retirement in 2008, the F-117A suffered only one loss due to enemy action, in 1999 in Kosovo war, when a Serbian Air Defense Battalion achieved to engage an F-117A, using modified targeting radar.

Shortly after the decision to develop the F-117A, the U.S. decided to develop also a long-range strategic bomber. In this way, the Northrop B-2 Spirit was born, a subsonic four-engine strategic stealth bomber, 20 of which are still operational today. The B-2 is capable to reach any place in the world (with air refueling), virtually undetectable. L.o. principles were applied also to the Rockwell B1, resulting to the B1-B Lancer supersonic strategic bomber, with lower radar signature but also lower maximum speed at high altitude with respect to the B1-A prototype. However, this compromise, along with several other improvements, allowed the rebirth of the B1 program, helping Rockwell (now part of Boeing) to obtain a contract for 100 aircraft.

2. Stealth Aircraft: Today

The F-117A, B-2 and B1-B can be regarded as the three emblematic l.o. aircraft of the late '80s [3]. Having realized the capabilities offered by l.o. technology, the U.S. went on developing a number of stealth jet fighters, such as:

1. The famous F-22A Raptor (first flight in 1997, production ended in 2011, with 195 planes built, 182 planes operational today): 5^{th} generation air superiority stealth fighter. Lockheed Martin (L.M.) was the prime contractor and Boeing the main partner.

Figure 2. An F-22A Raptor, ready to go (photo by USAF). A single-seat, twin-engine, super-maneuverable, 5th gen., air superiority stealth fighter. Taking into account its all-aspect stealth, speed, agility, situational awareness and combat capabilities, it is considered as one of the most capable jet fighters today. The U.S. have decided not to export it.

2. The L.M. F-35 Lightning II, a multirole 5th gen. fighter with stealth capabilities (first flight in 2006, currently in initial production and testing). There are three variants, the F-35A CTOL (Conventional Take-Off and Landing), the F-35B STOVL (Short-Take Off and Vertical-Landing) and the F-35C CV (Carrier Variant). The F-35 is based on the Joint Strike Fighter (JSF) program, which started in the mid '90s. In 2001 the L.M. X-35 won the JSF competition over the Boeing X-32. Consequently, L.M. was awarded the System Development and Demonstration contract, to develop the F-35, based on X-35. The development of the F-35 is funded primarily by the U.S. and also by several other partner-nations, at varying levels [4].
3. Boeing is proposing a l.o. variant of its venerable fighter F-15E, the F-15SE Silent Eagle. Initially, Boeing declared that the F-15SE would exhibit a l.o. level comparable to the one of a 5th gen. aircraft, implying the F-35 [5]. In the following days, a Boeing spokesman clarified that they meant that "the Silent Eagle could meet the level of stealth approved by the U.S. Government for release to international customers" [6], a point still reflected in their most recent description of F-15SE (Aug. 13) [7].
4. Also, Boeing has extensively applied l.o. techniques on the F/A-18E/F Super Hornet. Furthermore, in August 2013, Boeing started flight-testing of the "Advanced Super Hornet", a new variant of the F/A-18E/F Super Hornet, with

conformal fuel tanks, an enclosed weapons pod and “signature enhancements” designed to substantially increase the range and reduce further the radar signature ([8]).

Even though the U.S. retain a clear advantage, other countries are entering the "stealth domain" as well:

5. The Sukhoi PAK FA is being developed by Sukhoi for the Russian Air Force. Its prototype, T-50, flew for the first time in 2010. The PAK FA is a 5th gen., multirole, twin-engine jet fighter, which will replace a number of older Russian fighters. According to available information, the PAK FA is not expected to reach the stealth levels of F-22 ([9]), however, it may outperform it in other aspects ([10]). Based on PAK FA, Sukhoi will develop with HAL (Hindustan Aeronautics Limited), the “Fifth Generation Fighter Aircraft” (FGFA) for India.
6. China is developing the Chengdu J-20 (first flight in 2011) and more recently the smaller Shenyang J-31 (first flight in 2012), both twin-engined. Both designations (J-20, J-31) are rather unofficial [11].
7. In Europe, l.o. techniques have been applied to Rafale (Dassault Aviation) and Eurofighter Typhoon (EADS), reducing drastically their radar signatures, even though technically they are not stealth aircraft ([12]). Rafale is supposed to employ also active techniques to hide from enemy radars, using its advanced countermeasures suite ([13]).
8. Among other efforts towards developing a l.o. aircraft, one should also mention TF-X, a 5th gen. fighter being developed by Turkish Aerospace Industries ([14]), in partnership with SAAB AB, according to Turkish press. First flight is scheduled for 2023 ([15]). In the next decade, more than 250 TF-X are expected to serve alongside the 100 F-35 which Turkey intends to procure.

Apart from manned aircraft, l.o. technology is applied to Unmanned Aerial Vehicles (UAV) as well. An indicative list would include the Boeing X-45, the BAE Systems Taranis, the Dassault nEUROn (Greece participates in this project), the EADS Barracuda, the L.M. RQ-170 Sentinel, the MiG Skat and the Northrop Grumman X-47B, which on 10-07-13 landed on an aircraft carrier at sea (for the first time for a UAV).

Figure 3. The F-35A Lightning II during development phase. A single-engine, 5th gen. multirole fighter with stealth capabilities, set out to repeat the success of the F-16 ([4]).

3. Radar Cross Section

The Radar Cross Section (RCS) is a measure of the power scattered from a target to a certain direction, when the target is illuminated by electromagnetic radiation, i.e., a measure of how detectable a target is by radar. Concerning monostatic radars, where the antenna is used for both transmission and reception (the majority of radar systems), RCS is a measure of the backscatter or radar return of a target. A larger RCS means that an object is more easily detected with radar.

Trying to avoid formal definitions, the most intuitive description of RCS is the comparison with a metal sphere with a cross section of 1 m^2, i.e., with a diameter of roughly 1,13 m: the RCS of an object is the cross sectional area of a perfect metal sphere which yields the same radar return with the object. RCS is measured usually in m^2. To cope with the large dynamic range of the RCS values, it can be measured also in decibel with reference to one square meter (dBsm), which equals 10·log (RCS in m^2) ([16]). Typical RCS values for various targets can be found in Table 1. Real RCS values are highly classified. Thus, these values are indicative and should be considered in the sense of the “order of magnitude”.

The importance of the RCS relies on the fact that it takes part in the radar equation, affecting directly the maximum detection range of a target. The fundamental form of the radar equation is as follows ([17]):

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

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 monostatic radar), σ is the RCS of the target and S_{min} the minimum detectable signal. Therefore, for given radar parameters P_t, G, A_e and S_{min}, the maximum detection range is proportional to the 4th root of the target RCS: $R_{max} \propto \sqrt[4]{\sigma}$.

Figure 4. A Sukhoi T-50 during the recent MAKS 2013 air-show (photo from *lenta.ru*). The T-50 is the prototype for the PAK FA, a 5th gen. stealth multirole fighter, expected to equip the Russian Air Force and Navy in 2016. It will also be the basis for the FGFA for India.

For example, if a typical air-defence radar could detect a target with an RCS of 1 m² (small fighter) at 200 nautical miles (NM), it would detect a target of 5 m² RCS (large fighter) theoretically at 299 NM (however, the upper limit of most ground radars is set to 255 NM). A reduced RCS fighter of 0,1 m² RCS would be detected at 112 NM and a stealth fighter of 0,001 m² RCS would be detected at 36 NM. The same logic applies to any kind of radar. However, concerning fighter aircraft radars, as well as air-to-air missile seeker radars, the respective ranges are considerably shorter compared to the ones of a ground radar.

In theory, the RCS of some simple objects, such as a perfect sphere, can be well defined. In practice, most targets are rather complex objects and their RCS usually fluctuates considerably, as they move with respect to a radar. In fact, the monostatic or backscatter RCS depends on the following ([18]):

- Target geometry
- Target material composition, especially for the surface

- Position of radar antenna relative to target
- Angular orientation of target relative to radar antenna
- Frequency of the electromagnetic energy
- Radar antenna polarization.

4. Radar Cross Section Reduction

The four basic methods of reducing RCS are shaping, use of radar energy absorbing materials, passive cancellation and active cancellation ([18]), and will be analyzed in the following paragraphs.

4.1 Shaping

The most important factor affecting the RCS is the geometry or the shape of the target, not its size. In order to reduce the RCS, the surfaces and edges should be orientated in such way so as to reflect the radar energy away from an expected radar antenna and not back to it. Considering the flat surfaces (facets) and the acute angles of the F-117, it is understood that it was designed in a way that the expected radar energy would be reflected to irrelevant directions and not back to the emitting radar. The designers tried to avoid any possible surface or edge whose normal vectors would look at a direction where a possible enemy radar might be found, especially for the frontal aspect.

Therefore, in the frame of RCS reduction, all bumps, curves etc should be avoided. In the same way, any external load (pylons, bombs, missiles, fuel tanks, pods) would considerably augment the total RCS. This is the reason why l.o. aircraft carry their armament internally, in special bays. Furthermore, armament bay and landing gear bay doors should close tightly, with no gaps in between. Generally, any irregularity of the surface could incur an RCS increase. Propellers are strictly forbidden, while the first stage engine blades should be carefully hidden inside the intake duct. The whole air intake construction is critical, when designing a low RCS aircraft.

Figure 5. The Dassault nEUROn stealth Unmanned Combat Air Vehicle (UCAV). It is a "technology demonstrator" developed by Dassault (France), Alenia Aermacchi (Italy), SAAB (Sweden), EADS-CASA (Spain), Hellenic Aerospace Industry (Greece) and RUAG (Switzerland)[4].

Sharp dihedral corners and parallel surfaces contribute also to the RCS. Therefore, the twin vertical fin empennage, as in the classic F-15E (not the F-15SE), is prohibited. Stealth aircraft have either canted tail fins or no tail fin at all (as in the B-2 Spirit). Regarding existing stealth aircraft, it is also evident that the leading edges of the wings and of the horizontal tail fins (stabilizers) are parallel. This applies to the trailing edges, as well. The aim is always the same: reflect the radar energy to certain, irrelevant directions, and thus keeping the (monostatic) RCS low.

Conventional (mechanically scanning) radar antennas should also be avoided, since the antenna itself is an ideal radar energy reflector, increasing the RCS when another radar is looking at it. For this reason, the F-117A carried no radar at all. More recent l.o. aircraft make use of electronically scanned array radars, which offer lower RCS contribution, notably AESA (Active Electronically Scanning Array) radars. Furthermore, these radars should exhibit LPI (Low Probability of Intercept) characteristics, in an attempt to avoid detection by enemy ESM (Electronic Support Measures) systems, trying to detect and locate radar emissions.

Apart from the reduction of the aerodynamic drag, which is a positive side-effect of the absence of external loads, optimizing the aircraft design for RCS reduction is generally incompatible with the aerodynamic principles. Furthermore, it

[4] Photo: Zikidis, K. "nEUROn at Le Bourget air show". 2007. JPEG file

would be impossible to control aircraft such as the F-117A and the B-2 without the help of the electronic flight control system (Fly-By-Wire). In general, the application of low RCS principles is a trade-off of cost, aerodynamic performance, RCS and other parameters.

4.2 Radar absorbing materials

The special shaping is the most important l.o. method and it is responsible for the main part of RCS reduction. The second technique is the use of special Radar-Absorbent Materials (RAM) which absorb (part of) the received radar energy and convert it to heat, reducing in this way the reflected energy. RAM neither absorb all received radar energy, nor are efficient at all frequency bands. It is considered as a supplementary approach, helping in reducing RCS when shaping techniques cannot be applied, e.g., in leading edges or engine intakes.

Target	RCS (m^2)	References
Navy cruiser (length 200m)	14000	[19]
B-52 Stratofortress	100 – 125	[3], [19], [20], [21]
C-130 Hercules	80	[19]
F-15 Eagle	10 – 25	[22], [23], [20]
Su-27 Flanker	10 – 15	[22], [23]
F-4 Phantom	6 – 10	[3], [19]
Mig-29 Fulcrum	3 – 5	[3], [22], [23]
F-16 A	5	[20]
F-18 C/D Hornet	1 – 3	[20], [22], [21]
M-2000	1 – 2	[22], [23]
F-16 C (with reduced RCS)	1,2	[20], [21]
T-38 Talon	1	[19]
B-1B Lancer	0,75 – 1	[3], [19]
Sukhoi FGFA prototype*	0,5	[24]

Tomahawk TLAM	0,5	[20]
Exocet, Harpoon	0,1	[21]
Eurofighter Typhoon	0,1 class	[22], [23], [21]
F-18 E/F Super Hornet	0,1 class	[22], [23], [21]
F-16 IN Super Viper**	0,1 class	[12]
Rafale	0,1 class	[3], [12], [22], [23], [21]
B-2 Spirit	0,1 or less	[3], [21]
F-117A Nighthawk	0,025 or less	[3], [21], [20]
bird	0,01	[17], [20]
F-35 Lightning II	0,0015 – 0,005	[20], [22], [23], [21], [25]
F-22 Raptor	0,0001 – 0,0005	[20], [22], [23], [21]
insect	0,00001	[17]

Table 1. Indicative RCS values for various targets. All values given "as is". Real RCS values are highly classified. The above values, most probably, refer to the frontal aspect ("head on") RCS of a "clean" aircraft (without external loads), in the X-band (8 − 12 GHz).[5] [6]

This approach has been followed since WWII, where special paints containing carbon (an imperfect conductor) have been used to reduce the radar return of the snorkels of German submarines. Even though carbon is still being used for such purposes, today magnetic absorbers, based on compounds of iron, are preferred for operational systems [18]. The iron ball paint is a common RAM type and has been used in various l.o. aircraft.

In any case, the application of RAM is also a trade-off, since any special paint or coating add to cost and weight (reducing performance), while RAM may require

[5] * Refers to the derivative of the Sukhoi PAK FA for India. It is expected that the production versions of PAK FA (for Russia) and FGFA (for India) will incorporate more stealthy features than the T-50, their common prototype. In any case, perhaps it is too early to estimate the RCS of these types.

[6] ** An F-16 variant proposed to India, for the Medium Multi-Role Combat Aircraft competition

special treatment and maintenance. For example, the B-2 Spirit requires air-conditioned hangars and costly maintenance to retain its l.o. capabilities [26]. It should be mentioned that the F-35 features a new l.o. substance called *fiber mat*, which according to L.M. officials has been "cured into the composite skin of the aircraft", implying that it requires no maintenance [27].

4.3 Passive cancellation

Sometimes also mentioned as "impedance loading", passive cancellation is based on the idea of creating a (passive) echo source, whose amplitude and phase would be adjusted to cancel another echo source (e.g., by drilling a cavity or port of specific dimensions and shape on the object body). This may be possible for very simple objects, however it is prohibitively difficult for complex objects like an aircraft, while a small change of the radar parameters or the simple movement of the object-target could lead to the amplification of the radar return. In fact, this approach attracted some interest in the past but now seems not so promising anymore ([18]).

4.4 Active cancellation

Also called "active loading", active cancellation is based on the same principle as passive cancellation, which is the creation of an appropriate "destructive" echo, which would cancel the real echo of the target to the radar. Therefore, the target should emit electromagnetic energy synchronized with the received radar energy, with proper amplitude and phase in order to minimize the reflected signal. In other words, the target should take into account the direction of arrival of the radar energy, the amplitude, the frequency, the phase, its own RCS characteristics for the specific frequency and direction, and should be adequately intelligent to create the proper waveform, emitting the right pulse at the right time to the right direction. The technical difficulties are obvious, as well as the possibility to convert the target into a "beacon" of radar energy, in case of wrong implementation. This technique has been reported to be applied by the Rafale ([28], [29]) and has been implicitly confirmed by Dassault ([13]), without revealing any details ([30]).

Another attempt in the category of "active stealth" is the so-called "plasma stealth" technology. There have been reports that the Russians were conducting experiments on this idea. According to available information, this technology employs ionized gas (plasma), which is produced by a special device on-board and injected in front of the aircraft, creating a protective cloud and reducing considerably the aircraft RCS. However, apart from an interview in 1999 ([31]), there were no further updates on the issue ever since ([32], [33]).

5. F-35: the Hype, the Skepticism and the Reality

According to L.M. officials, the 5th gen. F-22 Raptor brings a considerable increase in capability and survivability over legacy fighters, combining situational awareness, fire power, speed, maneuverability and sufficient l.o. levels from every aspect ([34]). Actually, this point of view is shared also by many specialists. The U.S. have decided not to export the F-22.

On the other hand, the F-35, the derivative of JSF, began as an export program, funded by the U.S. and several partner nations. The F-35 is expected to equip mainly the U.S. (U.S. Air Force, Marine Corps and Navy) and 11 other partner nations. More than 3000 planes are expected to be acquired over the years (2443 by the U.S., the rest by the other partner nations) ([4]). Therefore, it is considered as one of the most important aircraft programs today. L.M. officials have claimed that the F-35 is a multirole, air-superiority stealth fighter, several times more capable than the aircraft types which is expected to replace, while it has been implied that it is comparable to the F-22 ([34]).

However, various issues which have been reported during the years of the F-35 development have proven such claims overwhelming. Since Nov. 11, DoD has officially acknowledged 13 issues which should be solved ([35]). Among these issues, there are possible structural problems concerning the life of the airframe, taking into account that the fatigue testing program had reached only 20% at that time. However, the main problems are the significant delays, with respect to the original schedule, and the cost, which has nearly doubled ([36]). The integration of the various subsystems is also retarded. Millions of lines of C++ code have yet to be written ([37]). Furthermore, the flight testing program has still a long way ahead, which means that new issues may appear.

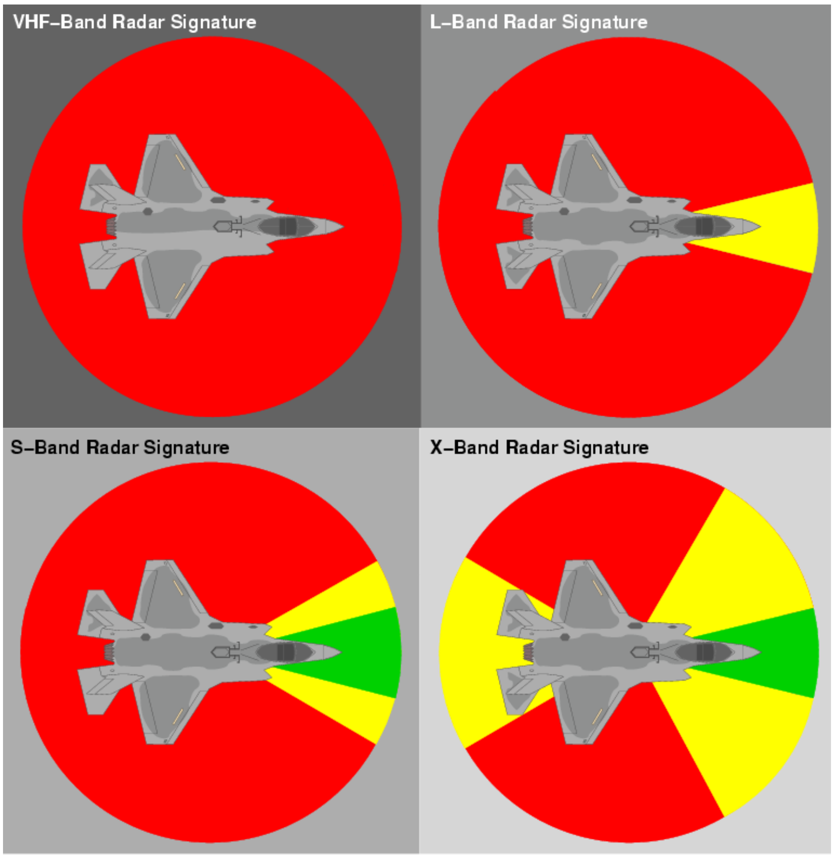

Figure 6. F-35 RCS (Radar Cross Section) estimation as a function of the viewing angle, from lower altitude (depression angle < –20°), at the VHF, L, S and X frequency bands ([44]). Green corresponds to very low RCS, yellow to low RCS and red means just "reduced" RCS. The best stealth performance is expected at the X-band, mainly from the frontal aspect and to a lesser extend from the rear aspect.At lower frequency bands, stealth performance is degraded.

Apart from the above, there have been serious doubts concerning the real operational capabilities of the F-35, e.g., the thrust-to-weight ratio, the limited ability to carry armament and fuel, the combat radius, the maneuverability etc [38][39][40]. There are also some concerns for the stealth levels of the export versions [41], especially after the U.S. denial to provide the source code to their partners [42], even to the U.K., the sole "Level 1" partner.

Concerning the stealth capabilities of the F-35, the well known *think tank* "Air Power Australia" has published a series of articles, highlighting the weaknesses of the F-35 in comparison with the F-22 and also modern Russian fighters and air-defence systems ([43][44]). Their line of thinking has raised controversy and they have been criticized ([45]). However, their approach is a relatively well documented one, among the very few publicly available, which leads to some plausible estimations.

Therefore, it is claimed that the F-35 fuselage design, as a result of a trade-off between cost and requirements, did not follow the “standard way”, as in F-117 or the B-2. For the F-35, the approach was the construction of a l.o. aircraft, taking seriously into account the cost parameter. Therefore, in the frame of cost reduction, some capabilities were “sacrificed”: RCS is really low in the X-band (8 – 12 GHz) and in the Ku-band (12 – 18 GHz), while it is not so low at lower frequency bands. The scope is the break of the killing chain: even if the F-35 is detected by surveillance radar, it will not be easy to be engaged by a fire control radar, which usually operate in the X or Ku bands. On the other hand, the F-22 presents a lower RCS from all aspects and at more frequency bands, of course at a considerably higher cost.

The production F-35 is expected to present a higher RCS than the prototype X-35, since more volume was required for the internal equipment and armament bays. The curves of the redesigned fuselage will incur an RCS increase, from some certain directions. It was calculated that the RCS will remain very low from the frontal sector and more precisely from a sector of 29^{o} in front of the aircraft. However, the RCS will not be so low from the lateral aspect and also from the rear aspect. The whole behavior deteriorates at lower frequency bands. The researchers of the Air Power Australia created a 3-D model of the underside of the fuselage and tried to calculate the RCS ([46]), using the POFACETS algorithm, developed at the Naval Postgraduate School of the USN ([47][48]), proving in this way their arguments.

After the initial hype and the subsequent criticism, a more balanced line of thinking is that many complex programs face cost overruns and schedule delays, but finally they reach their goals, which are maybe readjusted on the way. It is true that the F-35 is one of the most ambitious programs ever, trying to integrate state-of-the-art technologies, such as two complex electro-optical systems with a Helmet Mounted Display System, power-by-wire with electrohydrostatic actuators, a new AESA radar, a lift fan mechanism for the -B variant, etc, while retaining stealth capabilities, at a tight time schedule and certain cost constraints ([49], [50]). Even more, this program involves several partner nations, which contribute also to the manufacturing process. Some specialists say that the F-35 program is just too big to fail. Even though this is not so reassuring in today's volatile environment, it is expected that eventually most of the F-35 issues will be dealt with, more or less. The aircraft should live up to the expectations, even if some of them may have to be redefined to a certain degree.

6. F-35 detection estimation for various radar systems

In any case, no-one doubts that the F-35 will exhibit stealth capabilities, maybe not as good as the F-22 but most probably better than any other aircraft. In order to estimate the maximum detection range for the F-35, first there should be an estimation of the F-35 RCS, and then a calculation, using the radar equation and the logic mentioned before, with respect to the detection range for a standard target used for comparison purposes. As a “standard target” for the comparison, a 1 m² RCS target will be used. A target of 1 m² RCS corresponds to a small fighter, such as the Northrop T-38 Talon ([19]). The detection ranges for the standard target of 1 m² RCS for the radar systems under consideration are estimated as follows:

a. AN/APG68(V)9 (Northrop Grumman): the fire control radar of the most recent variants of F-16, like Block 52+, operating in the X-band. The detection range for a 1 m² RCS target is assumed to be 40 NM [51].

b. S-743D Martello (Alenia Marconi Systems): a 3-D long range surveillance radar, operating in the L-band (1 – 2 GHz). The detection range of a target with an RCS of 1 m² is of the order of 400 km (216 NM) [52].

c. AR 327 Commander (British Aerospace): an S-band (2 – 4 GHz) long-range tactical radar, providing 3-D coverage up to 470 km [53]. The 1 m² RCS detection range is estimated at 350 km (190 NM) [54].

d. HR 3000 HADR (Raytheon): another 3-D radar in the S-band. Maximum range: 500 km, a “standard target” is detected at 320 km (173 NM) [55].

e. Search radar 64N6E of the S-300 PMU-1 system (Almaz - Antey): operating in the S-band, with a maximum range of 300 km (162 NM), and 280 km for a target with RCS ≥ 4 m² [56]. The detection range for a 1 m² RCS target is calculated at 110 NM.

f. Engagement radar 30N6E1 of the S-300 PMU-1 system (Almaz - Antey): operating in the X-band, with a maximum range of 150 km (81 NM) [57]. Assuming that this range also corresponds to an RCS of 4 m², the detection range for the "standard target" is 55 NM.

g. AN/MPQ-65 of the Patriot PAC-3: operating in the C-band (4 – 8 GHz), it exhibits a max. range of 170 km, in a 120° sector [58]. Assuming that this range corresponds to a large fighter with an RCS of 5 m², then the "standard target" can be seen approximately at 60 NM.

h. DA08 (Thales): S-band, medium range surveillance radar used in some frigates, with a detection range of 78 to 92 NM for 2 m² RCS targets [59]. For calculation purposes, it is assumed that the "standard target" can be detected at 76 NM.

i. LW08 (Thales): L-band, long range surveillance radar used in some frigates, with a detection range of 145 NM for 2 m² RCS targets [59], i.e., 122 NM for the "standard target".

Frequency / IEEE Band	Peak value (in dBsm)	Average value (in dBsm)	Peak value (in m²)	Average value (in m²)
1 GHz / L	–14	–22	0,04	0,0063
3 GHz / S	–15	–25	0,0316	0,00316
8 GHz / X	–13	–35	0,05	0,0003
16 GHz / Ku	–18	–42	0,016	0,000063

Table 2. Estimated peak / average RCS of the F-35 fuselage, for an angle 45° off-beam from the front and a depression angle of –3,6° to –20° from below, taking into account the application of RAM (Radar-Absorbent Materials) by a further reduction of 10 dBsm ([46]).

Having established the base of comparison, the next step is to estimate the RCS of the F-35 for the respective frequency bands. As mentioned earlier, *the researchers of the Air Power Australia created a 3-D model of the underside of the F-35. In [46], there are matrices of the calculated RCS for certain conditions: in "angles off beam" 10°, 20°, 30° and 45°, for various depression angles (simulating long, medium and short range surface-to-air missile systems) and for 4 frequency bands. At all cases, the peak and the average RCS values were recorded. The calculated values (in dBsm) were further reduced by 10 dBsm, assuming the* *application of Radar-Absorbent Materials. However, the actual RCS is expected to be higher, since there will be other parts contributing to it, apart from the fuselage underside.*

Taking into account the case of an angle of *45° "off beam" (i.e., looking at the plane from the front-left or front-right side) and a depression angle of -3,6° to -20° (corresponding to a long range detection), the relevant RCS values are depicted in Table 2.*

Following the above and taking into account that the maximum detection range is proportional to the 4th root of the RCS, the estimated detection ranges for the radar systems under consideration can be found in Table 3. For comparison purposes, there are also the corresponding detection ranges for a target of 5 m² RCS (large fighter or conventional fighter in combat configuration) and of 0,0015 m² (F-35 RCS revealed by the US Air Force ([25])*).*

The results from Table 2 confirm the argument that the average RCS increases as the frequency gets lower. However, they also confirm that the F-35 RCS is really low, at least as far as the fuselage is concerned. Especially in the X-band, the calculated (average) RCS is even lower than the one revealed by USAF and the decrease in detection range with respect to the "standard target" is dramatic. For example, the APG68 of the F-16 is expected to "see" the F-35 at a distance of roughly 5 NM. The expected decrease of the detection range for the F-35 with respect to conventional aircraft depicted in Table 3 indicates that the F-35 will be a real danger, and not only as a first strike weapon. In the following sections, certain systems that are believed to exhibit anti-stealth capabilities will be presented.

Radar system (IEEE Radar Band)	RCS 5 m²	RCS 1 m²	F-35 @ 45° peak value	F-35 @ 45° average value	F-35 @ 0° RCS 0,0015 m²
AN/APG68(V)9 (X)	59	40	19	5	8
S743D (L)	255	216	97	61	>>43
AR327 (S)	255	190	80	45	>37
HR-3000 (S)	259	173	73	41	>34
S-300 64N6E (S)	162	110	46	26	>22

S-300 30N6E1 (X)	81	55	26	7	11
Patriot MPQ-65 (C)*	90	60	25	14	>12
DA-08 (S)	113	76	32	18	>15
LW-08 (L)	182	122	55	34	>>24
* Operates in the C-band (4 - 8 GHz) but the 3 Ghz RCS was used for the calculations.					

Table 3. Estimated detection ranges for the F-35 in nautical miles (NM)

7. Multistatic Radars

Taken into account that l.o. aircraft have been optimized mainly for the monostatic radar type, the multistatic approach (where there is one or more transmitter antennae and many receiver antennae, at different locations) has been proposed as a possible counter-stealth candidate. It is reminded that the basic l.o. principle is shaping, in order to reflect the radar energy to irrelevant directions and not back to the emitting radar. The main idea of the multistatic radar approach is that one or more receiver antennae will be in such a position to receive the scattered echo.

Such radar systems exhibit increased survivability, due to the redundancy of the receivers and their passive operation. If one receiver is eliminated, the system may continue to operate, even with degraded performance.

52E6MU Struna-1MU / Barrier E (NNIIRT, Russia): Actually, this seem to be the only proposed multistatic system. It provides early warning against low RCS targets, at medium to low altitudes. The transmitters operate at low power rating (1 – 10 Watt) at 390 – 430 Mhz. Up to 10 such systems can be connected together, separated by 40 – 50 km, forming a radar fence up to 400 km, controlled by a central station ([60], [61] and [62]).

AASR – Associative Aperture Synthesis Radar (Saab Microwave Systems, Sweden): This program was stopped in 2000, just before being tested, after 8 years of development. It was a system of UHF transmitters and 900 nodes – antennae. Expected to provide high accuracy (of the order of 1,5 m) but it was also quite costly (150 mUSD). However, the most important drawback was that, in order for the target to be detected, it should be between transmitters and receivers, i.e., it should already be over friendly ground ([63] and [64]).

8. Passive Coherent Location (PCL) Radars

Systems of this category consist of receivers utilizing the existing radio waves, e.g., radio (SW, FM, DAB), TV (analog, DVB, HD), mobile telephony (GSM, 3G) and Wi-Fi. They employ advanced techniques like digital beamforming, adaptive filtering and cross-correlation between the directly received signal and the one received after reflection on the target. There can be more than one receivers or transmitters used (multistatic passive radar).

Passive radars offer lower procurement and operating costs. The absence of any emission protects them also from being detected by ESM and targeted by anti-radar missiles. Their potential anti-stealth capabilities rely on the use of low frequency bands, where l.o. aircraft may be more vulnerable to detection, as well as to the fact that they are bistatic, i.e., the transmitter is at a different location from the receiver. On the other hand, there are some issues, due to the fact that such radio transmissions are not designed for radar use. PCL systems are expected to be used as complements to conventional radar systems, to cover gaps of the airspace monitoring, especially at medium to low levels. For example, they can be used for Air Traffic Control at terminal areas, since no transmission permissions are required ([65],[66]). *During the last couple of years, it seems that there is a considerable ongoing research and development on PCL systems and new systems are continuously revealed. E.g.:*

Figure 7. The Thales Homeland Alerter 100 ([68]).

Figure 8. The Cassidian passive radar ([71]).

Homeland Alerter 100 (Thales, France): Introduced in 2005, the HA 100 utilizes FM radio and mobile telephony signals. It covers medium to low altitudes, protecting sensitive facilities, such as factories, airports and other high value assets. It exhibits a range of 100 km, with an operational ceiling at 20000 ft. It can be fixed or movable, operating autonomously or connected with other radars or Control and Reporting Centers ([67] and [68]).

AULOS Passive Covert Location Radar (Selex Sistemi Integratti, Italy): Presented for the first time at Farnborough 2012, even though development had begun in 2005. Employs FM radio and digital TV signals and exhibits a range of “several hundred kilometers”. It is a compact system, transportable on a 4-wheel towed vehicle. Apart from its possible military use, it is suggested for Air Traffic Control, covering medium to low altitudes ([69] and [70]).

Passive Radar (Cassidian, Germany): In July 2012, Cassisian, a subsidiary of EADS, stated that they have developed a passive radar system utilizing existing radio and TV signals, for civil and military use, capable of detecting stealth aircraft. According to Cassidian, this is a state-of-the-art system and can be installed and used on a van type vehicle ([71]).

Recently, in September 2013, South Africa was reported to have successfully developed a prototype passive radar system, with a range of 150 km ([72]).

Silent Sentry (L.M., U.S.A.): Introduced in 1999, it can provide long range detection with fairly good resolution, tracking 100 targets up to 150 NM. It utilizes FM radio and TV transmissions. It is able to track aircraft, missiles, ships and ground vehicles, with a 250 m accuracy on the horizontal plane, 1000 ft for the vertical plane and ±2 m/sec for the speed. An HD signal would offer higher accuracy ([73] and [74]). In fact, this system has disappeared from the L.M. website, maybe in order to avoid competing with other L.M. products, like the F-35.

CELLDAR – CELL PHONE RADAR (BAE Systems – Roke, U.K.): It is supposed to use mobile telephony signals to detect and locate air and surface targets in 2D, up to 60 km and to an altitude of 10000 ft. However, there is no update during the last years ([75] and [76]).

9. ESM (Electronic Support Measures) Passive Sensors

ESM systems are able to detect and locate targets, exploiting any radio transmissions from these targets. Due to their passive operation, sometimes they are also referred to as passive radars. Their principle of operation is based on triangulation or multilateration, using TDOA (Time Difference Of Arrival) methods. Such systems exploit mainly omni-directional aircraft transmissions, such as V/UHF communications, SSR/IFF, TACAN/DME, tactical data links, and to a lesser extend radar and jammer transmissions.

Evidently, in order to detect a target with an ESM system, the target is required to emit something. However, strike aircraft, like the F-35, are not expected to use any of the above systems when in operational conditions, apart perhaps from their radar, which is anyway not so easy to detect, due to its narrow beam. Therefore, such systems do not offer any real operational advantage in detecting stealth aircraft ([77]).

Among the proposed ESM systems, one could suggest the following:

- Kolchuga (Topaz, Ukraine) ([78]).
- Tamara (Tesla) and its successor, Vera-NG (Era, Czechoslovakia) ([79]).
- VEGA 85V6-A (Rosoboronexpoert, Russia) ([77]).
- DWL002 (China Electronics Technology Corp. – CETC, China)([77]).

Figure 9. The 3D VHF AESA Radar 1L119 NEBO SVU, developed by NNIIRT (Russia) and offered for export by Rosoboronexport (the sole state export entity for defence products in Russia). It is a mobile, long range surveillance radar, featuring modern technology, able to detect stealth aircraft from considerable distances ([80]).

10. Low Frequency Band Radars

L.o. aircraft have been designed with the aim to reduce radar energy backscatter mainly in the X and Ku bands. At lower frequency bands, the RCS of a l.o. aircraft is expected to increase. This is due to the fact that, in that case, the wavelength becomes comparable with parts of the aircraft, e.g., the stabilators or the wings, and therefore scattering enters the resonance or Mie region ([17] and [30]): the RCS fluctuates considerably as a function of the wavelength, depending on the shape of the target, and it may become up to 10 times higher or even more, with respect to the RCS in the optical region ([81]). Furthermore, RAM are not so efficient at lower frequencies. For these reasons, low frequency band radars are expected to exhibit serious anti-stealth capabilities ([65] and [82]).

Most of the WWII radars were low frequency band radars, operating in the VHF or UHF bands, due to technological constraints. The U.S.S.R. kept using such radars, at least during the '50s and the '60s. However, the advances in electronics during the Cold War allowed the design of radars using higher frequencies, offering better performance and requiring smaller antennae. Thus, surveillance radars operating in the L or S bands were becoming more and more common. After the first Gulf war in 1990, where the Iraqi air-defence was proven impotent against the F-117A, Russia restored its interest on low frequency band radars, applying new technologies. It is noted that the only case of a stealth aircraft lost due to enemy action (the F-117A shot during the Kossovo war [30]) was associated with the use of a modified soviet-made VHF radar (P-18 "Spoon Rest") ([83]).

Another advantage that such radars offer is that they do not "warn" the targets they follow, since their transmission frequency is too low to be detected by an ordinary countermeasures system. For the same reason, they cannot be engaged by the majority of anti-radar systems, such as the AGM-88 HARM or the UAV Harpy. Some representative examples of low frequency band radars are the following:

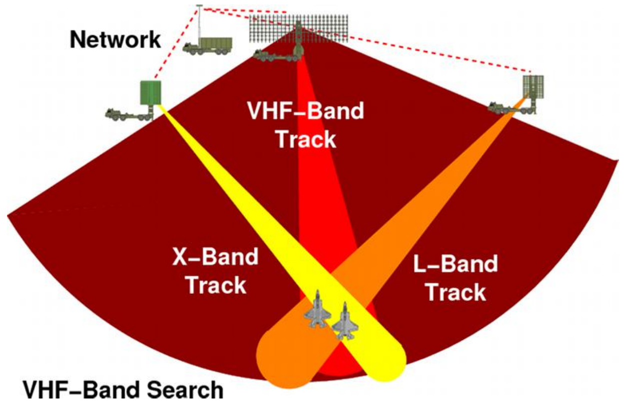

Figure 10. The pioneering Nebo M combines three existing 3D radars, the VHF band Nebo SVU, the L-band Protivnik G and the S/X-band Gamma S1. All tracks are fused in the command post. It is designed to counter l.o. threats like the F-35. Placing the radars as in drawing, left, with respect to the threat axis, the VHF radar offers early warning, while the L- and X-band radars offer finer track, illuminating the targets from angles where the RCS is increased. Furthermore, Nebo M exhibits better jamming resistance ([80]).

11. 3D VHF Radar AESA 1L119 NEBO SVU (Rosoboronexport, Russia).

Developed by NNIIRT (Russia), the 3D surveillance radar NEBO SVU has been operational since 2004. It uses digital processing and solid state electronics, employing an array of 84 Yagi type antennae. Installed on a vehicle, it can be transported within 20 min. The maximum ranges reported for its later export version, for a target of 2,5 m² RCS (typical target used as reference in many Russian systems) are as follows:

- 65 km for a target at 500 m altitude,
- 270 km for a target at 10000 m altitude,
- 380 km for a target at 20000 m altitude.

Accuracy: 200 m in range, 1,5° vertically and 0,5° for the azimuth. It can track up to 100 targets and can be connected to an S-300 system anti-aircraft system, to designate l.o. targets to the engagement radar [80][56].

3D Multiband Radar RLM-M NEBO-M (Rosoboronexport, Russia): Presented in 2008, the Nebo-M is a system of 3 pre-existing 3D radars of NNIIRT, which were properly upgraded and modified to provide radar picture to a central command and control station. These radars are: the above-mentioned Nebo SVU (VHF-band), the Protivnik G (L-band) and the Gamma S1 (S/X-band). All subsystems are on-board 8

× 8 trucks. There are no official statements concerning the range, however according to estimations, it is expected to be 40 % higher than the one of the NEBO SVU, with better resolution [62][80][81].

2D VHF Radar VOSTOK E (Agat/KB Radar, Belarus): mobile radar (on a 6 x 6 truck), able to deploy in 6 min, featuring digital, solid state design. In the case of a "heavy" environment of electronic warfare, it can detect the F-117 at 57 km (according to other sources, at 72 km [62]) and the F-16 at 133 km. In a clear environment, the F-117 can be detected at 350 km [84].

AESA L-band Airborne Radar (Tikhomirov NIIP, Russia): Presented at MAKS 2009, it is designed to be installed inside the leading edge of the wings of a fighter, such as the Su-35. It is expected to provide higher detection and tracking ranges for l.o. targets with respect to other airborne X-band AESA radars ([85]).

12. Over The Horizon Radars

If HF-band (3 – 30 MHz) waves are transmitted towards the ionosphere, under certain conditions, they may be reflected back to earth. The ionospheric reflection of the HF waves is the principle of operation of the Over-The-Horizon Radars (OTHR). Such radars offer extremely long detection ranges (from 700 to 4000 km) but also very low resolution (from some hundreds of meters up to 20 km). Apart from using very low frequencies, they “see” their targets from above, offering considerable capabilities of detecting l.o. targets. It is noted that stealth aircraft are optimized for radars in front and from below, while from above they may present higher RCS, due to the cockpit and the engine intake and exhaust.

An OTHR system requires large facilities of antenna arrays, offering a strategic advantage. Obviously, their cost and limitations, especially their very high minimum range, constrain their use. Some of the few existing OTHR systems are the following:

– AN/FPS-118 Over-The-Horizon-Backscatter (OTH-B) Radar, covering distances from 900 to 4800 km (L.M., U.S.A.) [86].

– AN/TPS71 Relocatable Over The Horizon Radar (ROTHR), covering distances from 925 to 3000 km (Raytheon, U.S.A.) [87].

– Jindalee Operational Radar Network (JORN), covering distances up to 4000 km (Australia) [88][89]. It has been reported that this system has detected F-117 aircraft [90].

– NOSTRADAMUS, from 700 to 2000 km (ONERA, France) [91].

13. Infrared Detection Systems

The infrared (IR) area of the electromagnetic spectrum is the part between microwaves and visible light. It can be defined as the electromagnetic radiation with frequency from 300 Ghz to 400 THz or wavelength from 1 mm to 0,75 μm, respectively. It corresponds to the thermal radiation emitted by everybody at any temperature above the absolute zero. There are quite many applications of the IR radiation, as in medicine, meteorology, telecommunications, etc, as well as in the common remote-controls.

IR allows night vision with FLIR (Forward Looking IR) systems and also target detection. Any aircraft flying has various hot points emitting IR radiation, such as the jet engine, the engine exhaust and certain surfaces due to aerodynamic friction. IR seekers of air-to-air missiles (e.g., AIM-9, IRIS-T, MICA IR etc), as well as IRST (IR Search and Track) systems, allow for passive detection and tracking of aerial targets, exploiting their own thermal radiation. In this way, the targets are not warned, since there is no emission from the seeker. Furthermore, IR seekers cannot be jammed, like a radar seeker.

Missiles with IR guidance have been used from the '50s and since then they have been continuously upgraded and improved. During the last 25 years, 90% of all US air combat losses can be attributed to infrared missiles, including surface-to-air systems ([92]). On the other hand, IRST systems appeared during the '60s but their evolution soon slowed down, as they were put to shade by the advances in radar systems. They were re-discovered later by the West, after being installed on most Russian fighters since the '80s. Today, all modern jet fighters are equipped with IRST systems, offering target detection (both air and surface), covering up to ±90° in azimuth and at considerable distances. Sometimes, a laser system is combined for range-finding or a zoom-able TV camera for identification purposes.

Even though stealth aircraft make use of various techniques for reducing their thermal signature, IR radiation cannot be totally eliminated. In the case of F-35, the F135 engine used is the most powerful jet fighter engine, with the highest combustion chamber temperature (more than 2.200° C ([93])). Even if this does not necessarily mean also high “external” temperature, it is expected that the F135 has a considerable thermal signature ([94] and [95]), allowing the detection of the F-35 by IR systems from a considerable distance. Some examples of IRST systems are the following:

AN/AAQ-37 Electro-Optical Distributed Aperture System (EODAS) of the F-35 (Northrop Grumman): comprises 6 Imaging IR sensors, providing 360° spherical situational awareness. It provides day/night vision, IRST capabilities with fire control, missile detection and tracking, etc ([96]).

AN/AAQ-40 Electro-optical Targeting System (EOTS) of the F-35 (L.M.): this is the second electro-optical system of the F-35, combining FLIR, IRST and laser. It provides detection, tracking and designation of ground targets, and also identification of aerial targets. It is based on the L.M. AN/AAQ-33 Sniper Advanced Targeting Pod [97].

Figure 11. The PIRATE IRST system on a Spanish Air Force Eurofighter Typhoon. Photo from *http://www.eurofighter.com/media*

Figure 12. The OSF (Optronique Secteur Frontal) system of the Dassault Rafale. Photo from *http://optronique.net/defense/systeme/optronique-secteur-frontal-rafale*

PIRATE (Passive Infra Red Airborne Tracking Equipment) of the Eurofighter Typhoon (EUROFIRST consortium): A 2nd gen. system (Imaging IR), combines FLIR and IRST, allowing the tracking of up to 200 targets, to distances up to 50 – 100 km ([98]).

OSF (Optronique Secteur Frontal) of the Rafale (Thales Optronique – SAGEM): Comprises an IR subsystem (with IRST and FLIR) with a range of 100 km and a second subsystem with a high resolution TV camera (range up to 40 km) and laser for range-finding. OSF is fully integrated to the aircraft weapon system. Due to cost constraints, the Rafale F3 aircraft were delivered without the IR subsystem, which can be substituted to a certain degree by the MICA IR seeker. If required, the IR subsystem can be easily installed, so fighters taking part in military exercises or war missions are equipped with a complete OSF system. The IR subsystem is expected to be replaced by a newer type in the future [99][100][101].

OLS-35 of the Sukhoi Su-35 BM (NIIPP): Includes an IRST, with a maximum range of 50 km on the frontal and 90 km on the rear aspect of the (non afterburning) target, a TV camera and a laser for range-finding and target designation [102].

SpectIR (L.M.): An IRST system based on the AN/AAS-42 of the F-14D Tomcat. It is in advanced testing stage. Is is designed to be installed in the front part of an external fuel tank (for the F-18 E/F) or as an external pod (for the F-15, F-16 etc) [103][104].

14. Conclusion

Stealth technology has become *sine qua non*: all military aircraft, tanks, ships etc, are designed or redesigned according to low observable (l.o.) principles. This technology allows a potential intruder to enter enemy area undetected and deliver a first strike before the defender realizes he is being attacked or at least before he has the time to respond effectively. Furthermore, l.o. techniques help to "break the kill chain": even if the l.o. aircraft is detected, it cannot be easily engaged by a fire control radar or a missile radar seeker.

On the other hand, stealthiness is not *panacea*: stealth aircraft are not invincible, they are just detected at shorter distances. Generally, the application of l.o. principles incurs a considerable cost, both in procurement as well as for maintenance. Actually, the l.o. approach is a trade-off among cost, stealth capability and operational performance, i.e., maneuverability, amount of weapons and fuel, etc. The point is that a *few* fighters with *l.o.* characteristics but with inherent *operational constraints* will not necessarily prevail against *more* fighters with *not so l.o.* characteristics but better *operational capabilities*.

In any case, a stealth threat is a serious threat, which should be dealt with appropriately. Traditional surveillance and engagement systems have proven to be inadequate. In fact, no radar system alone seems capable to confront effectively such threat.

A promising approach relies on a combination of the following:

– Very low frequency band radars, for medium to high altitude surveillance: as the frequency decreases, the wavelength increases and becomes comparable with major parts of the aircraft. Thus, scattering enters the resonance region, exhibiting a higher Radar Cross Section (RCS), at least momentarily. Also, the Radar-Absorbent Materials (RAM) are not very effective at lower frequencies. For these reasons, radars operating, e.g., in the VHF band, are expected to see a l.o. target at a longer distance with respect to “conventional”, higher frequency radars, transmitting in the L or S-band.

– Passive radars can complement their active counterparts, covering low to medium altitudes: such radars detect and track targets passively, measuring distortions and disturbances on existing signals from radio, TV, mobile telephony, Wi-Fi etc. They feature low frequency and bistatic operation (different locations of transmitter and receiver), offering increased probability of revealing stealth aircraft, which are optimized for monostatic radars.

– All information from every radar system or sensor should be fused in a central command and control entity (data fusion). If possible, low level, raw data should be taken into account. A few “hits” from a radar may not result to a “plot”, however a few “hits” from different radars corresponding to the same location certainly indicate a possible target.

– Any unidentified track should be transferred to combat aircraft via tactical data link, in order to be intercepted.

– The interceptors should be equipped with an IRST (InfraRed Search and Track) system, allowing detection and tracking of l.o. targets at longer distances, with respect to their radar sets. Ideally, they should be also capable of engaging a designated target sent to them via data link, even if they cannot "see" the target by their on-board sensors.

– Following the same way of thinking, IR air-to-air missiles should be preferred to radar seeker missiles, even for BVR (Beyond Visual Range) distances.

As a final conclusion, it should be noted that the development of l.o. technology and the proliferation of stealth aircraft have changed the modern warfare, rendering most legacy systems almost useless. In order to cope with this new type of threats, older systems should be upgraded, modified accordingly and interconnected, following the principles of the net-centric warfare doctrine, while new, suitable systems should also be employed, as described in this paper. If not, the danger of realizing you are being attacked, after having received several bombs on your air-force bases and facilities, is looming. However, as Dr. W. Edwards Deming has put it: "*It is not necessary to change. Survival is not mandatory*."

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