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Rethinking SEAD

Employment of contemporary Fighter Aircraft Capabilities

against an A2/AD-System of Systems of a peer Adversary

in Europe

Tim Saldik

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Abstract

The Russian full scale invasion of Ukraine has demonstrated, how relevant the discussion about a potential NATO article 5 intervention in Europe is. A frequently used term in this context is Anti Access/ Area Denial. While this term is not existent in Russian strategy, the Integrated Air Defense System it encompasses poses a major challenge to NATO's freedom of movement in case of a conflict. The air power role Suppression of Enemy Air Defenses can provide means to tackle the threat the Russian IADS poses to NATO. This thesis elaborates on NATO's capabilities to counter the Russian IADS with SEAD capabilities. The topics SEAD and A2/AD are analyses in an extensive literature review. A qualitative small-N study based on subject matter expert interviews is conducted in order to identify, how the way SEAD operations are executed must be adjusted based in the present SEAD capabilities in NATO

Contents

1 Introduction

February 24, 2022, marked an incision into the body of Ukrainian statehood and the mind of Western, specifically European defense and security architecture. The beginning of the brutal full-scale invasion by the Russian Federation's armed forces on Ukrainian sovereign territory, deemed irrational and unlikely by many analysts, constituted another act of salami slicing toward Russia's revisionist goals. (Massicot et al., 2023; Sakwa, 2019, p. 11) The previous landgrabs of South Ossetia and Abkhazia in the Russio-Georgian War in 2008 and the illicit annexation of Crimea, along with the occupation of the oblasts Donetsk and Luhansk in 2014, were left widely unreacted by European political leaders due to division among them, leaving Vladimir Putin with the expectation of another unpunished offense. (de Wijk, 2023, p. 74) The end of the Cold War was perceived as the "end of history" among Western European societies since apparently, no conventional war was to be feared. (Fukuyama, 1989) This postmodern perception allowed many European NATO allies to prosper on the peace dividends earned from continuously shrinking defense budgets while relying on the extended deterrence by the United States of America. The realization of this misperception in the face of Russian troops pushing toward Kiev forced a resolute and unified answer across Western leaders in support of Ukraine and an effort to stabilize the rule-based order, enforcing strong laws instead of a Russian autocratic approach of the law of the strong. Among those Western leaders was German Chancellor Olaf Scholz, who coined the term "Zeitenwende" as he proclaimed a substantial and permanent military budget raise and a down payment of 100 billion EUR, leading a wave of European leaders. On one side, this resulted in an immediate increase of military spendings to Cold War levels of 1989 and a total of 345 billion USD spent across Central and Western Europe compared to 86.4 billion USD spent by Russia in 2022 (SIPRI, 2023). On the other side, it soon became apparent that this was nothing more than a drop in the ocean of lacking equipment, personnel, and capabilities among European NATO allies after decades of underfunding. Capabilities that were thought to be obsolete based on military operations of the past 21 years suddenly became a prerequisite for national and allied defense of Europe again. Capabilities like the Suppression of Enemy Air Defenses (SEAD), a role of air power employment that constitutes an enabler to gain and maintain access to a contested operations area protected by large numbers of Ground Based Air Defense (GBAD) systems forming a network called an Integrated Air Defense System (IADS) as expected in the Baltic States or Eastern Poland in case of a confrontation between NATO and Russia.

Two reasons have led to a lack of SEAD capabilities in Europe. First, air operations since September 11, 2001, were focused on contributions to Counter Insurgency and Counter Terrorism Operations such as Close Air Support (CAS) against asymmetric adversaries in out of area operations as seen in Afghanistan (ISAF) or Iraq and Syria (Counter Daesh/Operation Inherent Resolve). (Wills, 2006, pp. 38–40) Since these asymmetric adversaries possessed little to no air defense capabilities, the past two decades were not demanding for SEAD operations, with the exception of Operation Odyssey Dawn in Libya in 2011. Second, the aircraft required to conduct SEAD operations, as well as weapons and equipment for this task are mainly dedicated, highly specialized developments and therefore expensive. Hence, other roles and capabilities of airpower employment have been prioritized. However, the Russian escalation in Ukraine has demonstrated that SEAD capabilities are not nice to have, they are a need to have to ensure freedom of movement in the air domain as a prerequisite for efficient operations on land and at sea.

"*In order to assure an adequate national defense, it is necessary—and sufficient—to be in a position in case of war to conquer the command of the air*." (Giulio Douhet, 2010, p. 28)

As Russian air defenses have continuously been renewed over the last decade, only two specially trained squadrons equipped with older but updated Tornado ECR aircraft have remained in Europe. This constitutes an essential lack of capabilities among European NATO allies. But can't just Uncle Sam bail European NATO allies and partners out? While the worldwide largest Air Force (US Air Force) and especially the second largest Air Force (US Navy) do have significant SEAD assets available, the US foreign policy Pivot to Asia leaves the European scenario with uncertainty. The 2014 US National Defense Strategy reduced the level of ambition for US force structure from an ability to fight two large-scale wars simultaneously to a fight in one large-scale and multiple other theaters. (Tama, 2018, p. 289) This trend was cemented in the National Defense Strategy Commission's assessment of the 2018 National Defense Strategy, stating that "The United States is particularly at risk of being overwhelmed should its military be forced to fight on two or more fronts simultaneously."

(Edelman et al., 2018, p. 7) While the US prioritization of the European scenario over the Indo-Pacific or vice versa remained open until 2022, the latest National Defense Strategy clearly prioritized China and the People's Liberation Army (PLA) over Russia as the main threat to the USA and shifted its main focus for defense and strategy planning. (*NDS*, 2022, pp. 4–5) In other words, US SEAD assets would prioritize the defense of Taiwan over Tallinn, should a NATO intervention be required in Europe simultaneously to a conflict against the PLA in the Indo-Pacific theatre.

These propositions lead to the central research question for this thesis:

Q: Does NATO have sufficient SEAD capabilities to counter the Russian IADS?

To differentiate between the various aspects involved, three hypotheses are derived from the research question, which will be either verified or rejected later on.

H1: The Russian Integrated Air Defense System as part of an Anti-Access/Area Denial complex is a powerful threat to NATO operations in Europe.

H2: NATO has the SEAD capabilities in Europe to counter the Russian Integrated Air Defense System threat.

H3: A traditional employment of SEAD capabilities such as Electronic Attack by Jamming and Anti-Radiation Missiles is a proper mean to counter the Russian IADS.

In order to answer these questions and verify or falsify the postulated hypotheses, the thesis is comprised of seven chapters. After the introduction in chapter one, the research design to explore potential solutions is presented in chapter two along with the delimitation of essential terms and a theoretical fundament for the discussion in the following chapters. Chapter three gives an introduction into SEAD as a role of airpower and elaborates on the changing character of SEAD operations through historical cases of SEAD missions. Chapter one through three are the foundation for a more nuanced analysis of both air defense capabilities and the suppression thereof. These two pillars form the core of the thesis. Chapter four points out to what extent the Russian armed forces' Anti-Access/Area Denial capabilities pose a security challenge for Western allies and partners in Europe on a strategic, operational and tactical level. Chapter five then explores SEAD capabilities that are available in NATO today and in the near future. Based on these findings chapter six develops different conceptual approaches to the employment of SEAD operations in the European theatre. Finally, chapter seven concludes with the findings of this thesis in relation to the research question.

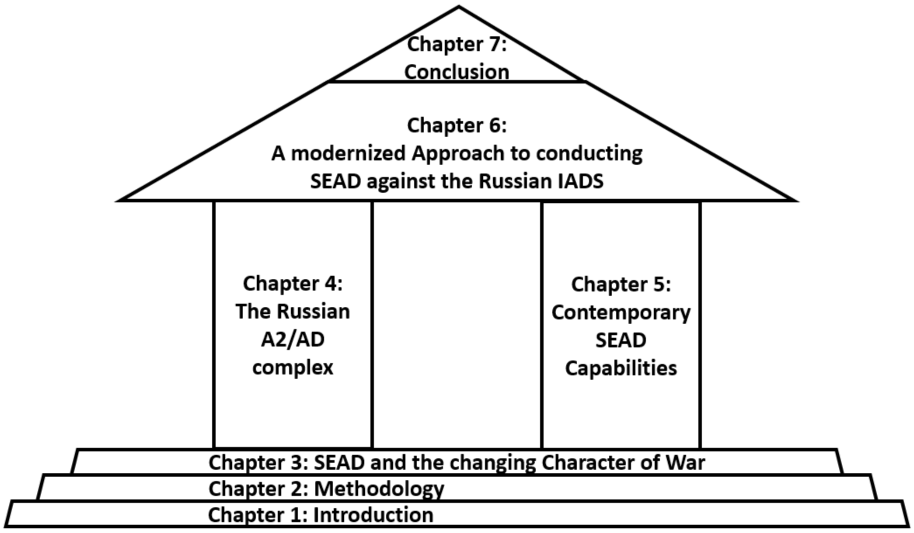


Figure 1: Structure of the thesis

2 Methodology and Theory

In „On War“ Clausewitz (1950) discusses in book two chapter three, whether war should be considered an art or a science. He points out, that thorough knowledge as an outcome of science is essential for correct judgement, which forms the basis for the art of putting knowledge into practice. War cannot be fought without either science or art but ultimately it is the art, the action on the battlefield based on good judgement, that matters most. The same holds true for SEAD as a discipline of warfighting. SEAD resides at the dividing line between the science behind gaining advantages and exploiting weaknesses in warfare in the non-tangible electromagnetic spectrum and relies heavily on technological advantages, while it succeeds through the practice of developing the most effective tactics, techniques and procedures (TTPs) and fielding them against an adversary’s air defense. In order to develop the theory behind SEAD and contribute to a deeper knowledge, “[…] so much is evident in itself, that this, like every other subject which does not surpass our powers of understanding, may be lighted up, and be made more or less plain in its inner relations by an enquiring mind, and that alone is sufficient to realise the idea of a theory.” (Von Clausewitz, 1950, bk. 2 chapter 3) Accordingly, this thesis seeks to contribute to improve the understanding around SEAD in NATO by adding to its epistemological foundation, respecting both, the science and the art behind it.

2.1 Research approach, design and method

Based on the research question for this thesis, there are two variables involved, SEAD capabilities and Russian IADS as a part of the A2/AD complex. Since the way the Russian IADS is structured lies outside of NATO's direct influence, the independent variable are the SEAD capabilities NATO can employ, while the Russian IADS is the dependent variable in the sense that the degree, by which the IADS is affected by SEAD operations varies depending on the SEAD capabilities employed. The resulting research problem is, how this dependence can be operationalized empirically. This operationalization is achieved by a variety of research approaches, designs and methods.

Regarding the research approach, there are a quantitative, a qualitative or a mixed option to choose from. (Jacobsen, 2016, pp. 24–31) A quantitative approach requires a numerically measurable research design and method. Since there are luckily no measurable data of real-world employments of SEAD against a Russian IADS based on observations from previous or ongoing conflicts against NATO, a simulation could generate the data required. Due to the classification level of this thesis being *unclassified – releasable to public* the exact parameters of Russian air defense systems and NATO SEAD assets can only be derived from open sources. Such a simulation is likely to be based on assumptions that are to far from the actual capabilities, resulting in generated data not meeting the requirements for scientific reliability. Alternatively, a qualitative approach relies on words rather than numbers and allows to observe the phenomena around the two variables on a conceptual level. It explores individual capabilities in depth by describing them, rather than measuring them and allows to point out their unique attributes. Therefore, a qualitative approach able to capture aspects of the art of SEAD was chosen for this thesis. This was however augmented by some quantitative measures in the form of calculations based on secondary data out of literature in order to emphasize the effects of some SEAD capabilities such as the effect of low observability in 5th generation fighter aircraft and the electronic attack capabilities of generation 4.5 aircraft representing the science in SEAD.

The research design is supposed to explore findings in line with the research question, utilize the chosen research approach and mainly assure the overall relevance of a research project by incorporating internal and external validity and reliability. (Jacobsen, 2016, pp. 16, 89) Internal validity is concerned with collecting the right data to answer the research question i.e., to collect the data that describe the causality between the observed variables and not any other variables that might also affect the observed ones. (Nyeng, 2018, p. 109) External validity is a measure of the generalizability i.e., can the findings of this research project be applied to another context. Reliability describes to what extent the results of a research project are correct and reproduceable and is influenced by the quality of the sources used and the accuracy in data analysis. (Denscombe, 2017, p. 298) This thesis employed a combined design comprised of a descriptive single-case study based on a qualitative literature analysis and a small-sample study (N=5) utilizing interviews. A descriptive case study design was chosen as this offers an ideal focus on the specific interaction between the variables Russian IADS and SEAD capabilities limited in time and space. The space was defined as Europe, the time as the time of writing up until 2025 to obtain a focus on the status quo. Additionally, the case study was further restricted to Russian IADS capabilities in the domains land and air. The Russian Baltic Fleet, apart from its primary purpose to counter maritime threats, has multiple assets with both long range land attack and medium range air defense capabilities but was not considered in this thesis, since it would exceed the overall length restriction of the document. The case study formed the theoretical pillars of the thesis and enhances its internal validity. Furthermore, it enabled the second research design, the small sample study. The findings of the literature review were reflected in the interview guide that was used to collect the data for the small sample study, in turn further increasing the internal validity. Additionally, reliability was enhanced by the selection of interview respondents. The interviews were conducted with subject matter experts in the fields IADS and SEAD capabilities distributed across different nationalities (UK, Norway, Germany, Sweden, Greece), organizations (NATO, German Air Force, RUSI, FFI, FOI) and affiliations (2 military aircrew, 3 civilian researchers), all of which have conducted extensive research in one or both fields or have relevant operational experience, which allowed a wide reflection angle on the case study and added depth to the thesis' findings enabling a thick description.

The research method chosen were structured individual interviews, providing a blend of guidance towards the thesis research question and the freedom to answer each of the nine questions asked extensively. Questions were focused on the discussion of A2/AD in present literature, the Russian IADS, SEAD Capabilities and NATO's ability to counter the Russian IADS with or without US Support employing either airborne means only or joint means. The interviews were conducted via an online video meeting software and took circa 45 minutes. The collected data were transcribed and both manually categorized across all respondents and automatically processed and clustered by data analysis software.

However, the chosen research design has some inherent limitations. Both the case study and the small sample study are designed to explore a narrow topic in a detailed manner. The downside to this design is, that the study lacks generalizability, as it only looked at a single case limited in time and space, as opposed to different IADSs like in Iran or China or over a longer time period. (Jacobsen, 2016, p. 100) The findings based on the European geography, as well as present NATO SEAD capabilities and Russian IADS assets only have a limited relevance for other scenarios. Therefore, the research design lacks external validity as a tradeoff for the scrutiny required to cover this highly relevant topic adequately. Additionally, the selection of research units i.e., the subject matter experts chosen to participate as well as the low number of respondents interviewed had an influence on how the theory was interpreted by the author. Therefore, a larger number of respondents e.g., an equal number of Russian experts could have further triangulated the findings and thereby increased the internal validity. (Denscombe, 2017, p. 346) Furthermore, given the authors background as a trained SEAD aircrew one might see the objectivity of the study compromised as a number of biases can apply like the my-side bias, favoring to highlight strengths of Western capabilities and point towards weaknesses of Russian systems or the confirmation bias, trying to prove preexisting assumptions rather than to neutrally observe the data collected and draw conclusions starting with a clean sheet. (Dobson-Keeffe & Coaker, 2015, p. 9) This was mitigated by the awareness of potential biases, the incorporation of opinions other than the author's through the conducted small sample study and the application of good research practices and ethics, honoring the researchers responsibility to society by openly pointing out how data were collected and applying general data protection regulations according to Norwegian standards. (Jacobsen, 2016, pp. 55–56)

2.2 Central Terms, Theory and Delimitation

Before the core topics of this thesis are tackled in chapters three (SEAD), four (Russian IADS as part of the A2/AD complex) and five (NATO SEAD capabilities), there are a few terms that help to delimitate the scope of this thesis and contribute to a clearer understanding of the discussion later on.

The first term to be clarified is *peer adversary* as used in the title. The term originates in the discussion of great power competition. Waltz (2010) defined a set of parameters that allows to compare the power of nation state actors in order to determine their role in realpolitik. Based on the measures of the"[…] size of population and territory, resource endowment, economic capability, military strength, political stability and competence […]", great power competition has changed from unipolarity, with the USA as the single great power after the end of the Cold War, to bipolarity with China as an emerging actor with unprecedented economic growth rates over the past decades. (Waltz, 2010, p. 131) Due to the closing gap in those measures between China and the USA, China is referred to as a near-peer or peer competitor, depending on whether China is perceived to be still catching up or has already caught up to the USA. Opposed to China, Russia lacks the economic capability, the conventional military strength and the technological sophistication, apart from its status as a nuclear power, to be considered a peer competitor and a great power. (Tunsjø, 2018) Yet, the scope of this thesis is limited to the military competition between the armed forces of the Russian Federation, referred to simply as Russia, and NATO forces in case of an article five intervention on the European continent, further funneled in to NATO capabilities for the Suppression of Enemy Air Defenses against the wide range of Russian assets in its Integrated Air Defense System with focus on land-based assets. In this particular niche, Russia is considered a peer adversary for this thesis, especially, should NATO allies in Europe be forced to defend themselves without US support.

The second frequently used term of interest is *air power*. NATO AJP 3.3 defines air power as: "The ability to use air capabilities to influence the behaviour of actors and the course of events." (*AJP-3.3*, 2016, pp. 1–2) The core attributes of air power, speed, reach and height enable air power assets to quickly deploy to an operations area and cover large distances in a short timespan both, over land and sea. This unique set of abilities causes air power to often be the first responder in case of crisis or conflict. To fulfill its task of gaining and maintaining control of the air as well as enabling and supporting joint operations, four roles of airpower can be distinguished. Counter air operations aim at control of the air, attack operations either deliver strategic effects or target an adversary's land and sea operations. Other roles are air mobility and the contribution to Joint Intelligence, Surveillance and Reconnaissance (JISR) operations. Part of counter air operations are Offensive Counter Air (OCA) operations and Defensive Counter Air (DCA) operations. SEAD, in its role of denying the enemy control of the air by engaging the enemy's GBAD is a subset OCA. (*AJP-3.3*, 2016, p. .1-9)

GBAD systems often rely on radar emissions, which are part of the *Electromagnetic Spectrum* (EMS). The EMS transcends all physical domains and is characterized by frequency, energy and time. It ranges from audible, low frequencies over radio frequencies organized in different radio frequency band nomenclatures, microwaves and infrared heat waves, visible spectrum waves to high energy gamma waves. (Curtis E. Lemay Center, 2019, p. 2)

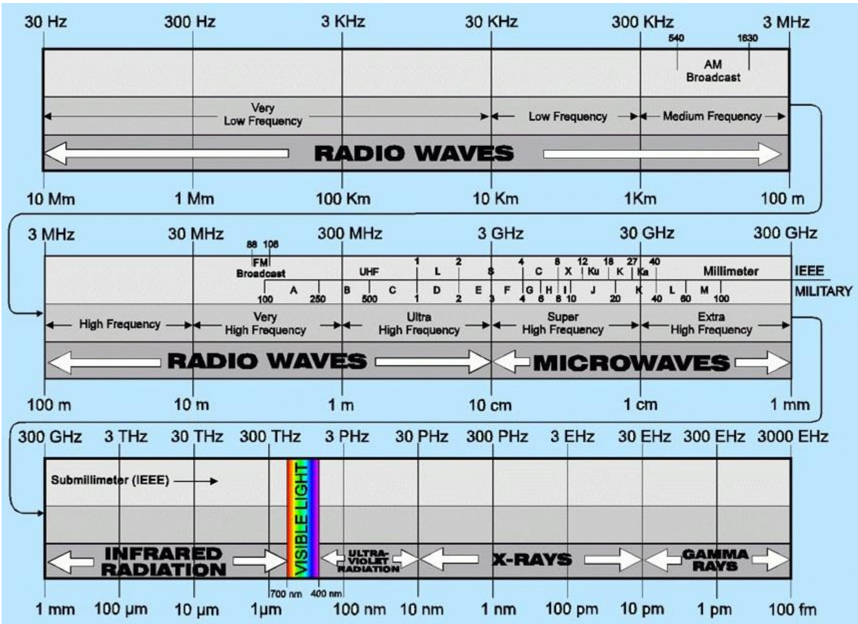


Figure 192: The EMS and Frequency band designations (Tsirlis, 2020, p. 74)

Generally, a low frequency wave has a high wavelength and vice versa. This is because electromagnetic waves propagate at the speed of light, resulting in the following formula for wavelength, where λ (lambda) is the wavelength, c is the constant for the speed of light and f is the frequency.

$$\lambda = \frac{c}{f}$$

Most relevant for EMS Operations for the air power role SEAD are the radar frequencies and infrared frequencies, since these are used by GBAD for target detection and engagement. As the name Radio Detection and Ranging (RADAR) implies, electromagnetic waves are used to locate an object's position in space. An electromagnetic wave is created, when an alternating current is applied to an antenna. The detection starts with a radar transmitter antenna sending electromagnetic waves for a specific time period called pulse width. The emission is then reflected by the tracked object back to the radar. Since electromagnetic waves propagate at the speed of light, the signal run time until the reception of the reflected emission at the radar receiver allows to determine the range. An alternative working principle to a pulsed radar previously described is the continuous wave radar, that constantly emits radar signals and modulates the frequency to determine when a particular frequency was send and received again in order to determine the signal run time. In a pulsed radar, the longer the emission lasts, the higher the radar range but the lower the range resolution, while the height and width of the radar beam emitted determine the accuracy in elevation and azimuth. The beamwidth is usually defined by an angle off antenna boresight, where only half of the peak radiated power, the -3db point, is emitted.

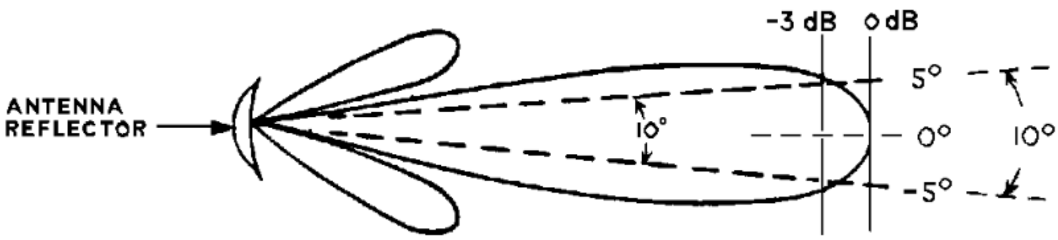


Figure 193: Beam width and side lobes of a parabolic antenna (*NAWCWD TP 8347*, 2013, p. 10 1.1)

Higher frequencies with smaller wavelengths allow a more accurate position finding at the expense of higher emitted power requirements to achieve the same range compared to radars operating with lower frequencies and longer wavelengths. Alternatively, at constant energy output, the radar range is reduced at higher frequencies. Usually, the radar antenna design determines the directional precision of the emitted radar beam. Older parabolic design radar antennas show higher scattering of emitted radar signals, form unintended sidelobes and therefore achieve a lower antenna gain. Modern Active Electronically Scanned Array (AESA) radars emit hundreds or thousands of narrow, precise beams forming either a single, focused high-power beam or multiple precision beams simultaneously. AESA radars are capable of high frequency agility i.e., frequency hopping in a pseudo random frequency pattern. This is difficult to detect for the opponent as a wide frequency range must be monitored permanently to intercept a transmission. Hence this capability is also referred to as low probability of intercept (LPI). (*NAWCWD TP 8347*, 2013, pp. 3-7.2-3-7.3) The same frequency agility characteristics also reduce an AESA radar's susceptibility to jamming. Another aspect influencing radar range is the tracked object's radar cross section (RCS) often labeled σ (sigma). It describes the area reflecting electromagnetic energy back to the radar based on the object's size and shape and the wavelength emitted.("Radar Fundamentals

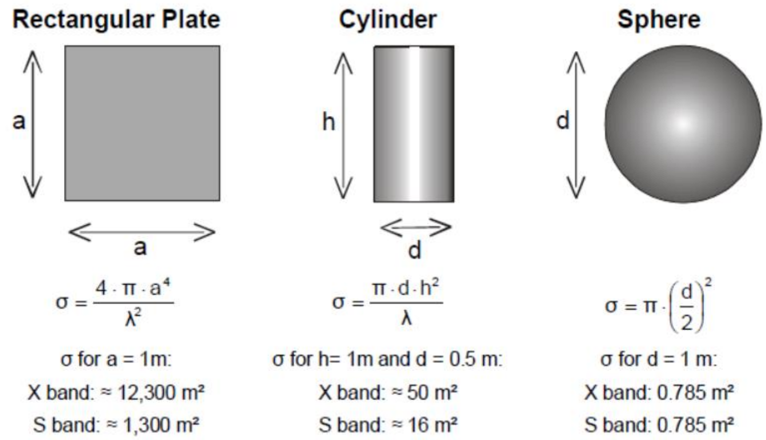
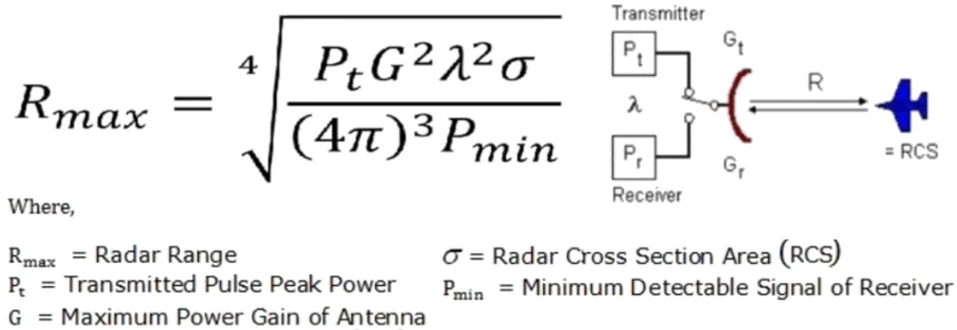


Figure 194: RCS is a function of size, shape and wavelength("Radar Fundamentals (Part II)," 2016)

(Part I)," 2016)

Now that all variables have been introduced, a look at the maximum radar range formula is taken:

The transmitted pulse peak power, the antenna power gain and the wavelength as well as the minimum detectable receiver signal are all considered constants for a respective radar design. Therefore, the primary modifier for maximum radar range is the radar cross section



of the tracked object. This simplifies the range equation to a proportionality of R_{max} to the 4th root of the RCS (σ). (Zikidis et al., 2014, pp. 135–136)

$$R_{max} \propto \sqrt[4]{\sigma}$$

For example, all other things being equal, against a generic radar, the detection range of a Rafale fighter jet with an approximated RCS of $\sigma=0.1m^2$ or $-10dBm^2$ is approximately three times higher than the detection range of an F-35 with $\sigma=0.001m^2$ or $-30dBm^2$.

An alternative to a low RCS as a means to reduce an air defense radar's maximum range, is to exploit the curvature of the earth. Since most radars rely on line of sight to the target the tracked aircraft can avoid radar detection by flying at low altitude. The detection range depends on the radar antenna height (h_{radar}) and the tracked objects altitude (h_{target}). The detection range at which the aircraft appears at the horizon can be calculated as follows:

$$R_{NM} = 1.23 \sqrt[2]{h_{radar}} + \sqrt[2]{h_{target}}$$

It must be mentioned though, that there are certain long range radar systems that can track targets beyond the line-of-sight restricted radar horizon and are discussed later in the thesis.

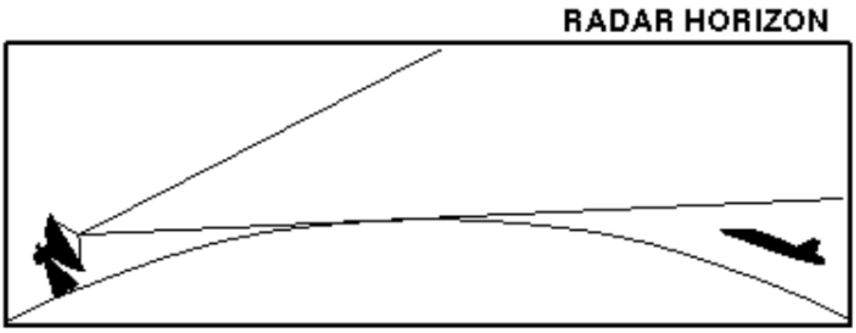


Figure 195: Radar horizon (*NAWCWD TP 8347*, 2013, pp. 2-9.1)

Once an aircraft is detected and approaches the missile engagement zone (MEZ) of an air defense system, one of three guidance types is used to intercept the target with a Surface to Air Missile (SAM). Command guidance sends steering commands to the missile based on the radars updated target track. Semi active radar homing requires a missile with a passive radar receiver. The missile steers toward the reflected radar emissions coming back from the target. Active radar homing requires a missile with an active radar seeker head. The missile is initially launched under guidance of a ground radar. Once the missile seeker acquires the target, the missile's own radar is used, offering higher precision under closing distance and a fire and forget capability. (Bronk, 2020, pp. 3–4)

In order to disrupt the tracking and engagement by a ground radar, a technical capability called *Jamming* can be utilized by the defending aircraft. Jamming is defined as "[…] the deliberate radiation, re-radiation, or reflection of EM energy for the purpose of preventing or reducing an enemy's effective use of the EMS, with the intent of degrading or neutralizing the enemy's combat capability." (Curtis E. Lemay Center, 2019, p. 28) It can be conducted as either Stand-off jamming (SOJ), Stand-In Jamming (SIJ) or Self-Protection Jamming (SPJ). SOJ is employed when the jammer remains outside of the MEZ while supporting other assets, requiring a precise positioning of the stand-off jammer on an axis from the radar to the protected asset. Alternatively, SIJ can be conducted when the jammer enters the MEZ in order to support other assets that are further away from the radar. A more flexible placement of the supported assets comes at the price of a possible targeting of the jammer.

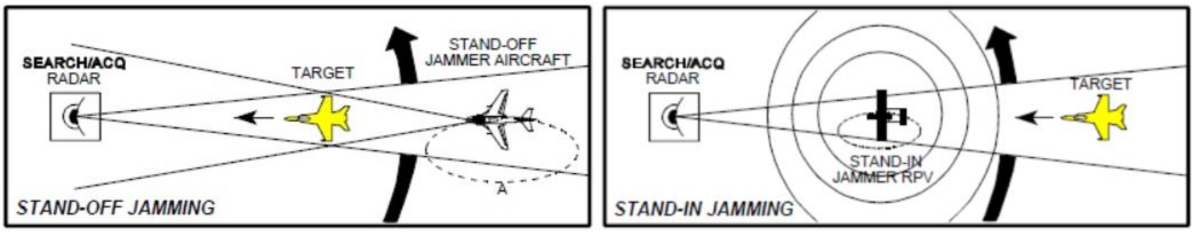


Figure 196: Positioning of the jammer in relation to the protected assed for Stand-Off and Stand-In jamming. C.f. Figure 2 in NAWCWD TP 8347 (2013, pp. 4-7.2)

Lastly, SPJ refers to jamming operations without other supported assets involved, mainly as a defensive measure to enhance survivability when targeted. A wide range of jamming techniques can be employed, with two subtypes, noise jamming and deception jamming. Noise jamming clutters the ground radars detection at the sector, where the jamming occurs, in turn denying the radars ability to locate aircraft in that sector up to a certain point. The point where the radar power overcomes the jamming signal is known as burn-through. (*NAWCWD TP 8347*, 2013, pp. 4-8.2) Noise jamming can be conducted as spot jamming, where a particular frequency is jammed with high power output or barrage jamming, where a wider range of frequencies is jammed at a lower power output per frequency. Instead of "blinding" a certain sector of the ground radar by putting out large amounts of electromagnetic energy in noise jamming, deception jamming is aimed at altering the aircraft position, size, speed, or the number of aircraft on the radar scope, in turn spoiling the targeting solution of the ground radar. This is enabled through a technology called Digital Radio Frequency Memory (DRFM), that allows to record and analyze radar emission of a ground radar and then reply pulses that do not match the actual received signal at the ground radar. This allows to manipulate the target range from the radar (range gate pull in, range gate pull out), the speed (velocity gate pull off) or the target position (inverse gain) among a variety of other deception techniques tailored to the ground radar type. ("Electronic Countermeasure (ECM)," 2016) Since a jamming signal only needs to travel from the jammer to the radar and not back to the jammer again as opposed to the radar signal, the power output of the jammer can be much lower. The jammer range is only affected by range between radar and target to the power of two as opposed to radar range affected by range between radar and target to the power of four. This signal attenuation per one way travel is also called the inverse square law. This means a more considerable advantage for the jammer at long distances to the radar, that eventually decreases with reduced distance. Accordingly, depending on jamming technique used, ground radar power and antenna design, jammer radar power and antenna design, radar cross-section and range between protected asset and ground radar, a point where the jamming signal strength (J) equals the radar return signal strength (S) can be calculated. This pint is called burn-through. Accordingly, the range at which burn-through happens is called burn-through range. This range is calculated by the following formula (*NAWCWD TP 8347*, 2013):

$$R_{BT} = \sqrt[2]{\frac{P_t \cdot G_t \cdot \sigma \cdot J_{\min eff}}{P_j \cdot G_{ja} \cdot 4\pi \cdot S}} \quad \text{where} \quad S = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot R^4}$$

R_{BT}	*- Burn through Range*	$J_{\min eff}$	*- Minimum effective jamming signal*
P_t	*- Power of transmitter*	P_j	*- Power of jammer transmitter*
G_t	*- Gain of tranmitter antenna*	G_{ja}	*- Gain of jammer antenna*
G_r	*- Gain of receiver antenna*	σ	*- Radar cross section*
R	*- Range from Radar to Target*	λ	*- Wavelength*

This shows, that jammer power P_t and RCS σ have a linear relation. When the RCS of the protected assets is 100 times lower, as in the previous example between a Rafale and the F-35, the jammer power can also be 100 times lower to achieve the same Burn-through Range. On the other side, the jammer power required increases by the power of two for a further decrease of Burn-through range. To summarize, the RCS of an object has an influence on the maximum radar detection range in relation to the fourth root of σ. The burn-through range is influenced by the square root of σ. σ has a linear impact on the jammer power output requirement.

3 SEAD and the changing Character of War

The previous introduction into fundamental working principles of radars, the targeting of which is an essential task of SEAD, showed how deeply this role of air power is woven into the fabric that makes up the electromagnetic spectrum. SEAD offers a vector to achieve effects in a pervasive and ubiquitous domain interlinking both air, land, sea, space and cyber. Ultimately the task of SEAD lies in its semantic. Generally, an effect against an enemy's air defense systems is achieved. This chapter discusses the underlying concepts of SEAD, lessons learned from precious SEAD campaigns and discusses whether the resulting expectations can be applied to conduct of SEAD in a conflict with a peer adversary in Europe. Capabilities and assets will be covered in chapter 5.

3.1 A SEAD Taxonomy

The Joint Publication 3-01 on Countering Air and Missile Threats (2018, p. I–6) defines SEAD as an "Activity that neutralizes, destroys, or degrades surface-based enemy ADs by destructive and/or disruptive means." This definition points out two things. First, what SEAD does is neutralize, destroy or degrade enemy air defenses. Expressed in a different order this can be summarized under the acronym ASK – Avoid, Suppress, Kill. Second, how SEAD does it is through destructive and/or disruptive means. This emphasizes that SEAD operations are already effective, when enemy air defenses are disrupted. Air defense system do not need to be destroyed for SEAD to deliver the desired effects. Effects are the denial of an enemy's capability to attain control of the air. This is pursued by targeting the enemy air defense systems that contest it through a variety of means. Hence, SEAD contributes to gaining air superiority i.e., control of the air in a limited space and time with potential adversary interference, or air supremacy i.e., control of the air of a specific space in which the adversary is unable to interfere. In order to cover the multifaceted

The Science - SEAD in Electromagnetic Spectrum Operations

Although most SEAD operations affect the EMS, not all types of EMS Operations (EMSO) contribute to SEAD. EMSO is a term used interchangeable with electronic warfare or more accurately electromagnetic warfare (EW). The Joint Publication 3-01 definition clarifies that only those EMSO, that have an effect on the enemy's air defense systems are considered SEAD. Other EMSO not counted toward SEAD include Electromagnetic Support Measures

(ESM) and Electromagnetic Protection Measures (EPM). ESM, among others, are the detection of threats through the Radar Warning Receiver (RWR) or the localization of threats by the use of an Emitter Locator Systems (ELS). EPM on the other side are measures to deny the enemy control of the EMS and are comprised of active measures such frequency agility during radio transmissions are radar operation or passive measures such as Emission Control (EMCON). (Curtis E. Lemay Center, 2019, p. 21) While ESM and EPM indirectly enable SEAD, the part of EMSO that is at SEAD's core are Electromagnetic Countermeasures (ECM). While

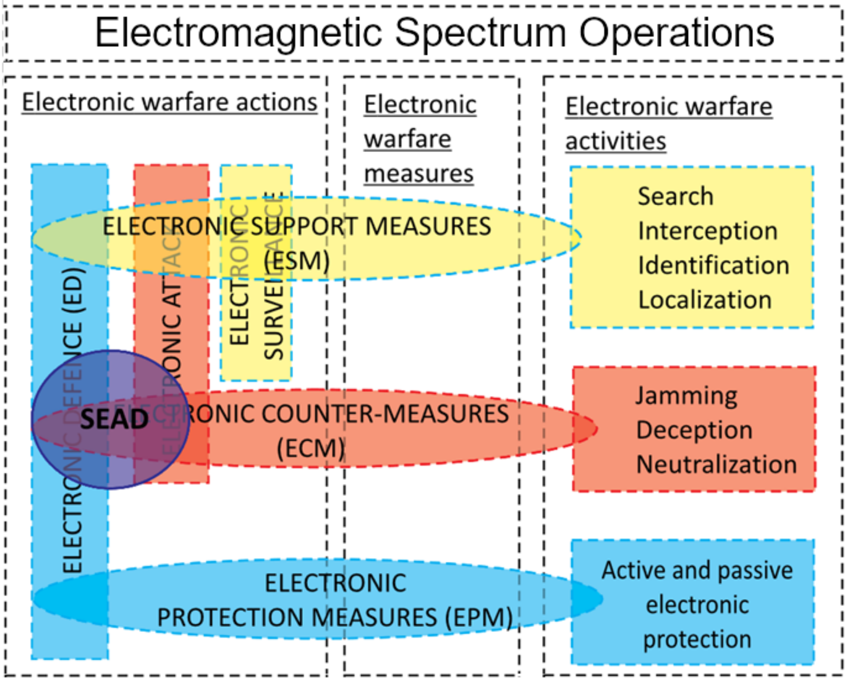


Figure 197: SEAD in Electromagnetic Spectrum Operations. Modified version of Figure 4 by Şerbeszki and Ignat (2019, p. 44)

there are also defensive countermeasures such as chaff, flares, self-protection jamming, towed decoys or design features like low observability, it is the Electromagnetic Attack (EA) capability of ECM that is relevant for SEAD. EA is implemented through two capabilities, support jamming and the employment of Anti-Radiation Missiles (ARM), both of which are the reason why SEAD is categorized as offensive counter air operations.

The Art - Tactical Implementation of SEAD

There are different avenues of approach to distinguish between the action chosen to conduct SEAD operations and the means of SEAD they are linked to in order to achieve battlefield effects. The means according JP 3-01 are denial, degradation, destruction and disruption. (U.S. Joint Chiefs of Staff, 2018, p. IV–13) Denial is achieved when an enemy's air defense system is hindered to obtain information about friendly forces and is usually achieved without physical damage. Degradation refers to a permanent partial or total impairment of an enemy's AD system, usually caused by physical damage. Destruction is the permanent and total elimination of an AD system. Disruption refers to the temporary denial, degradation, delay or neutralization of enemy AD systems. (U.S. Joint Chiefs of Staff, 2018, p. IV–13) SEAD actions to achieve the mentioned means can be lethal and non-lethal as well as kinetic and non-kinetic. (Şerbeszki & Ignat, 2019, pp. 46–47) The differentiation between kinetic and non-kinetic effects applies directly to the two EA options identified for SEAD. Support jamming is a non-kinetic effect as it only electromagnetic waves in order to deny or disrupt enemy AD systems. The use of ARMs on the other hand is considered kinetic, as it is supposed to achieve physical effects on the ground mainly through fragmentation, in turn causing a degradation of an enemy's AD systems. By design, an ARM more specifically seeks to degrade the radar of the targeted AD system as it homes in on the received radar signal utilizing a passive radar seeker head. Since SEAD can also be divided into lethal and non-lethal effects, with jamming as a non-lethal option, this working principle is an important aspect for the argument of how an ARM is designated. As long as the radar emitter is cooperative and radiates throughout the ARM's time of flight, the ARM has a high probability to degrade or soft-kill and a lower probability to destroy or hard-kill the AD system and therefore achieve lethal effects. However, in case the AD radar does not emit during time of flight, the probability of achieving lethal effects and degrading the system is low, especially if the targeted system is mobile. Should the air defense system have stopped its emission deliberately, since it was aware of being targeted, then the ARM's effect is non-lethal as it denied radar tracking and disrupted the AD system operation. Therefore, it is the AD system, that determines, whether the effect of an ARM is lethal through degradation or destruction or non-lethal through denial and disruption. Furthermore, this observation leads to the conclusion that an ARM is ultimately a suppression weapon designed for SEAD, not a destruction weapon optimized for DEAD. (see Appendix 4) Nevertheless, the likelihood of an emitter radiating while an ARM is inbound, can be influenced by confronting it with a dilemma, when targeted by other means such as precision guided munitions or stand -off weapons. Should the AD system's operator decide not to radiate, the system gets destroyed by a bomb. Should the operator decide to target the bomb, it is more likely to get hit be the ARM. This approach is called a saturation tactic since the AD system can only target a limited number of targets simultaneously and requires a certain time to execute the targeting cycle. The assets available for the tactical execution of SEAD operations provide some inherent characteristics, that determine, which effects they are capable to achieve. The support jamming capability of SEAD is realized by Stand-off Jamming, Stand-In Jamming or a third, combined form that underlines SEAD's support role. To conduct Escort Jamming, the jammer moves through the Area of Responsibility (AOR) in the vicinity of the protected asset utilizing both, SOJ for denial when operating near enemy SAM systems and SIJ when required to penetrate a SAM system MEZ, creating a disruptive effect. The only asset in NATO's repertoire capable to conduct airborne electronic attack operations by support jamming is the US Navy EA-18G "Growler", that carries a total of three AN/ALQ-99 jamming pods, two operating at high frequencies of 7.8 up to 20 GHz and one at low frequencies down between 68 and 500 Mhz. (Pike, 1999) In addition it is capable of carrying two AGM-88 E ARMs, also known as Advanced Anti-Radiation Guided Missile (AARGM) alongside two AIM-120 AMRAAM active air to air missiles. Furthermore, the Growler is equipped with an AN/APG-79 AESA-Radar with Synthetic Aperture Radar (SAR) and Moving Target Indicator (MTI) modes, as well as an AN/A Emitter Locator System integrated in the wingtip stations. This combines all aspects of SEAD in one platform, making it the most capable dedicated SEAD asset worldwide. In lack of a SOJ platform among European NATO members, there are five AGM-88 High Speed Anti-Radiation Missile (HARM) user nations in Greece, Italy, Germany, Spain and Turkey. While Turkey is in the process of replacing the AGM-88 by a domestic development called Akbaba (vulture), most likely as reaction to losing the USA's goodwill and being banned from the F-35 community after the procurement of the S-400 Triumf Air Defense system (D. T. Withington, 2021), other HARM users such as Greece, Germany and Italy upgrade their HARMs to the newer AGM-88 E AARGM. Only Spain keeps its stockpile of older AGM-88 missiles, that needs to be integrated with the Eurofighter Typhoon once the aging fleet of F-18 A/Bs retires in 2030. A basic integration of the HARM can be achieved quickly as the Ukrainian Air Force has proven with its MiG-29s ("HARM Missiles," 2022). However, in order to target a SAM system with increased precision, the HARM's seeker head should not be used as the sole source of target acquisition. Hence, dedicated SEAD assets like the German and Italian Tornado ECR employ a built-in Emitter Location System (ELS) or a pod-based solution like the HARM Targeting System (HTS) on US Air Force F-16CM in order to find, fix and track enemy AD systems. Such a system is absent in Greek and Turkish F-16s as well as the Spanish F-18 employing the missile and therefore lack the high level of platform dedication required to fulfill the SEAD mission. However, it is important to note, that neither the Tornado ECR nor the F-16CM feature support jamming capabilities and in turn also lack an essential part of the SEAD actions available. Another SEAD asset is the F-35 although often overlooked in this particular capability. With an approach opposite to e.g., the Greek F-16, since the latest version of the HARM, the AARGM-ER has not yet been cleared for operation with the F-35 at the time of writing yet and only limited support jamming capabilities, the unprecedented level of sensor fusion of different ESM and network inputs allow it to quickly gain Situational Awareness (SA) in the EMS and target air defense systems with e.g., glide bombs. This skill is practiced in basic F-35 training already and therefore should be considered by NATO SEAD planners. (Binnendijk et al., 2020, p. 129) Generally speaking, while the HARM ensures suppression by disruption at least during missile time of flight, should the AD system stop radar emissions, or even suppression by degradation should the AD systems radar emitter be cooperative and continue to illuminate its target during HARM time of flight, the lack of support jamming limits effects to the two or four HARMs carried by the weapons platform. Unless the enemy AD system stops emission due to the sole presence of a HARM shooter, in turn enabling suppression by denial, the HARM can only provide SEAD support for a limited time frame. Support jamming on the other side is available as long as the jammer asset can remain on station, hence enabling a disruption of the jammed AD system over a prolonged time period. The drawbacks of support jamming are, that a close coordination between jammer and protected asset is required to enable a proper jammer placement in order to achieve the desired effects. Furthermore, effects are limited to the burn-through range against a specific AD radar and are non-kinetic and therefore disruptive by nature, limiting its application, where destructive or degrading effects are required. In conclusion, airborne SEAD is most effective, when multiple actions are combined into the art of SEAD tactics. This diversification of actions can also include means of Joint SEAD operations. The list from long range land attack by maritime assets, direct and indirect fires by ground forces such as rocket artillery systems, the employment of Special Operation Forces (SOF) as well as Offensive Cyber Operations

(OCO) are only a few of a wide range of options beyond the conventional air power view on SEAD. (Gebhard, 1993, p. 39; Şerbeszki & Ignat, 2019, p. 43)

The Scope of SEAD Operations

SEAD doctrines commonly divide SEAD operations into three categories based on time and space of SEAD operations. These three categories are AOR-/JOA wide AD System Suppression, Localized Suppression and Opportune Suppression. (U.S. Joint Chiefs of Staff, 1995, p. III-1-III 11, 2018, p. IV-13-IV 15; U.S. Marine Corps, 2001, pp. 1–10) First, AOR-/JOA wide AD system suppression aims at strategically important nodes in the enemies Integrated Air Defense System. These nodes are typically C2 nodes and can be distributed over the entire AOR. Therefore, the duration and area of this type of SEAD operations depends on the size of the AOR, the number of C2 nodes, other critical elements, and the level of integration and redundancy in an IADS, which can vary to a large extent depending on the adversary. Second, the Localized Suppression is conducted in a confined geographic area at shifting locations in the AOR. Localized Suppression is often executed as an escort mission directly supporting operations of another component upon request and if the component lacks the organic SEAD capabilities required. It can be preplanned, when the requesting component has identified AD system threats affecting their task beforehand, or immediate when a threat arises during mission execution comparable to CAS. Third, Opportune Suppression deals with pop-up or moved AD threats. Upon relocation, an AD system targeted via Localized Suppression turns into an Opportune Suppression tasking. More specifically Opportune Suppression is divided into self-defense, target of opportunity when a new target is picked up by an ESM sensor, targets acquired by observers such as UAVs or ground forces and targets acquired by aircrew, which cannot be targeted by the aircrew itself due to target prioritization or weapons limitations. All four types of Opportune Suppression have in common, that a clearly defined set of ROE is necessary to give an aircrew guidance since these targets have not gone through the regular targeting process during mission planning.

The following figure summarizes the different concepts and considerations for conducting SEAD operations introduced in this chapter.

3.2 SEAD Campaigns of the Past

With a better understanding of how SEAD operations can contribute to countering an adversaries Air Defense System, this chapter now introduces different historical examples for SEAD campaigns ranging from the USA in the Vietnam War, the US war against Iraq in operation Desert Storm, NATO's Operation Allied Force intervening in Kosovo and Operation Odyssey Dawn in Libya. Special emphasize will be put on the structure, complexity and the level of integration of the enemy's air defense systems in the respective cases in order to deduct, whether observations form these campaigns can be transferred to a possible war between NATO and Russia in Europe today.

Vietnam War 1965-1973

In 1965 US President Lyndon B. Johnson ordered an offensive against the communist North-Vietnamese Army (NVA). The US Air Force conducted Air Inderdiction (AI) strikes in otder to cut off the lines of communication to the country's south an destroy military equipment. Due to technological advantages, the US F-4C fighter aircraft were able to gain air superiority against the North Vietnamese MiG-21 and MiG-19 fighters while avoiding the NVA's Anti-Aircraft Artillery (AAA) through medium altitude operations, effectively overflying the Air Defenses, in turn neutralizing them. Initial intelligence reports of newly developed, Soviet built S-75 (NATO SA-2 Guideline) Surface to Air Missile (SAM) systems and the NVA's plan to construct a network of these SAMs were ignored. This failure in assessing the relevance of

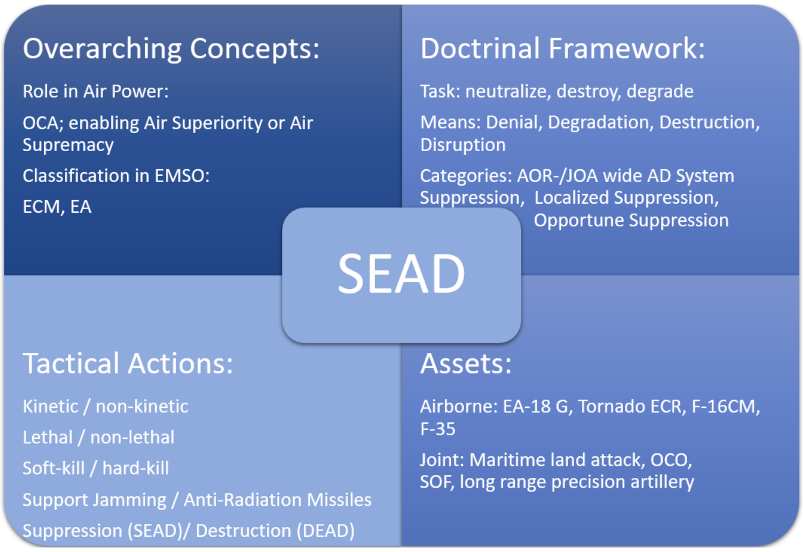


Figure 198: Taxonomy of factors affecting SEAD capabilities

this technical novelty proved to be costly soon. On 24 July, 1965 the first F4-C was brought down by an SA-2. By the end of 1965 the NVA had rolled out 60 SA-2 sites, accounting for 25 of the 171 losses of US aircraft in 1965. (Brungess, 1994, p. 5) The US Air Force answer to this new and by then recognized threat was a specialized variant of the F-100 equipped with basic ESM equipment enabling it to locate the SA-2 sites. Once a SAM system was localized, the F-100 pilots would enter the MEZ and target the site with unguided missiles. The high-risk profile of this type of mission was soon reflected in the term “Wild Weasel” operations, still used for SEAD missions with preplanned penetration into the MEZ today. To mitigate the risk involved, further technological developments were deployed, among them the integration of the Anti-Radiation Missile AGM-45 Shrike in the F-105G and the introduction of jamming capabilities by the EA-6 Prowler. The initial success of these measures was soon countered by a rudimentary integration of the SAM systems via a C2 system based on land line communication, constituting a basic IADS. Furthermore, more capable S-125 Neva (NATO SA-3 GOA) SAM systems, operating in different frequency bands than the SA-2, forced the US Air Force to adjust again. As the losses due to SAMs kept counting, a decisive reaction was conducted in 1972. In operation Linebacker II, the first coordinated use of EA capabilities in form of ARMs and jamming in support of B-52 bombing raids was observed. This operation successfully disrupted the Vietnamese IADS, in turn allowing the US Forces to gain air superiority and exploit the means of air power through massed bombing attacks, eventually forcing the NVA to seek cease-fire negotiations. (Thompson, 2000, p. 280) At the end of the Vietnam War, the US Air Force had conducted 219,407 sortied resulting in 1,437 combat losses due to air and ground threats, an attrition rate of 0.65 percent. Out if these, 11,389 SEAD sorties were conducted, accounting for 5.2 percent of the total sorties. (Bolkcom, 2005, p. 5) During the course of the war the coordinated use of SEAD capabilities, set the foundation of what later evolved into the electronic attack triad, consisting of HARM equipped F-4G, dedicated radar jammers like the EF-111A Raven and communication jammers such as the EC-130H Compass Call, the latter of which is still in service today. (Saldik, 2021, p. 4)

Desert Storm 1991

Operation Desert Storm commenced on January 17, 1991 as a UN resolution based, US led multinational intervention in Iraq and Kuwait. The Iraqi armed forces under command of

Saddam Hussein had previously occupied Kuwait in a two-day offensive on August 2 and 3, 1990. After Operation Desert Shield, which comprised the prepositioning and logistics for Desert Storm from August 1990 until January 1991, 46 percent of the US Tactical Air Command assets along with 100 percent of US Marine Corps airborne assets and two Navy carrier strike groups were stationed in the Gulf region. On the other side stood the most advanced IADS of the time. Iraqi MiG-25, MiG-29 and Mirage F-1 fighter aircraft were ready to be employed by Ground Controlled Intercept (GCI) stations relying on an extensive radar network made up of ground-based radars. The air defense consisted of 17,000 SAMs of Soviet and Western origin such as the SA-2, 3, 6, 8 and 9, Roland and I-HAWK along with 10,000 AAA piece. (Brungess, 1994, p. 38) The large and extensive IADS required US forces to adjust their tactics from previous campaigns. Rather than focusing on finding Iraqi SAMs, ISR operations were focused on a "critical node analysis" in order to identify those C2 nodes in the Iraqi IADS that had most effect on the whole Air Defense Network. Additionally, the advent of new technologies such as the stealth capabilities of an F-117 Nighthawk allowed new tactical approaches, while multi-role aircraft like the F-15E and F-16C were deployed in large numbers alongside the EA-triad assets previously mentioned. The campaign was planned to have four phases: gain air superiority, suppress Iraqi air defenses in Kuwait, keep pressure on the first and second phase while shifting emphasis to the Kuwait field army and support ground troops. (Baker, 2012, p. 4)Instead of executing them sequentially, however, the US lead forces conducted the first two phases at once in a massed, high intensity operation. Starting on January 16, 1991, F-117 stealth aircraft were used to behead the IADS by striking the previously identified critical nodes, leaving vast parts of the IADS operating autonomously. (Kwai-Cheung, 1997, p. 101) This was enabled by a centralized design of the IADS with little decision making at the level of the individual AD systems. Enemy fighter aircraft were either contained by the F-15C fleet or remained on the ground. Simultaneously the individual SAM systems were disrupted by jamming capabilities and HARMS allowing freedom of movement for the large bomber and air interdiction force, partially tasked with the DEAD missions. Additionally, Joint SEAD effects were achieved by cruise missile launches of maritime assets and multiple launch rocket systems. (Brungess, 1994, p. 41) After 42 consecutive days of high intensity bombing, the air war succeeded and with a far lower number of loses, than expected by military planners. Out of 68,150 combat sorties, only 33 were lost due to enemy actions. The resulting rate of attrition of 0.04 percent was also achieved due to effective SEAD operations that were able to handle the IADS threat. A total of 4,326 SEAD sorties was conducted, resulting in 6.3 percent SEAD sorties in the campaign.

Operation Allied Force 1999

The NATO air war against the Yugoslavian armed forces under autocratic leader Slobodan Milošević in 1999 constitutes another historical example of SEAD operations. In order to prevent an ethnical cleansing of the Albanian minority in the Province Kosovo, NATO allies intervened despite the Russian and Chinese Veto to a potential UN Resolution. The freedom of movement of allied assets in the air domain was impaired by an IADS consisting of 16 S-125 Neva (NATO SA-3 GOA) and 25 mobile 2K12 Kub (NATO SA-6 Gainful). Along with AAA, MANPADs and EW radars, the shoot and scoot tactics of the SA-6 were able to hamper NATO operations, especially when delivering laser guided precision munitions. To counter the IADS, 50 F-16 CJ alongside German and Italian Tornado ECR were equipped with HARMs, while E6-B Prowler jets provided stand-off jamming. With that many SEAD assets in the theatre, Serbian SAM operators avoided the destruction of their radars by very strict Emission Control (EMCON) procedures. The operators radiated only for a short time span, even discontinuing the target illumination, when they already had launched a missile in order to avoid being hit by a HARM. The EW radars integrated into the IADS were located on neighboring countries and therefore could not be targeted by NATO forces. Additionally, the hilly terrain made it difficult for ISR assets like the E-8 JSTARS to locate the SAM sites with their Moving Target Indicator (MTI) function. While the Serbian IADS could only harass NATO operations, NATO assets were neither able to effectively target the same systems. Out of a total 743 HARMs employed, only ten hit a SAM system. (Lambeth, 2002, p. 16) After a quick and intensive operation to gain air superiority in Desert Storm, the SEAD campaign now had to last throughout the whole war. Although doubt was raised about the effectiveness of the 250,000 US-Dollar HARM, only two allied aircraft were downed by the AD. Besides an F-16, for the first an F-117 stealth bomber got hit by a SAM, since the Serbian operator waited until the Nighthawk was right overhead, before target illumination was started, rendering the geometric design features useless. Overall, the air war lasted from March 24 until June 11, 1999 and saw two losses in 21,111 sorties amounting to a loss rate of 0.009 percent. With 4,538 SEAD sorties conducted, a SEAD sortie ratio of 21.5 percent was recorded.

(Bolkcom, 2005, p. 5) While the campaign goal was achieved with air power only, constituting a rare case in history where peace was achieved without boots on the ground, the observations from this campaign led to tactical adjustments, should NATO face an enemy IADS under EMCON again. (Cox & Gray, 2002, p. 341; Saldik, 2021, p. 5)

Operations Odyssey Dawn and Unified Protector 2011

Operation Odyssey Dawn was the US led portion of multiple missions starting on March 19, 2011. Previously UN Security Council Resolution 1973 had been passed in order to stop the atrocities against the civilian population of Libya in the war between Libyan dictator Muammar Gaddafi's regime and the Anti-Gaddafi forces as an outcome of the Arab Spring. The larger share of sorties was flown under NATO Operation Unified Protector to enforce a no-fly zone over Libya from March 31, 2011. The SEAD operation to target the Libyan IADS was already conducted at the outset of the war starting on March 19. The IADS consisted of outdated long range SAM systems like eleven batteries of S-75 Dvina (NATO SA-2D/E Guideline), another eleven batteries of S-200 Vega (NATO SA-5B Gammon) distributed over four prepared sites and 16 batteries of SA-3 GOA. Additionally mobile short to medium range SAM systems like the SA-6 Gainful, SA-8 Gecko, SA-13 Gopher and Crotale were in the Libyan forces' arsenal. These systems were fed by a number of Early Warning Radars (EWRs) like the P-18 Spoon Rest, the P-14 Tall King but also dual-use radars that primarily were used as aerodrome surveillance radars at civilian airports but were connected to the IADS as well. (Kassebaum, 2011, p. 60; Kopp, 2011, pp. 14–15). The SEAD force consisted of five newly commissioned US Navy EA-18 G Growler, four Italian Air Force Tornado ECR and up to twenty US Ari Force F-16CM from the 77th "Gamblers" an 55th squadron of the 20th Fighter Wing at Shaw AFB or the 480th Fighter Squadron at Spangdahlem AB. This fairly low number of dedicated SEAD assets showed the effects of NATO's focus on Counter-Insurgency (COIN) operations at that time and is still showing in NATO's SEAD capabilities today. (Greenleaf, 2013, p. 38) However, the conventional SEAD-type disruption of SAM threats was not demanded during Odyssey Dawn as the proliferation of precision guided munitions shifted the focus from SEAD to DEAD missions with 100 percent of bombs dropped being PGMs for the first time. (Mueller, 2015, p. 4) At the outset of the war on March 19, a salvo of 112 Sea-Launched Cruise Missiles was fired by US and British war ships and submarines destroying all the stationary SAM sites and EWR on day one. The SEAD assets were then rather used as ISR platforms with their ESM sensors. Located mobile SAMs were then targeted with Precision Guided Munitions (PGM) as they were not radiating employing EMCON procedures or not even ready to operate at all. The only remaining factor for air operations were the dual-use radars, since ROE initially precluded their targeting. By the end of Odyssey Dawn on 31 March, 2011 air superiority was gained and no SAM activity was reported under the NATO operation Unified Protector. Overall, not a single combat loss was recorded in over 26,300 combat sorties. 1,708 sorties were dedicated SEAD sorties accounting for 6.5 percent of all flown sorties. (Mueller, 2015, pp. 4, 146, 228)

Now that four cases of SEAD campaigns have been introduced, the unique features of each campaign will be pointed out in order to identify, whether they are worth considering in SEAD campaigns of the future.

3.3 Does History repeat itself? Implications for the next SEAD Campaign

Campaign	Combat sorties	Combat losses	Attrition rate	SEAD sorties	Share of SEAD sorties
Vietnam	219,407	1,437	0.65%	11,389	5.2%
Iraq	68,150	33	0.04%	4,326	6.3%
Kosovo	21,111	2	0.009%	4,538	21,5%
Libya	26,300	0	0%	1,708	6.5%

There are two schools of thought looking at the relevance of historical evidence for the war of tomorrow. These are summarized in the following quote by Sir John C. Slessor:

"If there is one attitude more dangerous than to assume that a future war will be just like the last one, it is to imagine that it will be so utterly different we can afford to ignore all the lessons of the last one."(Slessor, 2009, p. xiv)

Neither should the lessons learned from SEAD campaigns of the past be considered the blueprint for the next SEAD, nor should the findings of previous campaigns be viewed as outdated and irrelevant. Therefore, some of the unique features of previous SEAD campaigns need to be discussed. To begin the analysis of the four introduced cases, the following table summarizes the number of combat sorties flown and the share of SEAD sorties conducted along with attrition rates in the respective campaigns.

Table 1: Attrition rates in previous SEAD campaigns (Bolkcom, 2005, pp. 4–5; Greenleaf, 2013, p. 38; Mueller, 2015, pp. 146, 228)

A few observations can already be pointed out, without going into detail. The introduction of SEAD as a role of air power has contributed to a reduction of attrition rates in previous air wars. Since the Vietnam war in 1965 and the introduction of SEAD, the attrition rates have continuously decreased. This can be an effect of SEAD on one side, but might also be a representation of the growing technical advantage of Western, US led forces over their adversaries. The technological advantage against a peer adversary is however much smaller if existent at all. Additionally, attrition rates are also a function of the total numbers of sorties flown. While the NATO led operation Unified Protector saw approximately 150 sorties per day, a high intensity conflict in Europe will see as many as 700 sorties per day at the beginning and a sustained rate of 350 sorties per day. (Dalsjö, 2019, p. 31; Greenleaf, 2013, p. 39) This accumulates to over 10,000 sorties per month. As the attrition rate against a Russian IADS is likely to be somewhere between those of Desert Storm and Vietnam, this means absolute losses between 4 and 65 aircraft every month. These are numbers, that Western political leaders will not want to accept. Another observation is the relative share of SEAD sorties. With increasing SEAD capabilities among NATO allies, the share of SEAD sorties increased to 21,5 percent during Operation allied force. Odyssey Dawn than showed the impact of decreasing military budgets and a diminishing prioritization of the SEAD role with only 6.5 percent SEAD sorties flown despite a high SAM threat at the outset of the war. The European SEAD contribution was even lower with 208 sorties flown by Italian ECR Tornados accounting for only 0.8 percent of all sorties flown, while European contribution to air interdiction and counter air sorties was at 50 or 75 percent respectively. This shows that for a high intensity war against the Russian IADS, NATO in general and European NATO partners specifically have to increase their contribution to SEAD operations significantly. Looking at lesson learned from the individual cases, it is the impact of a technological revolution like the introduction of SAM systems, but also the technological evolution of weapons like ARM that stands out in the Vietnam War. The science behind SEAD makes this role of air power more dependent on technological superiority than other roles of air power. Operation Desert Storm showed the importance of thorough ISR operations and a critical node analysis long before a war begins, in order to maximize the effect of strikes on the degradation of an IADS. Operation Allied Force underlined the importance of SEAD tactics against an enemy, that operates under EMCON. While neglecting the SAM threat can be lethal, the search for the needle in the haystack can be both time and ordnance consuming and requires patience of military and politic leadership. Finally, Odyssey Dawn showed the importance of ROE against dual-use targets. Only with a clear legal guidance the concept of centralized command and decentralized execution can unfold its full potential. On the other side, there are also concepts, that cannot be applied in the context of war against Russia. This is mainly due to three reasons. First, all adversaries in the observed cases had single digit SAM systems i.e., no system more modern than SA-9 Gopher. The threat posed by the SAM systems will be fundamentally different when fighting against the most modern air defense systems in the world. Second, the Russian IADS is most likely not as centralized as the IADS seen in Iraq in 1991. Therefore, a degradation requires more nodes to be targeted and more time to achieve effects. Third, the reason why a Russian AD system operates under EMCON will be fundamentally different from the one observed by the Serbian forces in Kosovo. Russian SAM systems are more likely to wait with radar emissions until the targeted asset is within a defined doctrinal range to achieve a certain probability of hit, since they receive target track information from a series of EWRs. This primarily serves a higher offensive potential rather than an increased survivability, as observed in Kosovo. These observations are not comprehensive but rather aim to point out why the history of previous campaign is not likely to repeat. To provide a more nuanced explanation, why the Russian IADS as a part of an Anti-Access/Area Denial complex requires other means to gain air superiority than observed in previous wars will be elaborated on in the following chapter.

4 The Russian Anti Access/Area Denial Complex

Since the illicit Russian annexation of Crimea in 2014, the term Anti Access/ Area Denial (A2/AD) has become a commonly used buzzword whenever the re-building and modernization of Russian military capabilities are discussed. It is frequently used to draw a devastating picture of impenetrable, multilayered red circles on a map, a strategy of a defensive bastion of resilient and redundant systems able to lock incapacitated NATO forces out of the Baltic states. (Freedberg Jr., 2015; Sukhankin, 2018, pp. 28–30; Vershbow, 2015) This little nuanced exaggeration is neither analyzing Russian strategic implications, nor does it reflect on the operational level challenges of integrating the individual parts that make up

A2/AD as a system of system, nor does it take into account the tactical strengths and weaknesses of its components. Therefore, this chapter seeks to give a detailed view on the strategic, operational and tactical level capabilities and limitations of the Russian A2/AD complex. As this thesis focuses on the application of air power in a contested operational environment, the emphasis will be placed on the air defense portion of A2/AD.

The term A2/AD is comprised of two parts, Anti Access (A2) and Area Denial (AD). Although often used as one expression, each of these two parts has its own meaning. According to the US Department of Defense's Joint Operational Access Concept, Anti Access is defined as: "Those actions and capabilities, usually long-range, designed to prevent an opposing force from entering an operational area." (U.S. DoD, 2012, p. 15)

Area Denial is defined as: "Those actions and capabilities, usually of shorter range, designed not to keep an opposing force out, but to limit its freedom of action within the operational area." (U.S. DoD, 2012, p. 15)

These definitions are commonly used, supposedly due to the normative character a U.S. DoD publication embodies. Nevertheless, there are several reasons to reconsider their general applicability. One reason is the context these definitions originate in. A2/AD strategies are nearly as old as warfighting itself as examples of Great Walls ranging from the Limes Germanicus, built to keep the barbarians out of the Roman Empire, over the Great Wall of China fortifying the sphere of influence of the Ming Dynasty to the Berlin Wall as the manifestation of the Iron Curtain during the Cold War demonstrate. (Tangredi, 2013, p. 3) The recent incarnation of A2/AD was caused by China's rise to power challenging the unipolar world order dominated by the single superpower USA. The massive growth of military capabilities in the People's Liberation Army during the last 20 years led to a pivot to Asia in US foreign policy. The resulting concept for US force employment, the Air-Sea Battle, was published in 2012 coining the phrase A2/AD. (Dalsjö et al., 2015, pp. 21–22) Given the maritime operational environment in the South China Sea, the definitions of the Joint Operational Access Concept are appropriate. However, they do not carry over to a European scenario with a conflict between NATO and Russia. With the operational environment mainly over the landmass of eastern European NATO allies, it appears rather counterintuitive to define Anti-Access as long range in nature, while Area Denial is focused on short range effects, given the joint all-domain operations approach required in this scenario. Therefore, a concept of air power employment can be used to adjust the understanding of A2/AD towards a European scenario. While air superiority and air supremacy incorporate a similar understanding of the degree of denial of an adversary's ability to gain access to an operational area, air superiority adds the factor of time. "Air supremacy is that degree of control of the air wherein the opposing force is incapable of effective interference within the operational area using air and missile threats." (U.S. Joint Chiefs of Staff, 2018, p. 25) Hence, air supremacy shares a similar, but even stricter view of what an opposing force is able to do inside the respective operational area compared to Anti-Access. Air superiority on the other hand "[…] is that degree of control of the air by one force that permits the conduct of its operations at a given time and place without prohibitive interference from air and missile threats." (U.S. Joint Chiefs of Staff, 2018, p. 15) While air superiority is equally restrictive to an opponent's freedom of maneuver as air supremacy or Anti-Access, it only requires this high level of control of the air over a certain timeframe. For a European A2/AD scenario, that means that the addition of the dimension time to the Anti-Access concept, makes temporary A2 much more achievable and therefore relevant for a more differentiated discussion of A2 zones on one side and AD zones on the other side. Additionally, the distance of the observed operational area from the A2/AD assets plays a role in that the ability to target opposing forces decreases with increasing distance from the A2/AD assets, as there are more systems able to target with higher accuracy close in and fewer systems able to target precisely over long distances. This introduction of the factors time and the inverse proportionality of distance leads to an adjusted understanding of A2 and AD in a European scenario. Accordingly, Anti-access is described as actions and capabilities signed to permanently prevent an opposing force from entering the nearby operational area or temporarily prevent the opposing force from entering the extended operational area. Accordingly, area denial means actions and capabilities designed not to keep opposing force out, but to limit its freedom of action within a wide operational area.

4.1 A2/AD at the Strategic Level

With a clearer understanding of where A2 ends and where AD begins a closer look at the implications of this concept at the political strategic and military strategic level can be taken. Although the standard example of an A2/AD system in Europe is the Russian force concentration in Kaliningrad Oblast, it is important to see each of the A2/AD bastions, bubbles, rings and the likes, against its individual geographical and strategic backdrop. (Frühling & Lasconjarias, 2016; Sukhankin, 2018) In this thesis the 'bubbles' will be referred to as A2/AD complexes, as this describes the nature of multiple interconnected systems best and redirects the focus from the maximum effective range of a few assets to the combination of the capabilities of all assets connected with one another and underlines the complexity that this implied. A2/AD complexes range from the High North at Kola peninsula protecting the Northern Fleet with its nuclear armed submarines as a part of Russia's nuclear triad, over St. Petersburg as mainland Russia's only access to the Baltic Sea, Moscow as the country's capital, political and economic center, via the Kaliningrad exclave and a complex in

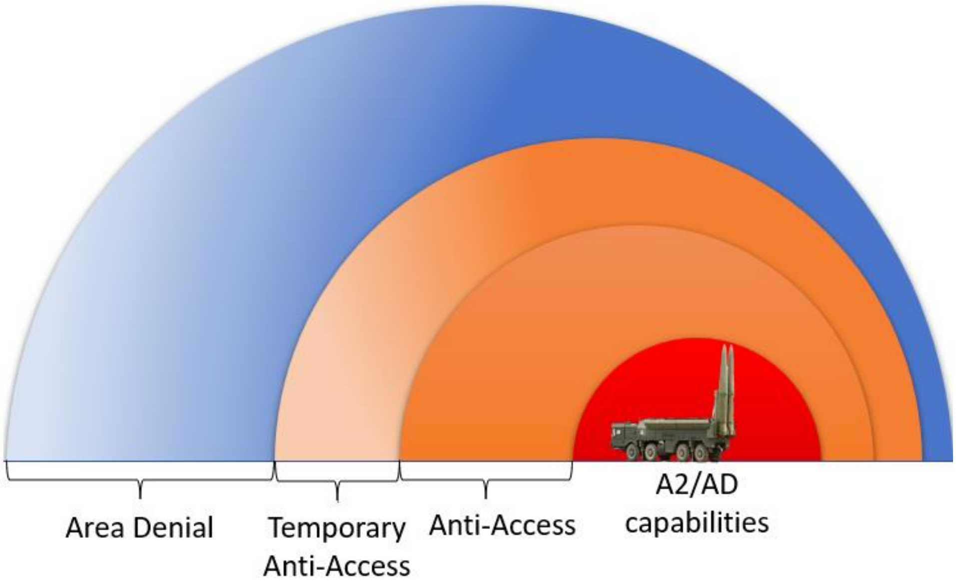


Figure 199: Delemitation of Anti-Access and Area Denial

Belarus to exert pressure on NATOs eastern flank to Air Defenses in Kursk and Voronezh to gain control over Ukrainian airspace. A2/AD complexes stretch further southeast over Krasnodar and Sevastopol to cement Russia's influence over the Black Sea Region, a complex on Armenian soil based on a bilateral agreement from 2016 to project power onto the South

Caucasus all the way down to Latakia in Syria safeguarding another Russian sphere of influence in the eastern Mediterranean and the Levant. (Giles & Boulegue, 2019, pp. 26–32) Although it once more feeds the narrative of angry red circles on a map, undermining a differentiated discussion of A2/AD complexes, the following illustration serves the purpose of visualizing how wide-spread Russian A2/AD complexes are. (cf. Williams, 2017)

A fact to take note of looking at the map is the sheer length of the Russian border with NATO member states (2533 km since Finland joined NATO on April 4, 2023) and non-NATO but westerly oriented states (Ukraine and Georgia combine for a 2869 km border) posing a strategic challenge to Russia per se. Each of the aforementioned A2/AD complexes, although not constituting a center of gravity by itself, has a strategic relevance as Russia deems something worth protecting at its center. (Kofman, 2020) Nonetheless, it is beyond the scope of this thesis to go deep into the weeds of a center of gravity analysis for each of the A2/AD complexes e.g., the importance of Sevastopol as the headquarters of the Black Sea Fleet, the historical implications behind the annexation of Crimea in the light of Russian revisionism and the relevance of unrestricted access to the Black Sea for Russian power projection. (Pisciotta, 2020, pp. 95–98) However, the most pertinent example from a Western- and NATO point of view is Kaliningrad, as it has many implications for a potential NATO Article 5 conflict in the Baltic region. Hence, it will be the A2/AD case to focus on going forward in this chapter.

Figure 200: Map of Russian A2/AD complexes (cf. Williams, 2017)

The narrative of a humanitarian intervention to prevent a genocide against Russian minorities is a recurring scheme in a strategic blueprint observed in the Russian annexations of the past and present. It has been applied from the landgrabs in South Ossetia and Abkhazia in the war against Georgia in 2008, to the illicit annexation of Crimea and the creation of the breakaway regions of the People's Republics of Donetsk and Luhansk in the ongoing war against Ukraine, that started in 2014 and resulted in a brutal full-scale invasion of Ukraine by Russian forces in 2022. It forms a pattern that can easily be imagined to be transferred to other Russian border regions mainly in the Baltic states with Russian minorities of 27 percent in Latvia and Estonia (Andžāns, 2022, p. 51) and to a lesser degree also in Finland or Norway with minorities below 4 percent in some border regions, all of which are NATO member states. Hybrid approaches such as information warfare by disinformation campaigns, cyberattacks and non-state-actors destabilizing local authorities, all non-attributable and denied by the Russian government are means known as "Maskirovka" and raise the tension in the disputed area to a grey zone conflict. (Roberts, 2015, pp. 1–2) A succeeding military "light speed war" accompanied by political and economic warfare escalate the conflict to a full-scale local war according Russian doctrine, mistakenly promulgated as the "Gerasimov Doctrine", and completes the fait accompli below the NATO article 5 threshold as NATO allies might neither have the ability to respond quickly enough nor do they show the political decisiveness to escalate into a regional war with a nuclear power, just as intended by the Kremlin. (Galeotti, 2018; Zysk, 2018, pp. 6–7) This repeating template of Russian salami slicing tactics, as it is on display in Ukraine since 2014, is leveraging Moscow's self-proclaimed great power status over smaller neighboring states and forms the core concern of security policies in small state realism. (Götz, 2017, pp. 101–103; Tamnes, 2019, pp. 56–58)

An enabler for Russia to achieve regional conventional force superiority in the Baltics is the A2/AD complex in Kaliningrad Oblast. It features assets to deliver effects in all domains including the electromagnetic spectrum (EMS), which the Russian forces dedicated an individual service branch to in 2009. (Kjellén, 2018, p. 29) While there is no such thing as an A2/AD strategy or doctrine in Russian strategic thinking, A2/AD complexes still serve multiple purposes on the strategic level. The self-induced buzz around the A2/AD complex in Kaliningrad among western analysts after the annexation of Crimea in 2014 had one primary effect. (Simon, 2017) Western political and military leaders were deterred. The causing factor however, was not to be found in the capabilities of the Russian A2/AD complex itself but rather a to superficial discussion thereof. Nine years of A2/AD buzz and some prepositioning programs in NATO such as “enhanced Forward Presence” and “Baltic Air Policing” later, there are tripwires in place to reassure the Baltic states of their extended deterrence against Russia through NATO. Yet, the debate on the actual relevance of an A2/AD complex in case a Western intervention in Kaliningrad was required and the role of A2/AD complexes in Russian strategy has just recently begun. (Dalsjö et al., 2019; Kofman, 2019) If Russian A2/AD was a purely defensive concept and NATO is a defensive alliance, then neither should ever end up attacking the other. Hence, it is necessary to take a closer look on Russian strategy, to be able to understand the role of A2/AD. Russia pursues a strategy of “Active Defense” i.e., it pursues a high readiness defensive posture, ready to carry out offensive interventions in its near abroad whenever it deems national interest at stake. Active defense follows a pattern of vertical escalation from non-attributable hybrid warfare over conventional to nuclear warfare paired with horizontal escalation from a crisis or conflict to local war over a regional war to global war. (Zysk, 2018, p. 6) At its core, Active Defense seeks to “[…] disorganize an enemy’s effort, degrade their ability to sustain operations, and affect their political will to continue armed struggle.” (Kofman et al., 2021, p. 13) To achieve the latter, a strategic ambiguity between strategic conventional and non-strategic nuclear weapons is exploited. The A2/AD capabilities staged in Kaliningrad can contribute to this concept, but do not form an individual strategy by themselves. They rather support other strategic objectives. The following Paragraph describes an example of what this strategic approach can look like in.

First, at the outset of a local war in the Baltic states, the disorganization of the enemy’s effort i.e., NATO’s effort, is achieved as NATO operations by prepositioned units are drastically impaired when the limited number of air and sea assets in the region gets targeted by the anti-air and anti-sea defenses while critical military and civilian infrastructure gets struck by long range land-based strike capabilities. This prospect of the effects of the Kaliningrad A2/AD capabilities in an initial phase of a local war between NATO and Russia in the Baltic area can be considered deterrence by denial, since there is a risk of significant losses of NATO forces, should NATO resist with the prepositioned troops.

(Schmidt, 2018, p. 253) In this early stage the Russian actions constitute a case of Area Denial, as it does not appear feasible for Russian forces to lock out all Western forces right from the beginning. Second, the follow-on attempts of NATO to quickly reinforce its posture in the Baltic states, as the remaining NATO troops regroup, get undermined. The forward location of Kaliningrad in combination with the long ranges of some of its A2/AD assets allows it to control the sea lines of communication from the Bornholm Basin to the Gulf of Riga effectively cutting of Finland and the Baltic States from the sea lines of communication. Air traffic needs to go through Sweden as almost the entire Polish airspace lies inside maximum engagement range for long range SAM systems, at least for larger and less maneuverable transport aircraft. This directly supports the strategic objective of degrading the enemy's ability to sustain operations according to Active Defense. From a Western point of view this would look like an Anti-Access effort. In the spectrum of military deterrence, the potential loss of logistic capabilities if a resupply was attempted is a form of deterrence by denial as well. As the war continues, a Russian effort to take the Suvalki Gap, a ca. 70km wide land bridge between Kaliningrad and the Russian mainland along the Polish and Lithuania border must be expected, in turn disrupting land lines of communication to the Baltic states. Simultaneously Russian forces eventually begin to conquer territories in the Baltic states. Third, the war progresses towards the final strategic objective in Russian Active Defense, namely, affecting Western leaders' political will to continue the armed struggle. After recovering from the initial shock, NATO will now begin to conduct coordinated Joint All-Domain Operations out of Northern, Central and Eastern Europe to regain territory and subsequently is confronted with Kaliningrad's A2/AD complex first. Now the main purpose of the Kaliningrad A2/AD complex takes effect. As Sam Tangredi (2013) puts it, firstly A2/AD's main purpose is to keep an attacker from striking the defenders center of gravity. Hence, as long as the defender succeeds, the attacker will never be able to achieve victory. Secondly, Tangredi continues "For the defender, the desired result is not just stalemate, but also attrition of the attacker's forces such that the attacker loses over time any ability to make a decisive strike at the center." (Tangredi, 2013, p. 2) I.e., applied in the Kaliningrad context, the main aim of A2/AD is to cause attrition against an attempt of NATO forces to strike the Russian center of gravity. This does not only buy Russia time to complete its landgrab in the Baltic states, but in addition exerts pressure on Western political leaders' will to continue an intervention facing high attrition rates. However, over time the local conventional superiority of Russian forces would fade as Anti-Access could only be ensured temporarily before further degrading to Area Denial. The longer the war lasts the, the likelier it gets that the Russian A2/AD complex can no longer sustain a conventional stalemate. Latest at this turning point, but potentially earlier, when Russian political objectives are met i.e., enough territory has been occupied, Russia would threaten to escalate by means of strategic ambiguity such as long-range conventional hypersonic strikes on Western capitals or tactical nuclear weapons on Eastern Europe, both of which have a more devastating effect from a forward position such as Kaliningrad. This “diplomacy of violence” approach enabled by the protection of A2/AD, falls under deterrence by punishment in order to break NATOs will to continue the attempt to regain the lost territories and rather settle for a truce with commitments to Russian territorial claims. (Schelling, 2008, p. 34)

While the presented scenario has described a possible impact of the all-out use of A2/AD capabilities in line with military-strategic objectives of the Russian Active Defense doctrine, this rather daunting picture has not considered the political-strategic considerations, yet. It might be militarily favorable to disrupt the lines of communication in the Baltic Sea or target every non-Russian aircraft inside a certain distance to Kaliningrad in order to achieve a credible deterrence and deny supply lines but it comes with a diplomatic price tag affecting international relations as well. An attempt to disrupt supplies to the Baltic states impacts trade relations of Finland and Sweden as well. A possible reaction is a deeper economical, informational and military cooperation between Norway, Sweden and Finland on the Scandinavian Peninsula and an abandonment of their policy of deterrence and reassurance, in turn forcing Russia to redirect military resources to the High North that it needed elsewhere. The political reactions by the international community to an all-out employment of a Russian A2/AD complex are to diverse and speculative to elaborate on in this thesis. Still the full-scale invasion of Ukraine has shown some effects, that can recur should Russia attempt another landgrab against a neighboring state, especially if that state is a NATO member. The unity among Western states causing diplomatic consequences by an increasing isolation of Russia in the international community, informational consequences as its adversaries share ISR-products openly with the invaded country, military consequences by attrition and economic consequences by sanctions will cause the Kremlin to carefully weigh an escalatory use of the A2/AD assets available if a full-blown NATO intervention cannot be outruled. (Nielsen, 2020, pp. 103–105) A global conventional war bears the risk for Russia to permanently loose its status as a peer competitor in international politics. In a global nuclear war, A2/AD has a subordinate role. Hence, from a Russian point of view the strategic efficacy over the full spectrum of A2/AD from Area Denial over temporary Anti-Access to permanent Anti-Access is highest in a conventional local to regional war i.e., in case of a Baltic scenario a NATO intervention with little or no support by the United States. In that particular case, the impact of diplomatic, informational and economic means is decisive to prevent conventional inferiority and excessive attrition among European NATO allies over time.

4.2 A2/AD at the Operational Level

So far, this thesis looked at A2/AD as one unitary complex with full SA and a seamless ability to employ means in the domains air, land, sea and the EMS. Just a as in any Western military, the Russian A2/AD complex relies on a robust Command and Control (C2) structure, that is able to integrate a variety of sensor inputs, evaluate them to update the recognized picture across the individual domains, assign engagements to subordinate weapons platforms and once again employ sensors to assess the outcome of an engagement. While C2 is conducted at all levels of military operations, both strategic, operational and tactical, it is mainly at the operational level where the kill chain management happens i.e., the different steps of the Find-Fix-Track-Target-Engage-Assess (F2T2EA) process are administered. “At its core, A2/AD is a concept related to the operational level of war.” (Nielsen, 2020, p. 96)

Anti-land, Anti-sea and Electronic Warfare Systems in an A2/AD Complex

With a focus on SEAD relevant capabilities a brief look at some anti-land, anti-sea and electronic warfare assets is taken, before a more detailed review of capabilities and assets in an integrated air defense system (IADS) will be provided. A Russian anti-land asset often referred to in an A2/AD context is the 9k720 Iskander-M (NATO reporting name SS-26 Stone). The short-range ballistic missile system, among others deployed to Belarus and stationed in Kaliningrad as well as Luga near St. Petersburg has a range of 500 km (270 NM) and can be fitted with a nuclear or a conventional warhead. A lighter 700 kg warhead increases the systems range to more than 700 km. Each Transporter-Erector-Launcher (TEL) carries two missiles. With 4 TELs in a battalion and 3 battalions per brigade, a total of 24 missiles is ready to launch per brigade with another 24 missiles available after a 30-60 minute reload. (Dalsjö et al., 2019, pp. 36–37) The less known cruise missile variant Iskander-K (GRAU index – 9M279) is responsible for the discontinuation of the INF Treaty as it reaches ranges of up to 2500 km (1350 NM) by far exceeding the contractual limit of 500 km and putting most European NATO member capitals in its reach. There are also variants that can be launched from surface ships (3M14T) or submarines (3M14K). (Dalsjö et al., 2019, p. 40; Musland, 2021, p. 19) Another variant of the Iskander missile is its air-launched sibling, the Kh-47M2 Kinzhal. It is claimed to have a range of 2000-3000 km (ca. 1100-1600 NM) while it remains unclear whether this includes the combat range of the MiG-31 fighter aircraft carrying the weapon. The high-speed release at altitude allows the missile to boost to velocities in excess of Mach 5. Hence, and due to the missiles ability to maneuver during all phases of flight shared with the Iskander-M, it is considered a hypersonic weapon. (Williamson & Wirtz, 2021, pp. 472–473) The combination of high speed and an unconventional trajectory compared to ballistic missiles create an unprecedented challenge to Western air defenses and make it a threat to aircraft carriers, airfields and C2 installations. However, the employment on targets in Eastern Ukraine rather than targets in the countries west hint at the missile rather being an evolution of the Iskander-M than the revolution the Russian strategic communication claims it to be. (Bugos, 2022, p. 33) The Russian arsenal also incorporates further air-launched cruise missiles such as the Kh-101/102 Kalibr with ranges claimed between2500 and 4500 km (1350-2400 NM) and intercontinental ballistic missiles with ranges up to 16000 km (8640 NM). (Musland, 2021, p. 19) All of the aforementioned missiles can be equipped with conventional or nuclear warheads.

Figure 201: Iskander-M TEL with Transloader (Photo: by Boevaya mashina under CC-BY-SA license)

The anti-sea portion of the Russian A2/AD complex is most credibly to achieve anti-access since it aims at comparatively large and slow moving targets limited to two dimensional maneuvering such as aircraft carriers or other large surface vessels. (Kofman, 2019; Nielsen, 2020, p. 100) The most recent development fielded in the Russian coastal anti-ship defenses is the Bastion-P system (NATO reporting name SS-C-5 Stooge). The wheeled launcher is equipped with two P-800 Onyx effectors capable of achieving speeds of Mach 2.5 at sea level due to its ram jet rocket motor. After a high trajectory to acquire its target via an active radar seeker it descends to sea level, thus leaving little reaction time for Western naval defenses to target a low and fast missile. It is reported to have a range of up to 300 km (162 NM). This is more than twice the range of its predecessor the Bal system, still in service, with the Kh-35 Uran sea skimming missile (SS-N-25 Switchblade) and a reported range of 130 km (70 NM). (Dalsjö et al., 2019, pp. 133–134; Musland, 2021, p. 20) Besides these two land-based anti-sea systems there are multiple air-, subsurface- and surface-launched cruise missiles in the Russian inventory such as the Kh-32 or the P-500 Basalt with claimed ranges between 500 and 1000 km (270-540 NM).

The establishing of an individual service branch for warfare in the electromagnetic spectrum, the Electronic Warfare (radioelektronnaia borba – REB) forces by the Russian ministry of defense in 2009 with subdivisions for the integration of EW into the existing command structure, for EW against airborne, ground-, space-based and terrorist activities, an own command structure with headquarters in Moscow, a training center in Tambov and an EW faculty at the air force academy in Voronezh underline the importance of EW-capabilities for the Kremlin. (Kjellén, 2018, pp. 29–33) Along with the REB-forces inauguration, an extensive rearmament program was initiated, to either modernize older systems from the Soviet era or develop new systems. A total of 24 new or updated EW systems have either been brought into service or completed state trials between 2009 and 2018. The effects of these systems cover a wide range. The armored, tracked Borisoglebsk-2 complex and its wheeled twin, the Diabazol complex consist of nine vehicles, collectively able to provide SIGINT, jamming, targeting radio, satellite communication and navigation to ground forces. They feature systems such as the R-330Zh Zhitel GPS jammer and the R-934UM Sinitsa, able to jam frequency agile VHF and UHF aircraft radios. The Rtut-BM system is capable of spoofing radar proximity fuses to detonate prematurely on an area of 50 hectare and the Leer-3 system can emulate a mobile phone network node in order to spoof and intercept cell phone communications. Especially relevant for air operations are the Moskva-1, Krasukha-2O and Krasukha-4S complexes. The Moskva-1 is an emitter locator system able to find aircraft through their electromagnetic emissions, such as radar signals or data link communications. These location data are relayed to Krasukha-2O, designed to jam airborne early warning radars of aircraft such as the E3 Sentry in the S-band. The Krasukha-4S is able to jam fighter radars, reconnaissance assets like the E-8 JSTARS, drones and low earth orbit satellites in the X- and Ku-band. Another EW-system is the Shipovnik-AERO, introduced into service in 2017. It is a counter UAV system, that is designed to detect and manipulate control signals to UAV's or spoof the UAV's navigation by providing fake GPS information, both resulting in the loss of control over the UAV. While it remains unknown, whether the Shipovnik-AERO system accounts for the high number of lost UAVs of Ukrainian forces under the Russian full-scale invasion, the effect of REB-forces can be observed as the initial success of attacks by smaller quadcopter-drones and larger Bayraktar TB-2 UAVs in the first three month of the invasion turned into loss rates of UAVs of 90 percent after the REB-forces were in position. (Zabrodskyi et al., 2022, pp. 2, 37) By 2025 the REB-forces aim to establish a C2 structure ranging from the RB-108S automated command system at EW commander HQ level over the

RB-109A Bylina at brigade level to RB-105S Less at individual unit level. (Kjellén, 2018, pp. 64–65) This will further enhance the EW effects of Russian operations while reducing incidents, where Russian forces have been affected by their own EW forces as overserved during the full-scale invasion of Ukraine. (Zabrodskyi et al., 2022, p. 38)

Figure 202: 1RL257 Krasukha-4S jammer and command post (Source: mil.ru under CC BY 4.0 license)

The Integrated Air Defense System of Systems

The Russian Integrated Air Defense Systems poses a major threat to NATO air operations in a high intensity warfare scenario in Europe, such as an article five intervention in the Baltic

States. While the Chinese People's Liberation Army, long dependent on Russian air defense system deliveries, has developed more capable radar systems to detect and track aircraft due to advances in AESA-technology in recent years, the Russian IADS remains unsurpassed in its lethality and resilience against SEAD and DEAD operations. (Bronk, 2020, p. 22) In order to achieve such a lethal kill chain in line with the F2T2EA targeting cycle, there are three main categories of systems involved in an IADS, Early Warning Radars (EWRs), command posts and weapon systems. First, the Early Warning Radar (EWR) systems enable an IADS to detect the presence of aircraft i.e., find it and derive a position and a vector with direction and velocity depending on the EWR's accuracy i.e., fix the target. The target information is then passed to a command post, where it is processed and possibly merged with other corresponding target information to create a track. Once the track approaches the engagement zone of a weapon system the track is tasked to be targeted by that system particular system. Depending on weapon system type, the system then commences its own targeting cycle by target acquisition or tracking through electrooptical sensors or radar. Once the weapon system has acquired the target it engages it, in case of a SAM system usually by two missiles. The assessment of the engagement's outcome can either be done visually for a short-range engagement or via radar for longer engagement ranges. While the Russian IADS lacks a precise assessment capability, the other assets i.e., EWR for find and fix, command posts for track and target and weapon systems for engagement will be scrutinized in the following paragraphs.

The Russian EWRs come in a wide variety of purposes, sizes and frequency bands. A general rule of thumb is, the larger the radar the longer the wavelength, the longer the range, the lower the accuracy. Very large over-the-horizon radars exploit the reflectivity of earth's atmosphere for certain frequencies. Instead of a direct line of sight to the target, the radar waves are emitted by the radar, reflected by the ionosphere, send toward the target and back. One examples for these so called backscatter radars is the 29B6 Container, featuring a bistatic design with the receiver 15 km south of the transmitter. The receiver consists of 144 masts with a height of 34 m each spaced seven meters from one another, therefore stretching out over 1.3 km. The system utilizes HF frequencies between 3 and 30 MHz. Detection ranges are claimed to be 3000km (1620 NM) with an altitude coverage of up to 100 km (328,000 ft). The 77YA6M Voronezh uses a similar frequency band but features a monostatic design with transmitter and receiver at the same location, achieving a claimed range of 6000km (3240 NM). (D. T. Withington, 2023) Another principle to work a way around the physics of the radar horizon are surface wave radars. They exploit the fact that radar waves bend towards a conductive surface such as a body of water. The Podsolnukh-E radar exploits this principle at the Baltic Sea and therefore can detect very low flying objects from 3m (10 ft) at ranges of up to 300km (160 NM) in the HF frequency range, defeating possible low level ingress plans for less survivable, older 4th generation fighter aircraft. (Kopp, 2007) While these Radars provide unique capabilities defeating the radar horizon, their physical size makes them easy to find and a stationary target. Although they are capable of detecting approaching aircraft at very long ranges, very low observable aircraft included, they most likely lack the resolution to determine how many aircraft exactly and what types of aircraft are approaching. Therefore other, mobile EWR are employed by the

Russian armed forces as well. While there is a trend to digitize these radars using comparatively cheap commercial of the shelf (COTS) technology, introducing AESA radars to the Russian IADS, there are a range of radars that are mainly mounted on trailers so they are road mobile or are even self-propelled with limited all terrain capabilities and can be set up within approximately 30 minutes. While there are many modernized derivates of the old P-18 (NATO Spoon Rest D) such as the Nebo (55Zh6) with an AESA variant in the Nebo SVU (1L119) operating in the VHF frequency range between 150 to 220 MHz, hence able to detect very low observable aircraft like the F-35, claiming ranges of up to 270km for regular fighter type targets. Other AESA 3D radars in service are the S-band (3-4 GHz) low altitude radar Podlet-E (48YA6-K1E) with a detection range of up to 200 km (108 NM) against an unspecified RCS from surface up to 33,000ft. One complex that stands out between these multiple EWRs is the Nebo-M complex. It integrates the latest iteration of three preexisting AESA radars into one fused track employing different frequency bands. A more compact Version of the Nebo SVU in the VHF band called the RLM-M is combined with the Protivnik G radar operating in the L-band (1-3 GHz), now called RLM-D and the Gamma S1 radar in the S- and X-bands (3-12 GHz) called the RLM-S. The track fusion is done by the RLM-KU command post and then forwarded to a SAM system command post for targeting.
This combined radar solution allows early detection against low observable aircraft which is then refined by the L-band as well as the S-/X-band radars. Since the RCS of an aircraft changes with shifting elevation angles and aspect angles, this forces a detection from less preferable angles in terms of RCS. This means that low observable(LO) aircraft can be

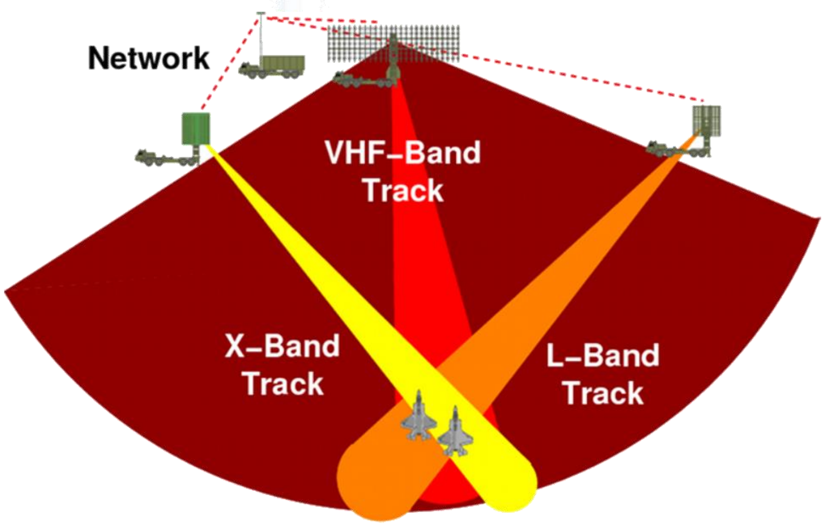


Figure 203: Mutiranging Radar Complex Nebo M (Kopp, 2008)

detected. Nonetheless, the detection range is still lower than the detection range of non-LO assets.

Now that an aircraft has been found and fixed, the target data is handed off to a command post representing the C2 element in the IADS. The Russian forces use different command posts for different levels in the chain of command, but also for the different branches of the forces. At this point, it is necessary to introduce how the IADS is split up in the Russian forces. The National Defense Management Centre at the strategic level commands the country's IADS. Below this level, the different branches have their headquarters. Relevant for the IADS for the scope of this thesis are the Air Defense Troops of the Ground Forces (PVO-SV: Voyská protivovozdúshnoy oboróny Sukhoputnykh voysk) and the Aerospace Forces (VKS: Vozdushno-Kosmicheskiye Sily) with their sub-branch of Air and Missile Defense Forces.(T. Withington, 2022) While the VKS systems are usually used as point defense for strategically important installations such as airfields, critical C2 nodes or critical infrastructure, the PVO-SV air defense is designed to protect army divisions on the move against both, air to surface and surface to surface missile threats. (T. Withington, 2020) At the lowest level, there are the Air Defense batteries, consisting of the individual air defense systems and, depending on the system, an additional radar, and a command post. At the highest level is the branch-specific headquarter. The structure in between is fundamentally different in the VKS and the PVO-SV, respectively. The following analysis of the structure inside each branch is mainly based on automatically translated data from manufacturer websites, expressing the author's interpretation of these data. The VKS appears to have a clear structure, with one mobile, wheeled command post 55K6E in every regiment of S-400 (SA-21 Growler) strategic air defense systems. This command post links up to six 98ZH6E fire units and up to six short-range air defense system Pantsir (SA-22 Greyhound) on the lower level to the assigned EWRs on the same level, connecting the whole regiment to the Air Defense Division Command Post on the higher level. The distance between the 55K6E command post and each fire unit can be up to 100km with data transfer via telecode data link or voice. (Lemansky et al., 2008) On the PVO-SV side, there are more hierarchical levels between batteries and headquarters, leading to a more complex command structure. On the lowest level is a battery of four Tor short-range Air Defense Systems (SA-15 Gauntlet) controlled by a single tracked or wheeled Ranzhir 9S737 command post vehicle. This Ranzhir command post streamlines the target allocation between the four Tor systems, can be up to 5 km from each SA-15, and connects the batterie to the battalion command post on the next higher level up to 30 km away.(Rosoboronexport, 2023) The Tor battalion usually consists of four batteries, each with four AD systems and a Ranzhir command post, combining 16 AD systems along with four command posts in a battalion.(milkavkaz.net, 2017) A similar structure is used for the Buk medium-range air defense system (SA-27 Gollum), relying on the tracked 9S510M battery command post vehicle. The command post connects the 9S18M1-3 Snow Drift target acquisition radar to three pairs of Transporter, Erector, Launcher and Radar (TELAR) vehicles at the lower level. A battalion of Buk AD systems consists of three batteries each with one Snow drift target acquisition radar, one 9S510M battery command post. (milkavkaz.net, 2017) The third major SAM system operated by the PVO-SV is the S-300V4 (SA-23 Gladiator/Giant), designed as a ballistic missile defense system, but also intended to target high-value C2 and ISR airbreathing assets. Its integration is similar to the previously described S-400 with the difference that its 9S457 tracked command post is not directly linked to divisional level. On the next higher level, both the 9S510M of the Buk batteries and the 9S737 of the Tor batteries and the 9S457 of the S-300V4 battalion are integrated via a Polyana-D4 9S52 command vehicle. Each Polyana is able to integrate up to 6 controlled nodes from lower levels, cooperate with four nodes at the same level, connect three EWRs, and report to one higher-level command post.(arms-expo.ru, 2010) While not described in literature, it appears that the individual SAM batteries are aggregated via Polyana control posts at battalion level to report to another Polyana command post at brigade level. The brigade level then reports to the division or branch headquarters. While each branch has its own chain of command along the command posts at the different levels, it is not clear whether they are integrated with the chain of command of another branch. That means that the VKS C2 system is most likely separated from the PVO-SV command system. The occurrence of red-on-red incidents at the beginning of the Russian invasion in Ukraine, the different mobility patterns between the two branches, with point defense on the VKS side and constant movement with own ground troops far from Russian turf on the other side, and the procurement of the S-350 medium-range SAM system for the VKS, with the similar perfomring SA-27 Buk-M3 already in service in the PVO-SV support this assumption. (Dalsjö, 2023, p. 4) A factor not considered yet in the triad of sensors, control and weapons of an IADS is the connection between these items. Besides the already mentioned telecommunication link for data or voice, physical fibre optic cables are used for prepared radar sites. Additionally, satellite communications and high frequency radio links form long range alternatives, that increase the redundancy of communication channels, in turn hardening the entire system. Furthermore, computer communications are enabled through a Closed Data Transfer System without an internet gateway, limiting vectors for cyber attacks. (T. Withington, 2022)

Since the large number of systems that make up an A2/AD complex in general and an IADS more specifically, as well as the interactions between them, can be confusing when looked at as one wholistic entity, the Integrated Air Defense System will subsequently be observed as a system of systems (SoS). This approach out of the systems engineering theory provides means to compartmentalize the individual components of large systems and identify the added value that is created by the systems' interaction. The following definition for a SoS is widely used in a military context. "In relation to joint warfighting, system of systems is concerned with interoperability and synergism of command, control, computer, communications, and information (C4I) and intelligence, surveillance, and reconnaissance (ISR) systems)." (Keating et al., 2003, p. 38; Manthorpe, 1996) Besides the high relevance of C2 and ISR the US DoD (2008, p. 4) adds that an SoS is "a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities." The idea of individual systems forming a greater, more powerful common entity when combined with other systems in order to amplify strengths and cancel out weaknesses is picked up again in the characteristics of an SoS, which Maier (1998) describes as:

- Operational Independence: Every system in an SoS must be able to operate independently when not integrated with an SoS.
- Managerial Independence: Every system in an SoS serves a purpose by itself, thus operating even if it is not attached to an SoS.

- Geographic Distribution: The systems inside an SoS are distributed over a vast area, allowing them to exchange information but not commodities such as energy sources or mass.
- Evolutionary Development: A SoS is steadily subject to change as there are constantly systems entering or exiting the SoS, changing its appearance.
- Emergent Behavior: Through the collaboration between the systems in an SoS, a synergism is reached in which the system behavior fulfills a purpose that cannot be achieved by, or attributed to, any of the individual systems. (Nielsen, 2020, p. 18:5)

Out of these five characteristics, the first two, Operational Independence and Managerial Independence determine whether an entity is considered a System of Systems or not and therefore form the discriminator for the lower limit of SoS depth. (Maier, 1998, p. 271) In other words, these two characteristics help to understand where an IADS ends. A Tactical SAM battery, e.g., consists of a command vehicle, supply trucks, TELARs, and Loaders. The individual components or systems in a Tac-SAM battery are able to operate independently and the battery as a whole serves a purpose by defending its assigned battalion even if not connected to other batteries. A TELAR as part of the air defense battery SoS might have managerial independence since it is able to engage targets without external inputs by integrating transport, missile launch, and radar capabilities, but the radar, missiles, chassis, engine, etc. it consists of are not able to operate independently, when not part of the TELAR. Hence, the TELAR itself is not considered an SoS anymore and instead forms the lowest level of its superseding systems of systems, the batterie. Based on the previous analysis, the two chains of command will be considered individual systems of interest as they have different attributes and contributions to the IADS as a whole. With the PVO-SV Tactical SAMs and the VKS strategic SAMs representing the weapons, the other categories are consequently the EWRs and the Command and Control system. The following table rates the contribution of the individual systems to the IADS as an SoS according to the criteria defined by Nielsen in order to identify whether there is a System of Interest (SoI) in the IADS, that provides a critical contribution to the SoS and therefore is of strategic importance, both for Russia to protect and for NATO to target.

System of Interest / System characteristics	Command and Control Systems (e.g., Polyana-D4M1)	Early Warning Radar Systems (e.g., NeboSVU)	Surface to Air Missile Systems	
			Tactical SAM systems (PVO-SV)	Strategic SAM system (VKS)
Operational Independence	Independent command post vehicles usually able to operate without external support for more than 24 hours.	EWR troop consists of all items necessary for independent remote operation	Integrates all items to conduct own targeting cycle	Is comprised of all components necessary to operate independently
Managerial Independence	Has a command and reporting function even without SAM integration but has limited effect	Can be used to track targets without external connection, but defeats its purpose	Can be and is often used independently.	Highly relevant, also without IADS connection
Geographic Distribution	Limited to controlled assets but flexible within communications range	Wide distribution increases both, radar coverage and survivability if attacked	Short weapons range limits standoff to protected assets	Distribution defined by location of protected strategic assets
Evolutionary Development	System is capable of adapting to SAMs to be controlled	Can integrate with other EWR or changing command posts	Main factor in the changing appearance of an IADS	Can adapt modularly by removal of firing units or addition integrated of EWR
Emergent Behavior	Main contributor to optimized targeting efficiency and enabler for extended radar range for AD systems	Increases SA, especially for Short Range Radar (SHORAD) systems	Covers Strategic SAMs weaknesses to target close-in threats with better efficiency	Provides the long-range threat, is the main challenge for air power operations in the Russian A2/AD

Table 2: Characteristics of an IADS as a System of Systems

As the comparison of the characteristics of the individual Systems of Interest shows, there is not a single subsystem in the IADS that appears overly important or superfluous. Each system has its contribution to making the Russian IADS a capable threat. Therefore, this approach has not pointed toward a weakness in the IADS design but rather highlighted the value of what System of Systems theory calls emergent behavior. Each subsystem helps to cancel out the weaknesses of another subsystem. EWRs help to extend the detection range of short-range radars, which in turn are able to target threats of too low priority for expensive long-range SAMs. Long-range SAM systems keep threats to EWRs at a distance, and the lack of integration between PVO-SV and VKS is mitigated by the rigidity of the C2 structure within each chain of command, respectively. And yet, if there is one system that influences the behavior of the other system most, it is the C2 system. More specifically, based on the previous analysis of the C2 structure in an IADS, the battalion command posts seem most critical. They provide the batteries with EWR information, enable automatic targeting controlled by higher echelons, and streamline the effects between different battalions. After an extensive analysis of the operational level factors of the Russian IADS the tactical level considerations with regard to individual system capabilities will be looked at.

A2/AD through IADS at the Tactical Level

At the tactical level, there is a large number of weapons systems to be considered to cover all aspects of an IADS. An extensive analysis of Russian fighter capabilities, man-portable air defense systems (MANPADS), and anti-aircraft artillery (AAA) would miss the scope of this thesis. Russian fighter jets pose a threat in themselves and would be used to cover gaps in the Russian GBAD. MANPADS, AAA, and small arms fire increase the risk of low level operations. Yet, the focus for SEAD operations lies on SAM systems. Starting with VKS systems, the most capable in the Russian inventory is the S-400 Triumf, which is the successor to the S-300PMU2 still in service. In addition to the 55K6E command post, the system complex uses its own 91N6E Big Bird S-band surveillance radar with a claimed range of 600km at the battalion level, which can be enhanced by EWRs like the Nebo M complex or the 96L6E Cheese Board. The track data are fed to up to six fire units consisting of a 92N6E Grave Stone X-band radar for target engagement and up to twelve TEL vehicles carrying up to four missiles each. (Kopp, 2009a) A regular battalion consists of three fire units with the Grave Stone radar along with three TELs equipped with four to 16 missiles depending on type. The often cited range of 400km (215 NM) can only be reached with the 40N6E missile.

The shorter range 48N6E2 missiles has a claimed range of 250km, while the active radar seeker head 9M96E2 is claimed to reach 120km of range.

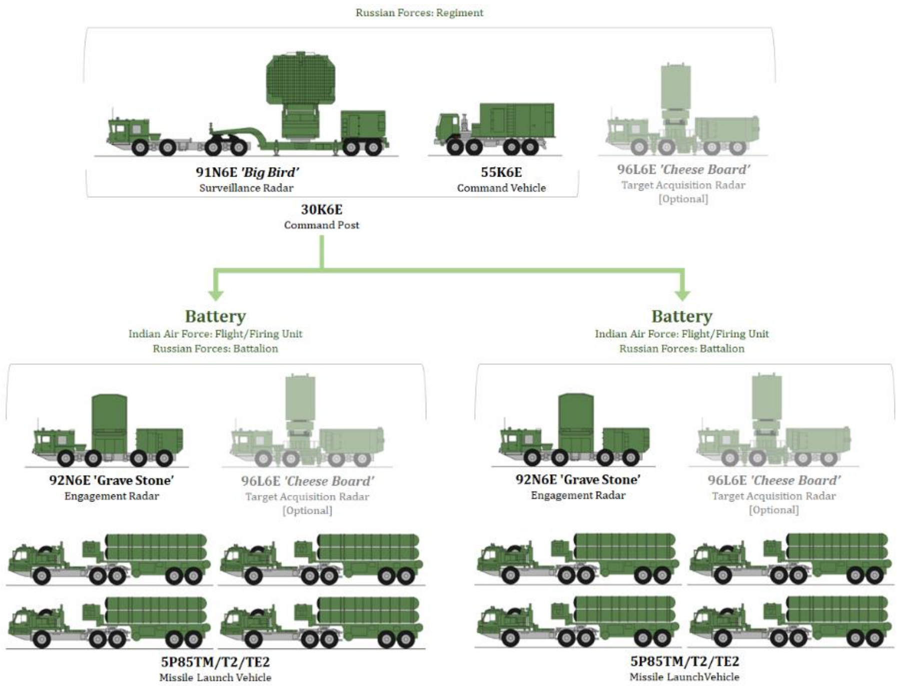


Figure 204: Structure of an S-400 Regiment Copyright: Mihir Shah/LiveFist Defence

A regiment of S-400 is usually protected by a batterie Pantsir-S1 (NATO SA-22 Greyhound) short-range air defense system consisting of six TLAR vehicles. While each Pantsir can operate autonomously, their doctrinal role is to utilize the EWR detection of the S-400 and defend against small threats as a second layer of defense. This can be done by handing over the fire control to the S-400 command post or directing fires by on lead vehicle in the Pantsir battery. Each SA-22 has a Hot Shot radar operating in S- and Ka-band, eight 57E6-E missiles with a range of 15-20 km and two 30mm canons for short range engagements. (RusArmy.com, 2010) An upgraded variant with an AESA radar and a doubled detection and engagement range has been announced in 2016. (TACC, 2016) With the S-350 a new medium range SAM system has recently been introduced to the VKS. It consists of a 50K6E command post, a up to two 50N6E radars and up to eight 50P6E TEL vehicles, each carrying 12 9M96E2 active radar missiles with the claimed 120km range known from the S-400. The system can engage 8 targets per radar with 16 missiles. A passive infrared short range missile with a range of up to 15km will be introduced as well. (oruzhie.info, 2023) The S-500 is another new VKS system. Little is known about the system yet, but it is designed to target Balistic Missiles, hypersonic glide vehicles and high value airborne assets such as jammers or

ISR aircraft at range of up to 600km. In terms of PVO-SV systems, there has been an upgrade to the Buk air defense system. The medium-range Buk-M3 (NATO SA-27 Gollum) has seen an upgraded range of 70km for the 9M317M over its predecessors SA-11 and SA-17. The number of missiles per launcher is either six for a TELAR or twelve for a TEL. The 9C18M3 target acquisition radar allows target detection at 16o km and the mast mounted 9A317M target illuminator is claimed to achieve tracking at 120km range. The target engagement radar can steer up to six missiles simultaneously. During the Russian invasion in Ukraine the Buk missile system has supposedly intercepted HIMARS rocket artillery rounds. (Thakur, 2023) The last PVO-SV tactical SAM system observed is the Tor-M2 (NATO SA-15 Gauntlet). It is an updated version of a short-range SAM system. It can carry up to 16 missiles and achieve a maximum engagement range of 16km. The system is able to engage four target simultaneously.

System	**Radar (band)**	**Range**	**Missile**	**Range**	**No. simul. Tgts/Msl**	**MSL per launcher**	**MSL per battery**	**MSL per battalion**
S-400 **SA-21**	91N6E (S) Big Bird	380km @4m² RCS/ 30km (Karpenko, 2014)	40N6E Semi-active	400km 215NM	6/12 per Grave Stone	4(40N6E)-16(9M96E2)	12-48	36-144
	92N6E (X) Grave Stone	380km	48N6E3 Semi-active	250km 135NM				
			9M96E2 Active	120km 65NM				
Pantsir-S1 **SA-22**	Hot Shot TA(S) TI(Ka)	25km @ 1m² RCS (RusArmy.com, 2010)	Semi-active	15km 8NM	2 / 4	8	48	-

S-350	unknown	-	9M96E2 Active	120km 65NM	8/16	12	96	-
			9M100 IR	15km 8NM		48	352	
Buk M3 SA-27	9S18M3 Snow Drift (S)	160km @ 1.5m² RCS (Missilery.info, 2023)	9M317M	70km 38NM	6 / 6	6-12	12-24	36-72
	9S36M Chair Back (X)	120km @ 1.5m² RCS						
Tor M2 **SA-15**	Scrum Half TA(X) MG(K)	40 km 30 km	9M338K	16km 8.5NM	4/8	16	64	-

Table 3: Summary of SAM system capabilities

4.3 Discussion of IADS Capabilities

The Russian IADS poses a challenge to NATO air power, that it has never faced before. It constitutes a multilayered challenge in multiple ways. The strategic purpose as part of the Russian A2/AD complex is ultimately to attrite NATO air forces. An air defense system with that many long-, medium- and short-range threats will be very difficult to pick apart without losses. This could raise the question, whether it is necessary to penetrate the A2/AD bubble or whether it can simply be avoided. In case of a NATO article five intervention, there will be no way around it, without sacrificing the alliance's credibility. By avoiding the IADS, NATO would leave air superiority in the contested area to Russian Forces, resulting in an even more difficult ground situation. After it is clear, that there is no way to avoid the IADS, it is essential to be aware of the strengths and weaknesses of that system of system in order to exploit them. The first strength addressed, lies in the sheer quantity of air defense assets of the Russian forces. The following table shows the Air Defense Forces of the Western Military District alone. This seems to underline what Joseph Stalin once meant as he stated that quantity has a quality of its own. Just the pure numbers of dedicated air defense brigades and regiments challenges the Western military industrial complex as there are neither enough dedicated SEAD assets among European NATO allies, nor sufficient stockpiles of specialized ammunitions to effectively counter an air defense system of such size.

Branch	Army	Division	Anti-Aircraft Missile Brigade	Anti-Aircraft Missile Regiment
PVO-SV	6th Combined Arms Army		5th - Lomonsov, Leningrad Oblast	
	20th Guards Combined Arms Army	3rd Motor Rifle Division		1143rd - Belgorod Oblast
		144th Motor Rifle Division		1259th
	1st Guards Tank Army	2nd Guards Motor Rifle Division		1117th - Golitsyno, Moscow Oblast
		4th Guards Tank Division		538th - Naro-Fominsk, Moscow Oblast
				49th - Smolensk, Smolensk Oblast
			53rd - Marshala Zhukova, Kursk Oblast	
	Western Military District		202nd Separate - Naro-Fominsk, Moscow Oblast	
Baltic Sea Fleet	11th Army Corps	44th Air Defense Division		22nd - Kaliningrad, Kaliningrad Oblast
				183rd, Gvardeysk, Kaliningrad Oblast
				1545th, Znamensk, Kaliningrad Oblast
VKS	6th Air and Air Defense Army	2nd Air Defense Division		500th Air Defense Regiment - Gostilitsy
				1488th - Zelenogorsk
				1489th - Vaganovo
				1490th - Novolisino
				1544th- Vladimirsky Lager
		42nd Air Defense Division		42nd - Izhitsy
				108th - Shilov

Table 4: Disposition of Russian Western Military District Air Defense Forces sorted by Branch (cf. Harris & Kagan, 2018, pp. 18–20; Muzyka, 2021, p. 39)

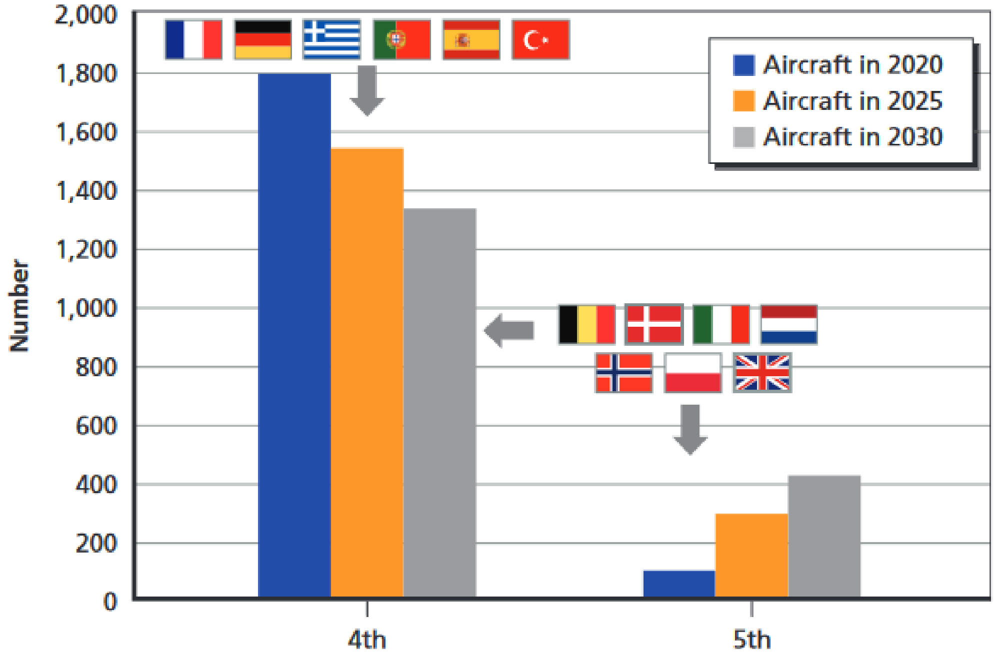
On the other side, a large structure has a number of disadvantages. The Russian approach to handling such a large and complex system is based on a high level of automation in combination with the enforcement of a culture of command and control as opposed to mission command like in many Western militaries. While a strict leadership culture discourages initiative of individual system operators, a high level of automation leaves the operators with little experience and confidence when a SAM system must be operated manually. This exposes another weakness. A long chain of command through a number of command posts is vulnerable to disruption at an intermediate level in the chain. Hence, critical nodes in the IADS need to be identified to leverage the friction that is created, when lower-level units are suddenly on their own. Additionally, the different chains of command between VKS and PVO-SV can be utilized to put operational focus on only one chain of command at a time. The second challenge identified is posed by the Russian IADS is the mobility of almost all Air Defense assets in the scenario. This challenge is unprecedented in any other previous NATO SEAD campaign. It requires the persistent employment of ISR assets to keep the Electromagnetic Order of Battle (EOB) as current as possible and shift the tone of operations from large preplanned force packages to smaller, more flexible elements able to dynamically react to an updated threat situation. Another requirement is the ability to intercept moving targets, nearly all Russian tactical SAM systems are other able to shoot on the move or employ shoot and scoot tactics, changing their position just seconds after missile firing. For strategic SAM systems, it is once again the intelligence portion of ISR that is required to recognize a pattern of life to identify, which prepared site a Strat-SAM choses next, at least in a geographically confined area like Kaliningrad Oblast. The third challenge that differentiates the Russian IADS from previous adversary air defenses is the technological sophistication. It is a matter of fact, that all SAM systems introduced in this chapter are able to target small or fast-moving targets like cruise missiles, HARMs and PGMs. Additionally, the advancing proliferation of AESA radars among Russian air defense systems poses a major challenge to previous concepts of employment. Low probability of intercept, pseudo-random radar emission patterns make it nearly impossible to employ deception jamming techniques, as it is plainly not possible to anticipate the next pulse, the ground-based radar is going to send, especially with non-AESA radars on the jammer side. This is just one example for a number of SEAD standards that need to be rethought when facing a modern day, electromagnetically hardened IADS. Furthermore, concepts like a cooperative engagement capability i.e., the blind, unguided launch of a missile by one air defense system with the intent to illuminate the target or guide the missile by another, geographically displaced radar, are discussed in literature and must be considered as an eventuality during SEAD planning. With these three unique challenges of the contemporary Russian IADS the argumentation made, that hypothesis one for this thesis can be accepted.

H1: The Russian Integrated Air Defense System as part of an Anti-Access/Area Denial complex is a powerful threat to NATO operations in Europe.

Figure 205: Russian IADS at strategic, operational and tactical Level

5 Contemporary SEAD Capabilities

Now that it is pointed out, why the Russian IADS is a different threat from the ones observed in previous SEAD campaigns, this chapter is dedicated to analyzing the SEAD capabilities that exist at the time of writing and in the near future until 2025. I.e., the latest variant of an ARM, the AARGM-ER and the Next Generation Jammer Medium band and low band will be considered, while other capabilities, like a future Eurofighter ECR or the Next Generation Jammer High band will not be part of the analysis. Since this chapter refers to different generations of fighter jets, a brief overview is given. In a study to quantify a nations air power compared to other nations Saunders and Souva defined the following criteria as decisive to categorize fighter aircraft (2020, pp. 739–740): sophistication of the aircraft’s avionic equipment, the top speed of the aircraft, the presence of sophistication of an aircraft's radar, the range and sophistication of weaponry commonly carried and the level of stealth technology employed. Beginning with the introduction of jet engines in World War II generation 0 aircraft like the P-51 Mustang lack all of the defined characteristics, while generation 1 aircraft like the Havilland Vampire gained extra maneuverability and speed by their jet engines. Generation 2 fighters, such as the MiG-15 or the F-86 "Sabre"saw the first on board range finding radars and short range guided missiles, but was still limited to subsonic flight. Generation 3 aircraft like the MiG-21 or the F-104 "Starfighter" were able to achieve and maintain supersonic speeds at level flight and employ radar guided beyond visual range missiles. Generation 3 also marks a point, where no longer better flight characteristics but superior SA were the decisive advantage in air warfare. Generation 4 fighters like the F-16, F-15 "Eagle" and MiG-29 incorporated look down- shoot down radar capabilities, advanced avionics, fly by wire systems and swept-wing aircraft designs. Characteristics of Generation 4.5 are first and foremost the introduction of AESA radars but also supermaneuvrability, limited sensor fusion and limited stealth by an intentional reduction of RCS. Examples are the F-15 "Strike Eagle", the F/A-18 E/F, and the Dassault Rafale. Finally, characteristics of generation 5 aircraft are described as supercruise and thrust vectoring based on the only fifth generation aircraft in the study, the F-22. This is an essential part of the criticism on the F-35 since it lacks many features, that are deemed essential to 5th generation fighters depending on their intended role. The F-35 does not feature supercruise, supermaneuvrability and thrust vectoring along with the reduced payload compared to generation 4 fighters. Nevertheless, since the F-22 is not offered for export and European NATO allies collectively lack an own 5th generation fighter development, the F-35 is the only option available on the market has become the common platform among European NATO members and partners. In the foreseeable future there will be 545 F-35 in Europe as of the time of writing. (Finland 64, Germany 35, Switzerland 36, UK 138, Italy 90, Belgium 34, the Netherlands 37, Poland 32, Denmark 27, Norway 52) This however, hides the fact, that a larger fleet of F-16s, Tornados, Harriers and other 4th Generation assets will be retired in exchange. The following chart from 2020 visualizes the share of 4th and 5th generation fighter fleets in Europe until 2030 although it does not reflect the latest procurements of F-35s by Switzerland, Finland and Germany.



SOURCE: RAND analysis based on IHS Jane's, *The Military Balance*, interviews, and open source reporting.

Figure 206: Fleet development with regard to 4th Generation and 5th Generation Fighter Aircraft in Europe until 2030 as of 2020 (Binnendijk et al., 2020, p. 83)

Looking at the challenges posed by the Russian IADS, European military leaders can and must not overlook the vast potential for SEAD operations that lies in these numbers. This raises the question, how the European NATO allies, supported by US assets where inevitable, can face the SEAD challenge in front of their doorstep.

5.1 5th Generation Fighter Capabilities

The F-35 will be the only 5th generation SEAD asset available in Europe until further notice. Since the aircraft was designed for this role of air power, the unique features for SEAD operation will be elaborated on. Although the F-35 does not provide the same level of 5th generation capabilities, like an F-22 due to reasons of cost effectiveness, there are two features qualifying the F-35 as an excellent SEAD asset, first sensor fusion and second very low observability in this order. (Annex 6,7) The F-35 provides a real time sensor fusion capability, that merges the information of a variety of sensor inputs such as RWR, radar, ELS, and IRST as well as inputs by other flight members via Link 16 and the proprietary data link MADL (Multifunction Advanced Data Link) into one situational awareness picture. This is nothing new by itself, as efforts to integrate similar cooperative ESM operation (CESMO) projects in 4th generation platforms show. However, the level of usability and simplicity for the pilot to effortlessly receive fused sensor tracks and focus on mission execution is unprecedented. The following figure shows the different levels of sensor fusion from 4th generation over 4.5th generation to 5th generation platforms.

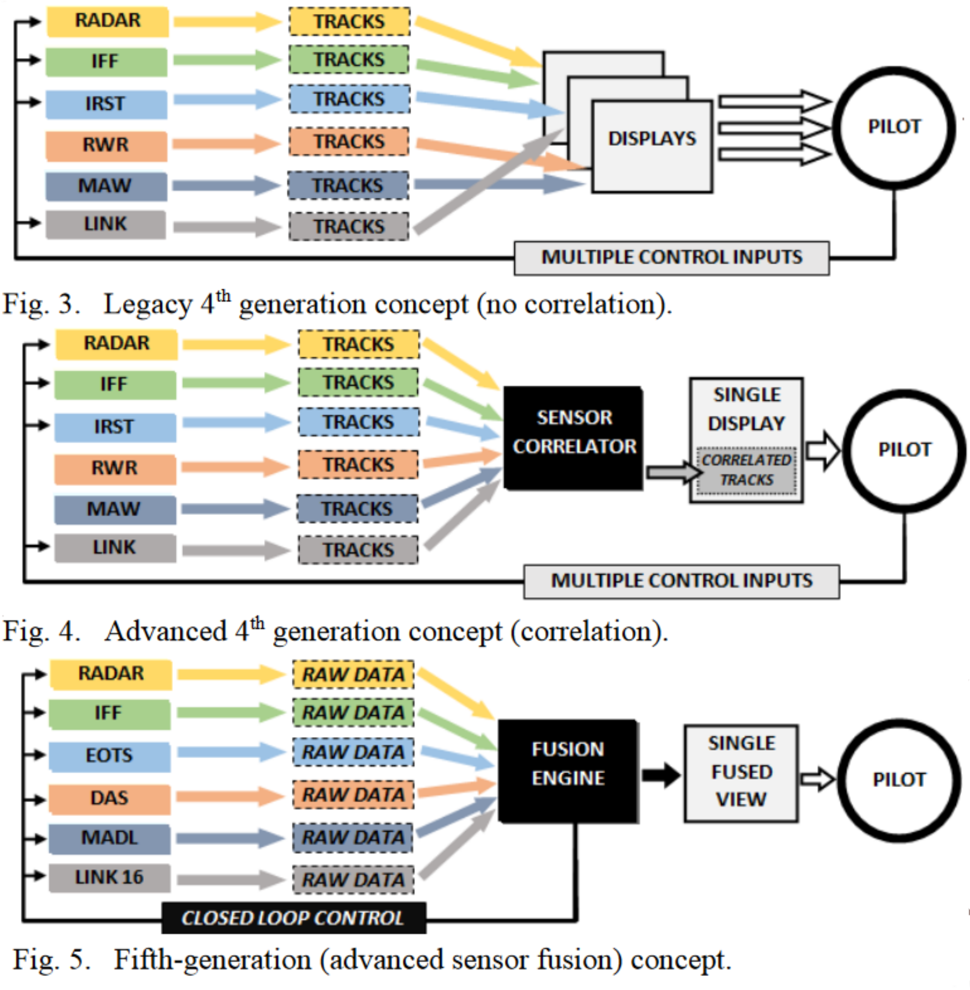


Figure 207: Sensor Fusion from 4th generation to 5th Generation Fighter Aircraft. Modification of (Svoboda et al., 2019, pp. 2–4).

The sophisticated sensor suite and the high level of sensor fusion allows the F-35 to gather information, that in a traditional 4th generation force composition only high value airborne assets like the E-8 JSTARS for Synthetic Aperture Radar (SAR) applications or the RC-135 Rivet for ELINT, could collect. This comes with implications for standing C2 procedures. While the target engagement authority usually does not lie with the weapons platform, but is taken care of by airborne or ground controllers in line with higher headquarters, the level of SA provided by the F-35 can exceed the SA of a controlling agency. Therefore, C2 procedures must be adjusted to utilize the information available and avoid hindering the decision-making and targeting process. The second feature of the F-35, that is an enabler for

SEAD operations is the very low observability for air defense radars, due to its design and the application of Radar Absorbent Material (RAM). While stealth measures should reduce the footprint in the entire EMS including audible noise and heat emissions, the focus for the F-35 was put on reduced radar reflectivity. Since the RCS varies with different angles from radar to target e.g., when the aircraft turns, climbs or descends the RCS is not a fixed value but varies depending on viewing angle and wavelength. Additionally low frequencies in the in the VHF band (30-300MHz) have a wavelength identical to some F-35 part lengths, therefore inducing a resonance turning these parts into an antenna amplifying the received radar waves. This phenomenon called resonant scatter is less likely to occur in larger stealth aircraft like the B-2 Spirits since the frequency to induce resonance in larger parts needed to be in the HF band below 30MHz and is therefore not practically achievable for EWRs. For smaller stealth aircraft like the F-35, this means an increased RCS in the VHF band emitted by self-proclaimed anti-stealth radars like the NEBO-SVU. Nonetheless, the detection range in other radar bands, especially the X- band (8-12GHz) and Ku-band (12-16 GHz) frequently used for missile guidance or target illumination is still largely reduced. In other words, the Russian IADS can see an F-35 but is not able to target it, until it gets close to the SAM systems fire control radar. The following table is based on RCS values for the F-35 out of three independent open-source articles and applies the corresponding RCS to the respective radars band. (“F-35 vs J-20 vs Su-57 Summary,” 2023; Kopp, 2009b; Zikidis et al., 2014, p. 146) The radar data is taken from table 3 in this thesis. For the other examples, a fixed RCS value independent of the radar band was used for simplification, as this example is meant to show the concept behind very low observability rather than develop TTPs.

Radar Data according Table 3			**MSL Range**	**Expected Detection Range with given RCS approaching head on**		
Radar Type	Reference Range acc. Source (see table3)	Reference RCS acc. Source (see table 3)	Maximum effective targeting range	F-4/ Tornado RCS 5m²	Eurofighter 0.1m²	F-35 L-band 0.0063m² S-band 0.00316m² X-band 0.0003 m²
91N6E (S-band) Big Bird S-400 Target Acquisition	380km 205NM	4m²	400km 216NM	402km 271NM	151km 81.5NM	64km 34.5NM

9S18M3 (S-band) Snow Drift Buk-M3 TA	160km 86NM	1.5m²	70km 38NM	216km 117NM	81km 44NM	34km 18.5NM
9S36M Chair Back (X) Buk-M3 Target Illuminator	120km 65NM	1.5m²	70km 38NM	162km 87.5NM	61km 33NM	14km 7.7NM
Pantsir S-1Hot Shot TA(S)	25km 13.5NM	1m²	15km 8NM	37km 20NM	14km 7.6NM	6km 3.2NM

Table 5: Expected Detection Ranges in Relation to RCS

The previous examples have shown how the very low observability attributes of an F-35 reduce the expected detection range well below maximum missile range of the respective SAM system. This concept allows the F-35 to penetrate deep into the enemy's air defense with significantly reduced risk of being targeted. However, this does not cater for ambush tactics, where the radar is intentionally kept off until the F-35 is overhead as observed with the loss of an F-117 in Kosovo. In order to reduce the probability of detection even further, the F-35 features an AESA radar and the MADL, both capable of low probability of intercept communications. A tradeoff for the low observability design is a reduced payload, as the stealth features are only retained as long as no external stores are carried, while the bomb bay capacity is limited. Furthermore, the opening of the bomb bay doors just prior weapons deployment spoils the stealth attributes in turn increasing the probability to be detected upon weapon release. Therefore, the survivability inside the Russian IADS is highest, when the F-35 serves as an ISR asset under EMCON conditions.

5.2 4.5th Generation Fighter SEAD Capabilities

As opposed to 5th generation fighter jets, there are more options available among generation 4.5 fighter jets, also called generation 4+. While there are more and more modernized 4th generation fighters equipped with new AESA radars, there are still only very few dedicated SEAD assets among them. The most prominent example is still the EA-18G Growler. It features an AN/APG-79 AESA radar with MTI and SAR modes capable of generating target coordinates on its own when required. Like many generation 4.5 fighters, the Growler also has a reduced observability capability, with an RCS of approximately 0.1m², comparable to its European counterparts Eurofighter Typhoon and Dassault Rafale. (Zikidis et al., 2014, p. 140) Since the SEAD capabilities implemented by AGM-88E and AN/ALQ-99 low and medium band jamming pods have been introduced earlier, their effect on the Russian IADS is discussed at this point. The AARGM provides more accurate targeting than its HARM predecessors due to the integration of GPS for midcourse guidance and a millimeter wave radar for terminal guidance. Additionally, this increases the probability of hit. However, the AARGM does not provide the range and standoff required to target the strategic SAM complexes such as S-400 or S-300V4 that are omnipresent in the A2/AD debate. Therefore, the AARGM is a suitable weapon against medium and short-range air defenses. The downside to that is that all SAM systems observed in this thesis are ARM aware i.e., they either start defending against the AARGM or they just simply turn of their radar to avoid destruction as they move from their previous position. While this was the desired effect in previous campaigns as the radar was successfully denied, allowing a force package to exploit that defenseless moment in order to ingress to the target area and wreak havoc, chances are that today there is just the next layer of air defense systems waiting. Therefore, it seems irrational to shoot an expensive high-tech missile at an aware SAM system to buy 30 seconds of suppression or exchange one ARM for two SAMs. In a dense, multilayered air defense system the benefit of the AARGM is rather in its high speed compared to other stand of munitions like glide bombs or air launched cruise missiles. Launched as a reactive shot in terminal mode at fairly short range, considered a target of opportunity attack under the label of opportune suppression according doctrine, the AARGM has a fair chance to hit its target and achieve weapon effects. Facing a ridiculous number of air defense systems, suppression by kinetic means through preemptive targeting is not on demand in a high intensity conflict. DEAD is the new SEAD, since only destructive effects peal a layer of the Air Defense onion. This does not mean that ARMs are irrelevant in a future conflict. It just means that a conventional preemptive ARM shot plan should at least support the destruction of the targeted system through other assets with less expensive ordnance. Alternatively, and specifically when an EA-18G Growler is available, this kind of support can be provided by standoff jamming. While jamming can be a cost effective SEAD option available for as long as the jammer is on station, it also poses a couple of challenges. First, at the time of writing, the only standoff jammer among NATO air assets belongs to the US Navy and will be much needed in the Indo-Pacific Theatre, should the United States continue their pivot to Asia. This unveils one of the greatest weaknesses among NATO members in Europe for the foreseeable future. The Eurofighter ECR variant includes a pod based stand of jamming solution and can fill the Growler gap in Europe in the long run, but not within the next five years. (Scott, 2020) In addition this pod based solution needs to be equally specialized, as the next generation jammer program for the Growler. The technological challenge behind a growing number of Air Defense Systems employing AESA radars has a decisive impact on stand off jamming. First, the extremely high frequency agility, the signal complexity and most importantly, the pseudo random sequence of signals makes it impossible to use deception jamming techniques that need to anticipate the next radar signal to be effective. One option to counter this frequency agility is barrage jamming, which requires a high total power output with little effect in each frequency band, also known as low Watts per MHz. Another challenge in jamming AESA radars is the precise beam steering with small side lobes of an AESA radar. This increases both, the power required to jam the main lobe as well as the power required to effectively jam the narrow sidelobes. Ultimately

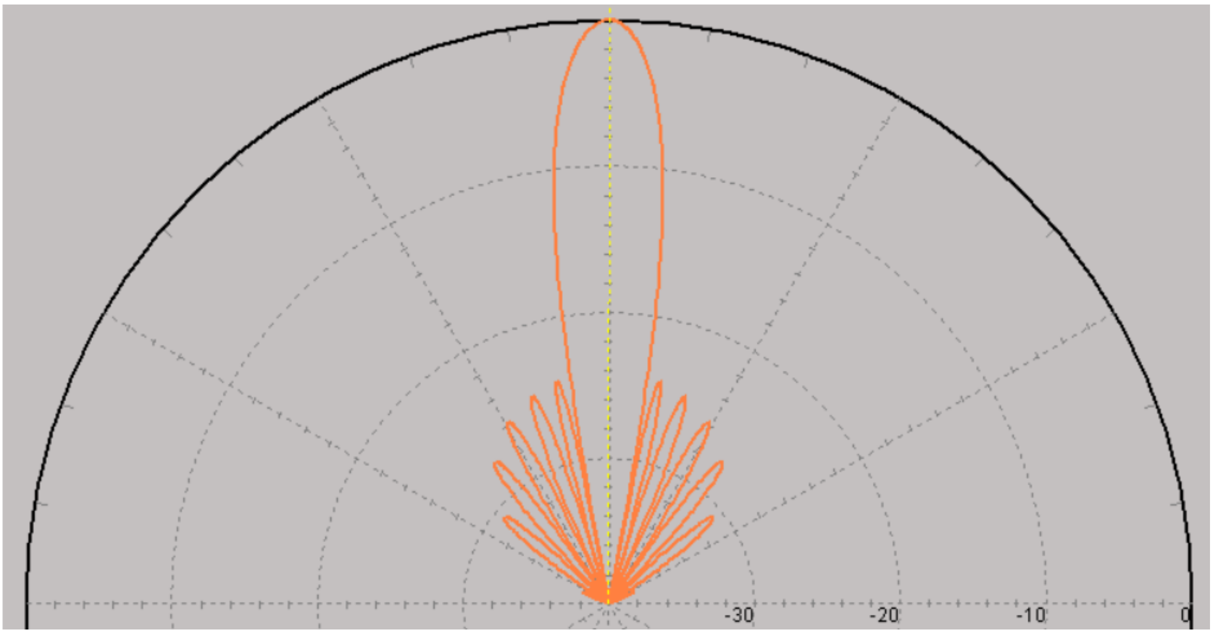


Figure 208: Polar plot for estimated azimuthal plane sidelobe / mainlobe performance of an Nebo SVU EWR; peak sidelobe level of -24 dB; created by Karlo Kopp. (Kopp, 2008)

this means, that it requires an AESA radar to effectively jam an AESA radar, ideally in a pod-based solution with own power generating capability and state of the art Gallium Nitrite (GaN) radars, that are able to distribute the heat, that is generated during high power jamming. Such a solution is about to be introduced by the US Navy and is not in sight yet in Europe. The announced solutions for the Eurofighter and recently also for the French Rafale will not be available before the end of this decade. (Defense.fr, 2023) The fact that there are two European solutions underway shows that the importance of these SEAD capabilities has been realized. Only the timeframe might create a major capability gap, when Growlers are prioritized elsewhere. The only spark of hope in European stand-off jamming is the Arexis jamming suite in the Swedish Saab Gripen-E. This system has been integrated in the Gripen-E from scratch and entails a highly specialized solution for a generation 4.5 fighter including low band jamming capabilities that are especially useful against anti-stealth EWRs. However, the power to conduct jamming operations is drawn from the jet itself as there is no external power generating system like in pod-based solutions. This means, that the system can cover a wide range of frequencies, but with limited power output. Finally, this means that the Gripen-E has an excellent self-protection suit, allowing it to operate inside the IADS almost like an F-35, with a major drawback. Jamming can be homed on by SAMs and therefore precludes extensive excursions by jamming assets into the IADS bubble.

At this point a clear enough picture has been painted to draw a conclusion regarding hypothesis two for this thesis.

H2: NATO has the SEAD capabilities in Europe to counter the Russian Integrated Air Defense System threat

This hypothesis must be rejected. NATO as a whole does have the capabilite required but an essential piece to the SEAD puzzle is a standoff jamming capability. Only the US Navy EA-18 G can presently provide this capability. But the Growler is neither permanently stationed in Europe, nor will it be available, should a conflict between the US and China escalate. A growing F-35 fleet and own European standoff jamming capabilities will establish the capabilities required by the end of the decade. But at the time of writing European NATO SEAD capabilities consist of two squadrons ECR Tornados, that will simply not suffice if forced to counter the Russian IADS.

6 A modernized Approach to conducting SEAD against the Russian IADS

By now, a thorough understanding of the status quo of the Russian IADS as part of the A2/AD complex on one side and the ability of European NATO allies to conduct SEAD operations on the other side has been built. The Russian IADS poses an extraordinary threat to NATO's freedom of movement, should a Baltic State become victim of Russian revisionism. This extraordinary threat must be met by an extraordinary joint combined SEAD effort, exploiting weaknesses in the Russian IADS and leveraging strength among NATO forces. It is of utmost importance to keep in mind, that the purpose of the Russian IADS ultimately is the attrition o Western Air Forces. The defense of Europe by European NATO allies and partners only does not appear feasible. Therefore, a modernized approach to SEAD operations, far beyond standoff jamming and HARMS will be developed on the foundation of the previous chapters. The modernized approach combines two concepts described in literature. One dimension distinguishes between SEAD from the inside out and from the outside in. (Schmidt, 2018, p. 254) The other dimension distinguishes between three different levels of SEAD. (Binnendijk et al., 2020, p. 86)

6.1 5th Generation SEAD

Level 1 SEAD describes SEAD at the outset of a high intensity conflict. It utilizes means of Joint SEAD to achieve a diversification of effects in order to mirror the complexity of the Russian IADS with an equally complex array of vectors to deny, degrade, disrupt and destruct the enemy IADS. It consists of multiple lines of operation in order to orchestrate effects across the different domains, integrating land, sea, air, space, cyber and electromagnetic warfare effects. Level 1 SEAD was successful when sufficient gaps have been breached in the enemy IADS for less survivable assets to operate in. Level 2 SEAD is conducted under temporary air superiority and allows SEAD assets to conduct conventional SEAD operations by the use of electromagnetic attack in order to isolate remaining Air Defense Systems from the IADS. Level 3 SEAD targets the remaining scattered enemy air defense systems. Close attention must be paid to air defense systems operating under EMCON in order to avoid loses by ambushes.

Level 1 SEAD will be preceded by a Phase 0 in order to gather intelligence on the enemy IADS. Phase 0 utilizes ISR assets in order to generate an electromagnetic order of battle and conduct a critical node analysis of the chain of command of the enemy IADS. This critical node analysis contains those elements along the chain of command, that have the most disruptive effects on the operations of the enemy Air Defense. Additionally, air, sea and land and EW assets are prepositioned to achieve a high readiness state for the upcoming operation. Upon commencing of phase one multiple formations of very low observable F-35 aircraft penetrate the enemy IADS under strict EMCON procedures and provide real time target updates without targeting any air defense systems on their own. Updated target positions of the previously identified critical C2 nodes are then forwarded via Multifunction Advanced Data Link (MADL) to a formation F-35 outside of the IADS that acts as an interface and distributes the updated target information via Link-16 to other assets in the COMAO. Typical targets for the initial phase of level one SEAD are expected to be battalion command posts of log range S-400, S-500 and S-300V4 strategic air defense systems, integrating individual fire control modules with EWRs and C2 to higher level command structures. A timely rotation of these deep reconnaissance missions is required in order to maintain SA on the enemy C2 without interruption. While the F-35 formations support JOA SEAD through EOB gathering and ISR operations, the data will be forwarded from the most forward element via low probability of intercept data link MADL and the interface element to other airborne assets outside of the IADS. Parallel to the ingress of the F-35 formations at the beginning of phase 1, a saturation attack by maritime long range strike assets, land-based rocket artillery and is conducted on air defense assets close to the FLOT. Offensive Cyber Operations (OCO) are employed in order to deny, degrade or disrupt the enemy’s C2 structure. Electronic warfare operations contribute to the diversification of vectors to target the Russian IADS. Furthermore, generation 4 and 4.5 SEAD assets conduct localized suppression operations against mobile tactical SAMs in the vicinity of the FLOT. The ingress of the F-35 fighters will be covered by the deployment of expandable EW means such as MALD-J or Spear-EW. Once the target set has been updated by the F-35 formations, a barrage of network enabled standoff weapons such as the AGM-154 Joint Standoff Weapon or the Joint Strike Missile is employed by conventional 4th generation fighter aircraft outside the IADS. The target information is updated by the F-35 tasked as the interface unit between

Link-16 and MADL network participants. This pattern of operations is maintained until enough long-range strategic SAM systems have been destroyed so that less survivable SEAD assets can commence with Level 2 SEAD operations from within the IADS.

Level 2 SEAD operations eventually begin to resemble conventional SEAD operations utilizing Standoff and Escort jamming to secure the ingress and egress of 4th generation fighters to individual patches inside the IADS, where air superiority for Western air assets has already been obtained. From there dynamic targeting operations using the F2T2EA cycle can be initiated and supported by localized suppression operations by kinetic and non-kinetic SEAD means. SEAD assets can contribute to EOB gathering operations and conduct opportune suppression in targets of opportunity. During these operations, the tasked SEAD assets need fighter escort support against airborne threats inside the AOR. Once air superiority has been extended from single patches to larger, consecutive areas, the pattern of operations can be shifted to Level 3 SEAD.

Level 3 SEAD can be conducted once the C2 system of the IADS has been degraded to an extent, where individual SAM systems are forced to operate autonomously. Level 3 SEAD can be conducted by AESA radar equipped fighters with a moving target indicator function. This aids the finding and fixing of individual target acquisition radars, which then can be targeted via the regular targeting cycle. This process of SAM-hunting can be aided by UAVs equipped with Synthetic Aperture Radars. At all times it must be kept in mind, that Russian tactical SAM systems are nearly a potent individually as they are in a battery attached to the IADS.

6.2 Considerations for high Intensity SEAD Operations

The presented approach to SEAD operations in a highly contested environment, especially the Level 1 operations show little resemblance with SEAD campaigns of previous SEAD campaigns. This is for two main reasons. First, the lethality of the Russian Integrated Air Defense Systems is far higher than previous IADS encountered. Second, the technological opportunities of 5th generation fighter aircraft demand a different approach to SEAD operations. This finding allows to reject the third hypothesis of this thesis.

H3: A traditional employment of SEAD capabilities such as Electronic Attack by Jamming and Anti-Radiation Missiles is a proper mean to counter the Russian IADS.

The result is a humble approach to SEAD operations that mitigates risks in order to keep losses to an acceptable level. This implies that there will be losses, a reality of high intensity warfare, that European political leaders had long forgotten and need to be made aware of. The military leader on the other hand might not have the patience to wait days or weeks until locally and timely limited air superiority can be achieved, before air power can finally support other lines of operation in an article 5 scenario in Europe. A faster operational tempo is likely to come at the expense of higher attrition rates as well. Once more it is essential to be aware of the strategic role of the IADS in Russian doctrine: attrite the enemy and slow down operations to create more time for a fait accompli. To defeat the IADS, either time or attrition must be accepted with the NATO forces as they stand today. This points to another finding of this thesis. European NATO forces lack fundamental SEAD and support capabilities to prevail against the Russian threat. Although tanker capacities have increased in recent years, there are still ISR capabilities missing, that UAVs are too vulnerable for to cover against a 600km range of an S-500, not to mention the absence of a standoff jamming capability. A third finding is the necessity for Joint SEAD to achieve the diversification of effects necessary to challenge the diversity of the Russian IADS. The integration of joint fires in SEAD operations is a highly complex topic in itself and requires extensive training, for it to actually work. Presently Air Forces in Europe hardly train SEAD, which makes a successful Joint SEAD operation unlikely. These finding can be summarized under the following terms:

Educate: both political and military leadership need to be made aware of the relevance of SEAD operations as the essential enabler to defeat the Russian IADS and the A2/AD complex it is part of in order to maintain or regain freedom of operations. This will involve attrition.

Train: Only two SEAD squadrons in Europe will not be enough to multiply the SEAD knowledge and capabilities needed to counter the Russian IADS. Especially F-35 user nations need to train both SEAD and Joint SEAD capabilities.

Invest: SEAD is a highly specialized role of Air Power that requires dedicated equipment and munitions. Decades of underfunding must be met with decisive investments to attain capabilities and weapon stockpiles bitterly needed in the light of Russian revisionism

7 Conclusion

The Russian full-scale invasion in Ukraine has reanimated the spirit of a NATO article 5 intervention in the Baltic States. The discussion on how NATO will react to that scenario revolves around the Russian exclave of Kaliningrad and the A2/AD complex that Western analysts have made out of a Russian strategy called Active Defense. An essential part of the implementation of that strategy is the Russian Integrated Air Defense System. A logical response to the challenges posed by an IADS is the air power role Suppression of Enemy Air Defenses. The central question this thesis was dedicated to answer is therefore:

Q: Does NATO have sufficient SEAD capabilities to counter the Russian IADS?

The short answer to that question is: Yes, but. The last thirty years of Counter Insurgency and out of area operations have let to budget cuts in Western militaries around the world. A highly specialized role like SEAD requires dedicated aircraft and ammunitions. While the United States of America with the first and second largest Air Forces in the world, the US Air Force and the US Navy, have managed to sustain a minimum level of SEAD capabilities, the situation for NATO allies in Europe is much worse. In all of Europe, there are only two squadrons left that are specialized in SEAD, both flying a dated airframe with the Tornado ECR. As a reaction to the Russian full-scale invasion, a German and a French project have is underway but will not show results until 2030. Simultaneously this thesis has demonstrated that the Russian IADS is likely the most capable in the world. New Early Warning Radars with anti-stealth capabilities, a constant modernization of Surface to Air Missile systems and the introduction of new developed systems like the S-350 or the S-500, all integrated in a networked multilayered Air Defense Systems have led to the conclusion that the Russian IADS as a potent threat to NATO operations in Europe. This has been emphasized by a review of historical cases of SEAD campaigns, summarizing that there are individual items that can be reapplied when facing the Russian IADS, but ultimately it poses an unprecedented challenge. A closer look at the options NATO and more specifically European NATO allies have at hand resulted in the conclusion that the F-35 as Europe’s only fifth generation fighter aircraft provides excellent capabilities to counter the threat posed by the Russian IADS. The aircraft features a low observability capability, a low probability of intercept data link and a leading sensor fusion solution. Only the way these new technological opportunities are employed under the framework of SEAD leads to a fundamentally different approach, compared to previous campaigns. So ultimately the F-35 can be the answer to the question, how European NATO allies defend themselves against the Russian IADSs, should the United States be committed to a war in the Indo-Pacific. There are however three main lessons identified to that need to be tackled for this option to work. European NATO allies must educate, train, invest. They need educate by pointing out the obvious to the political and military leadership. SEAD is a conditio sine qua non. A war between NATO and Russia is likely to involve loss rates, political leaders will not want to accept and take time military leaders are not willing to spent. Without proper training, the limited SEAD capabilities in Europe will not revive and the level of ambition, namely Joint SEAD operations cannot be met. NATO Allies must invest in a highly specialized capability, that nice to have during the last thirty years and suddenly turned into a need to have withing weeks, to fill gaps in equipment and weapon stocks.

There are many topics this thesis could not cover in detail, but are necessary to get a deeper understanding of both the enemy IADS and the way own capabilities need to be employed. These are specifically, whether Russian forces do have a Cooperative Engagement Capability, how exactly the C2 portion of the Russian IADS is structured and how far joint engagement zones are impacted by that.

Ultimately, time will fix most of the issues, that have been identified in this thesis. The only question is, whether European NATO allies can address these issues timely enough to resond to an actual Russian aggression. Let us all hope for the best, that question must never be answered.

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Annexes and Appendices

Annex 1 – List of Acronyms

(H)ARM – (High Speed) Anti-Radiation Missile

(J)ISR – (Joint) Intelligence, Surveillance and Reconnaissance

A2/AD – Anti-Access / Area Denial

AARGM(-ER) – Advanced Anti-Radiation Guided Missile (- Extended Range)

AD – Air Defense

AESA – Active Electronically Scanned Array

BMD – Ballistic Missile Defense

C2 – Command and Control

C4I – Command, Control, Communication, Computers and Information

CAS – Close Air Support

CESMO – Cooperative Electronic Support Measure Operations

COIN – Counter Insurgency

COTS – Commercial of the Shelf

DEAD – Destruction of Enemy Air Defenses

EA – Electromagnetic Attack

ECM – Electromagnetic Counter Measures

ELS – Emitter Locator System

EMCON – Emission Control

EMS – Electromagnetic Spectrum

EMSO – Electromagnetic Spectrum Operations

EPM – Electromagnetic Protection Measures

ESM – Electromagnetic Support Measures

EW – Electromagnetic Warfare

EWR – Early Warning Radar

F2T2EA – Find, Fix, Track, Target, Engage, Assess

FFI – Forsvarets Forskningsinstitut - Norwegian Defence Research Establishment

FOI - Totalförsvarets Forskningsinstitut - Swedish Defence Research Agency

GBAD – Ground Based Air Defense

IADS – Integrated Air Defense System

ISAF – International Security Assistance Force

LPI – Low Probability of Intercept

MANPAD – Man Portable Air Defense

MEZ – Missile Engagement Zone

MTI – Moving Target Indicator

NATO – North Atlantic Treaty Organisation

PGM – Precision Guided Munition

PVO-SV – Voyská protivovozdúshnoy oboróny Sukhoputnykh voysk (

RAM – Radar Absorbent Material

RUSI – Royal United Services Institute

RWR – Radar Warning Receiver

SA – Situational Awareness

SAM – Surface to Air Missile

SEAD – Suppression of Enemy Air Defenses

SHORAD – Short Range Air Defense

SIJ – Stand-In Jamming

SoI – System of Interest

SOJ – Stand-off Jamming

SoS – System of Systems

SPJ – Self Protection Jamming

TEL – Transporter, Erector, Launcher

TELAR – Transporter, Erector, Launcher and Radar

TLAR – Transporter, Launcher and Radar

TTPs – Tactics, Techniques and Procedures

UAV – Unmanned Aerial Vehicle

VKS –Vozdushno-Kosmicheskiye Sily (Aerospace Forces)

Annex 2 – List of Figures and Tables

Appendix 3 – Interview Guide

Interview guide "Rethinking SEAD"

Target audience of the SME: a group of people interested in Suppression of Enemy Air Defense-Operations with background knowledge in air power employment and a basic idea of warfare in the electromagnetic spectrum, modern fighter aircraft and Russian Surface to Air Missile systems but no detailed idea of how SEAD is conducted and how the individual components of a Russian IADS interoperate.

Classification level: NATO unclassified – releasable to public or national equivalent

Does the interview partner consent to have their name and position published along with the transcript? YES / NO

START RECORDING

Q1: In the present discussion of the Russian A2/AD complex, I observe two directions. One discusses whether the A2/AD complex is overrated in its capability to either partially or completely deny access to an operations area. The other direction discusses whether the Western perception misinterprets the role of A2/AD in Russian strategy. One focuses more on the tactical level, the other more on the strategic level. Which discussion do you think is more important, what is your standpoint in that and what can be learned from that for NATO operations if required to penetrate an A2/AD bubble?

Q2: What do you think, are the main strengths and weaknesses of the IADS-portion of the Russian A2/AD complex and how should NATO and its partners avoid or leverage those strengths and weaknesses respectively if forced to an article 5 intervention?

Q3: What do you assess to be the main advantages of fighter aircraft of generation 4.5 (EA-18 G "Growler", Saab JAS 39 Gripen E, Eurofighter/Typhoon ECR) and generation 5 (F-35) respectively over older jets of previous generations regarding the conduct of SEAD operations in a contested air environment?

Q4: In a war with Russia, the initial phase of the war would be air dominant by NATO based on historical evidence and Russian strategic expectations. To what extent is NATO, together with its partners, able to suppress or destroy Russian integrated air defenses if it relies on air power only?

Q5: How can SEAD operations be augmented by the implementation of means of joint all domain operations?

Q6: Why can NATO or why can NATO not, as it stands today, sustain air operations in or around Russian IADS when forced to in the initial phase of a high intensity conflict?

Q7: To what extent does your answer to the last question (Q6) change if European NATO allies and partners had to respond to an article 5 invocation without US support?

Q8: Are there any lessons identified from the Russian full-scale invasion in Ukraine that should be reflected in the way NATO conducts SEAD operations?

Q9: Is there anything else you would like to emphasize regarding SEAD in a European Scenario or the Russian A2/AD complex?

Appendix 4 – Transcript 1

Interview 1 – Professor Justin Bronk - Senior Research Fellow, Airpower & Technology at the Royal United Service Institute

Pending

Appendix 5 – Transcript 2

Interview 2 – Doctor Robert Dalsjö – Director of Studies at the Swedish National Defence Research Institute (FOI)

Pending

Appendix 6 – Transcript 3

Interview 3 – Christian Becker – Capability Manager Electromagnetic Warfare Flying Platforms – German Air Force HQ

Pending

Appendix 7 – Transcript 4

Interview 4 – Stian Betten – Reserch Fellow and Specialist 5th Generation Fighter Capabilities – Norwegian Defence Research Establishment (FFI)

Pending

Appendix 8 – Transcript 5

Interview 5 – Charilaos Nikou – Subject Matter Expert for SEAD at the NATO Joint Air Power Competence Center

Pending