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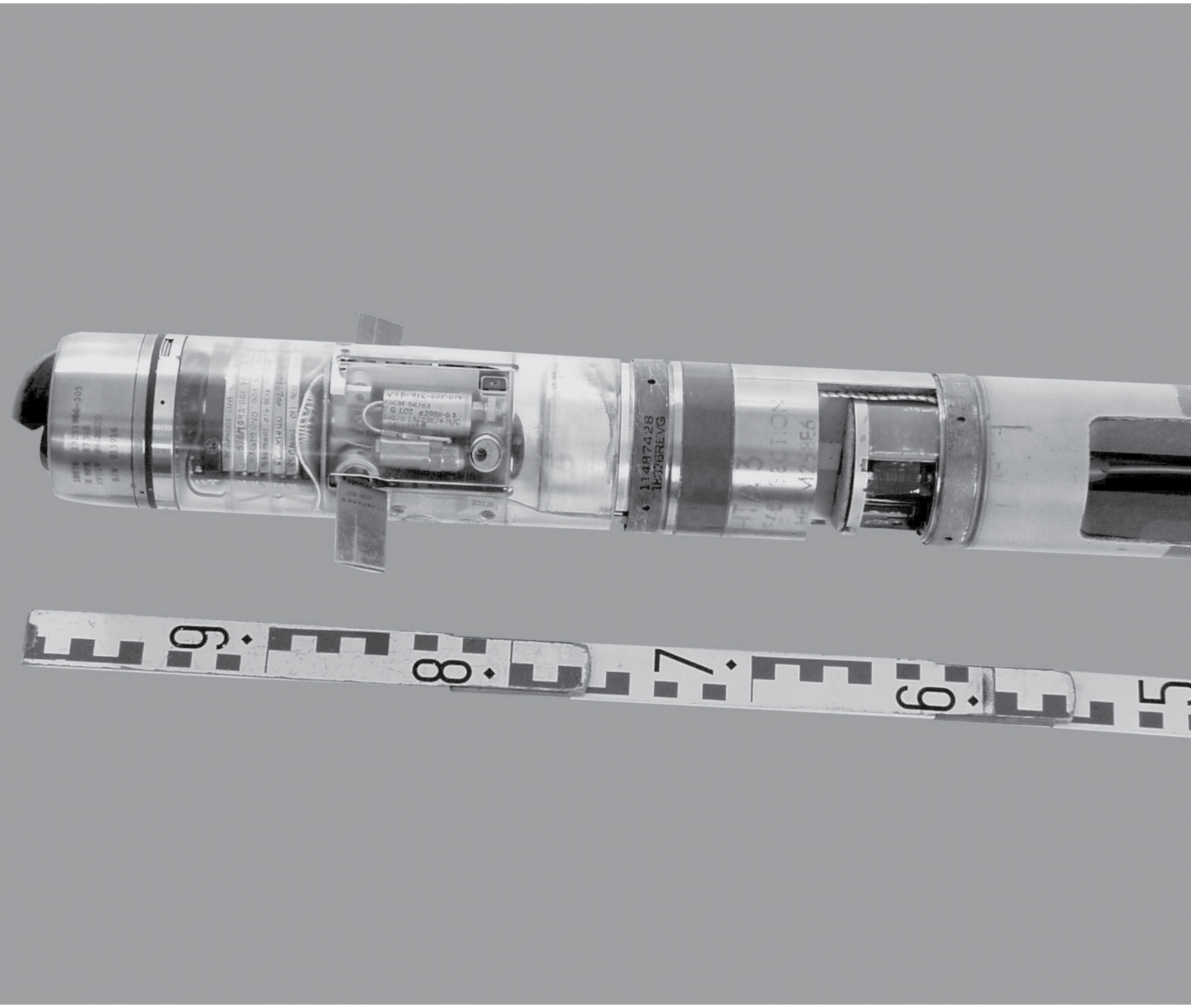
2 Technical aspects and components of MANPADS



This chapter will examine the architecture of different types of MANPADS, as well as their components, as a basis for understanding the threat these weapons represent. It will first identify the components of MANPADS, describe the role they play in the MANPADS' functioning, and assess component criticality.

The second part of this chapter will analyze to what extent the characteristics of each individual component can contribute to limiting the proliferation of MANPADS. This can be the case (a) when a component is sensitive to shock, extreme temperature, improper storage or handling and thus has an increased chance of failure as time progresses, (b) when a component increases the complexity of the MANPADS and makes it significantly harder to operate without proper training, (c) when a component plays a particularly critical role in the MANPADS' functioning (d) when a component is difficult to replace with spare parts or with improvised craft components.

MANPADS architectures—An overview

Out of the wide array of possible strategies to guide a missile to its target, only three have been used in MANPADS: nearly all missiles rely on **passive homing** and **command guidance;** the exception is the Chinese FL-2000B (QW-3) which employs a **semi-active homing** system.

In **passive homing,** the missile is equipped with a sensor unit (the 'seeker') that tracks radiation 'naturally' emitted by the target. This approach has several consequences:

1. After launch, no further communication between operator and missile is necessary, which has earned this type of missile the nickname 'fire and forget'. As the gunner does not have to track the target after launch, he can reposition himself to evade incoming fire or acquire another target.
2. It does not rely on an external source of radiation to 'illuminate' the target, and thus does not alarm the target that it is being attacked.
3. The missile is susceptible to decoys that imitate the radiation emitted by the target.

Passive homing is the technique employed by the vast majority of MANPADS. It is used by the US Redeye and Stinger, the Japanese Type 91, South Korea's Chiron (also known as Singun), and the French Mistral. The most significant representatives of this missile type, however, are the Russian Strela and Igla families, as they are the most copied and most widely available MANPADS in the world. Amongst its various derivatives and reverse engineered models are the Egyptian Sakr Eye, the Chinese HN-5, QW-1 and QW-2 series, the Polish Grom-2, Romania's CA-94M, Pakistan's Anza family, as well as the Iranian Misagh series.

In **command guidance**, the unit which tracks the target is 'outsourced' to a system on the ground. It then communicates guidance commands to the missile and thus directs it to the target. This has several implications:

1. The missile is reduced to warhead, (flight) control unit, propulsion, and a receiver for guidance commands from the ground. That makes it more lightweight and reduces missile costs.
2. The gunner needs to track the target until impact (usually maintaining line of sight with the target) and is thus more exposed to attack.
3. Both missile and target have to remain within line of sight until impact, somewhat limiting the engagement envelope.
4. The launching unit needs to track the target, calculate a missile course, and transmit the relevant data to the missile. It is thus bulkier and heavier, making it less mobile. In most cases, this type of MANPADS is fired from a tripod rather than from the gunner's shoulder.
5. The missile is immune to most counter-measures (cf. Chapter 6).

Command guidance, usually in a beam-riding configuration, is employed by two MANPADS families. The first is the British Blowpipe, Javelin, Starburst, and Starstreak series. The Blowpipe was used in Afghanistan in the 1980s, as well as in the Falklands War, where it proved very ineffective. Out of 100 launches only two succeeded in downing the target (Hillson, 1989; Freedman, 2005, p. 734). The gunner needed to track both the missile and the target, and had to steer the missile to the target manually. In later members of the series, the missile is tracked automatically by the launching unit, which also assists the gunner in tracking the target. This approach is called semi-automatic command to line-of-sight (SACLOS) guidance. The second series of MANPADS to rely on command guidance is the RBS-70 family, produced by Saab-Bofors in Sweden. Both Starstreak and RBS-70 use a laser beam to guide the missile to its target. While they have performed well in tests, the newer command guided missiles are yet to be tested under battlefield conditions. Generally, command guided missiles are far less common and less widespread than the passive homing variants.

The 'odd one out', **semi-active homing,** while unusual for MANPADS, is frequently employed in precision-guided munitions, like laser-guided bombs or missiles. It is 'semi-active' in that the target is illuminated by an outside source, in the case of the QW-3 a ground-based laser. The missile is equipped with a seeker which detects the reflected laser light. This means that:

1. Like with passive homing missiles, no further direct communication between gunner and missile is necessary after launch.
2. The gunner (or another ground-based unit) needs to illuminate the target with a laser beam until intercept and is thus more exposed to attack.
3. Through the illumination, the target has a high chance of being alarmed of the attack.
4. The missile is immune to most counter-measures.

The only specimen of this type is the FL-2000B variant of the Chinese QW-3 MANPADS (the FL-2000 variant employs infrared passive homing), which entered service with the Chinese armed forces in 2005 (Richardson, 2003; NA, 2007; Jane's, 2012a; NA, 2009). It should be noted that it remains unclear whether this system is available in a MANPADS configuration at all or only as a self-propelled system. For the sake of comprehensiveness, the technology will be included here nonetheless.

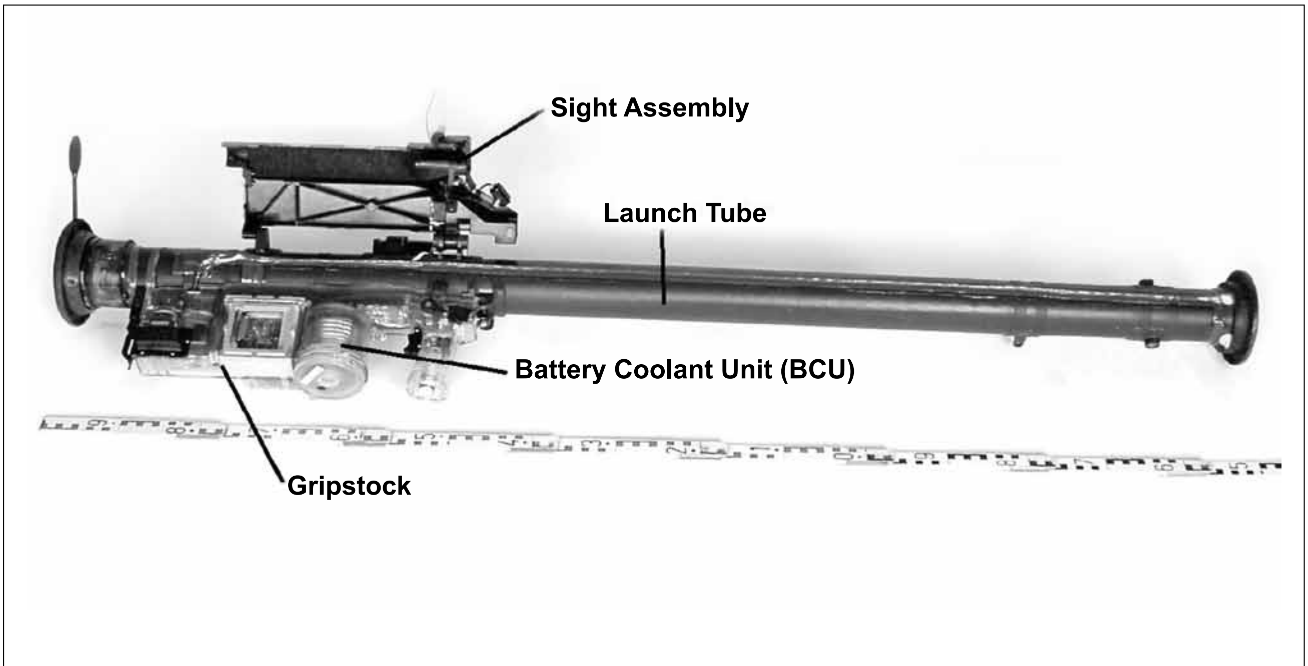
The following sections will consider each of these missile types—passive homing, command guided, and semi-active homing—in detail and introduce their individual components.

Passive homing

Passive homing MANPADS consist of three major separate elements: The missile in a launch tube, a detachable triggering unit called a 'gripstock', and a unit to supply power and cooling for the missile called the battery coolant unit (BCU). Terminologically, it is usual to differentiate between a 'missile round', consisting of missile and launch tube, and a 'weapon round', which is a fully functional MANPADS including gripstock and BCU.

MANPADS missiles, including spares, are not delivered as is, but are always contained in a launch tube. The launch tube includes the sight assembly for acquiring a target, sockets for gripstock and BCU (in some cases, notably the US Stinger displayed in Figure 3, the BCU is inserted into the gripstock, not the launch tube), and sometimes for an IFF (identification friend or foe) antenna. While the launch tubes are reusable in principle, they are not intended to be reloaded with a missile on the battlefield. Reloading is done—if at all—in a factory setting and requires both appropriate tools and expertise (Hughes, 2007).

Figure 3: Cutaway model of a Stinger weapon round



Source: Adapted from Klaus Holtkamp, First Sergeant, Technische Schule Landsysteme und Fachschule des Heers für Technik, Bundeswehr.

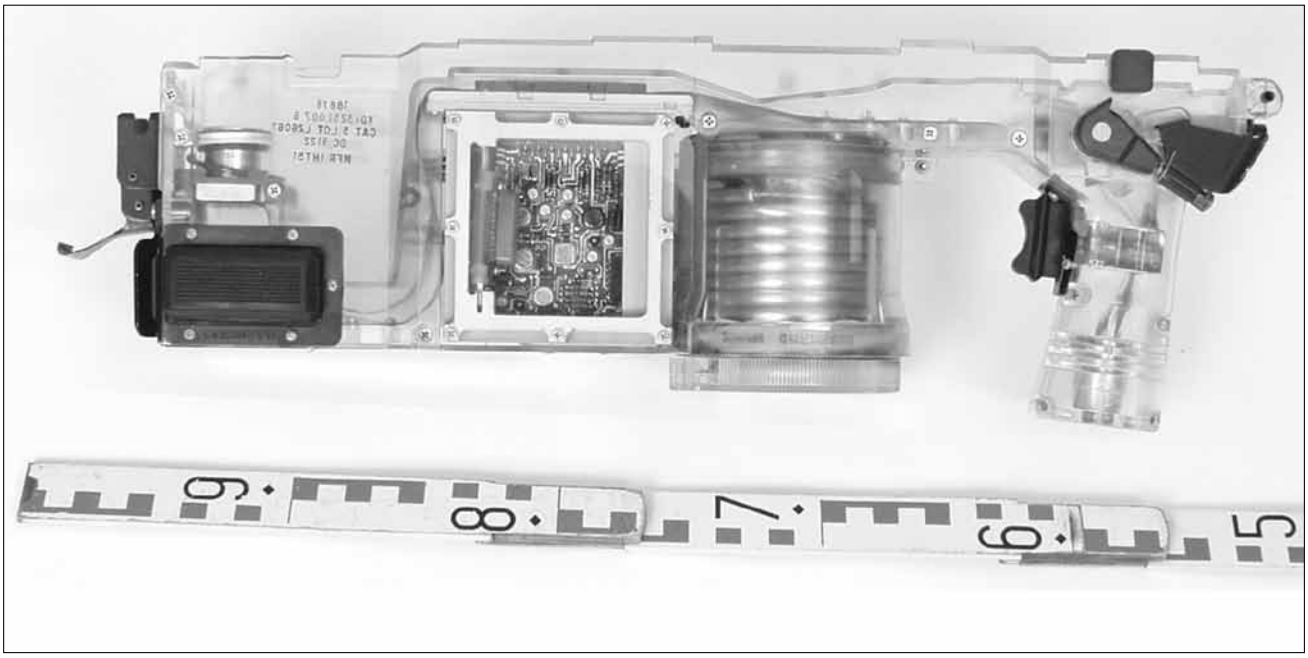
The gripstock forms the main interface between the MANPADS and the gunner. It consists of a handle with trigger and a housing, containing, depending on MANPADS type, targeting and other electronics. The gripstock is attached to the launch tube before launch and removed after the missile has been fired. Only the US Redeye, the first MANPADS ever built, had a gripstock which could not be removed.[3] 'Redeye II', which would later be renamed 'Stinger', already had a reusable gripstock to save costs and withhold crucial information from the enemy, as used launch tubes were often jettisoned after an engagement.

All three elements are integral parts of a complete MANPADS and the system is inoperable with any of them missing. The heart of the MANPADS, however, is the missile itself, which is a complex piece of engineering. The following section will look at each of its components from a technical perspective.

Seeker

In passive homing MANPADS, the seeker is the 'eye' of the missile. It is located at the front of the missile and is used to detect radiation emitted by the target. This radiation usually falls into the infrared (IR) spectrum, i.e. electromagnetic waves slightly longer than those of visible light. The human eye can typically detect wavelengths between 390 and 750 nanometers (nm), while IR radiation ranges from 750nm to 1mm (1mm=1000μm; 1μm=1000nm). IR radiation is emitted by warm or hot sources at different wavelengths depending on the temperature of the source.

Figure 4: Cutaway model of a Stinger gripstock with BCU



Source: Adapted from Klaus Holtkamp, First Sergeant, Technische Schule Landsysteme und Fachschule des Heers für Technik, Bundeswehr.

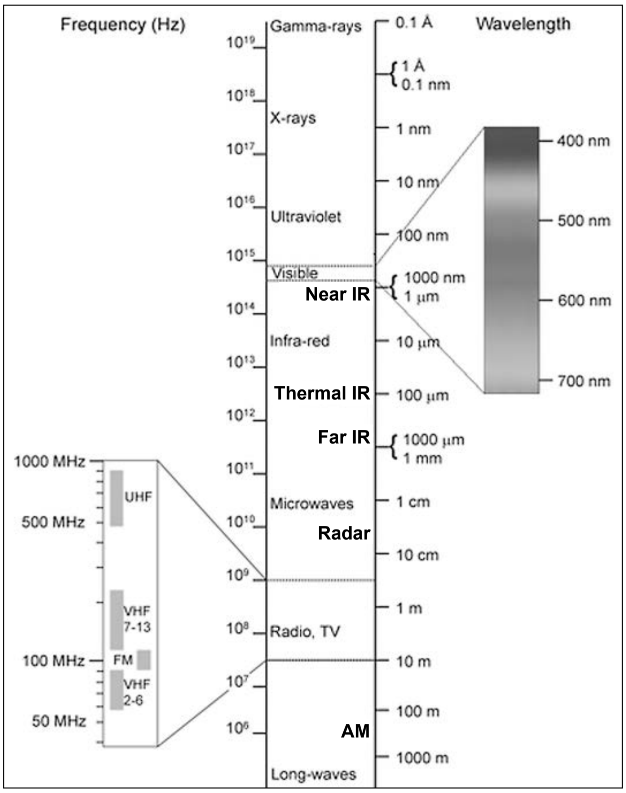
To provide energy for start-up and for cooling the infrared (IR) seeker, a BCU is attached to the launch tube before each launch. The BCU consists of a thermal battery that provides energy for the pre-launch phase of the missile and of a pressurized gas tank that cools the seeker head before missile launch. Once activated, it supplies power for a limited amount of time (about 30 to 90 seconds, depending on MANPADS type) and is then discarded. Typically, a missile is delivered with two BCUs, one main and one spare.

3 The early Redeye prototypes had a detachable gripstock as well, but it was later decided to switch to a 'unitized' system to increase the weapon's reliability (Cagle, 1974, pp. 69–71).

Figure 5: Cutaway model of a Stinger battery coolant unit

Source: Adapted from Klaus Holtkamp, First Sergeant, Technische Schule Landsysteme und Fachschule des Heers für Technik, Bundeswehr.

Figure 6: The electromagnetic spectrum



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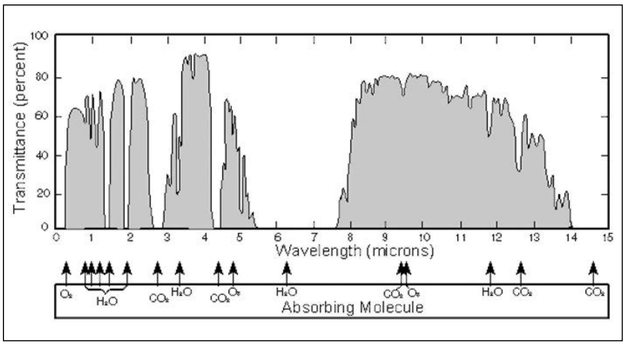
The seeker thus has to be able not only to detect IR radiation, but also to distinguish between different IR sources. Passive homing seekers can be categorized according to the range of the electromagnetic spectrum in which they seek or according to the size and shape of the area they scan.

The range of the electromagnetic spectrum in which a MANPADS seeker is designed to seek, is influenced on the one hand by the range of wavelengths in which the target emits radiation. On the other, it depends on the 'atmospheric windows', i.e. the ranges of electromagnetic radiation that are not easily absorbed, scattered or scintillated by the atmosphere, leading to a distorted or weak signal (Kopp, 1982).

Figure 7: Atmospheric windows



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Early models, as the Strela-2 or Redeye, scanned in just one range (or 'color') of the spectrum, initially in the 2–3μm band (Cagle, 1974, pp. 60, 199; Fiszer and Gruszczynski, 2002, p. 49). While this enables the seeker to distinguish between the IR radiation of the earth (around 10μm), the sun (around 3μm), and a fighter jet (2μm for the tailpipe, 4μm for the aft airframe and 4–8μm for the exhaust plume), it can easily be fooled by flares designed to radiate in this spectrum (Kopp, 1982). Also, early seekers were only able to detect the hot jet engine of the aircraft, limiting it to tail-chase engagements. Newer generation models switched to the 3–5μm range (Strela-3; Fiszer and Gruszczynski, 2002, p. 49), and later added a second 'band' of wavelengths to increase target discrimination. The latter are thus called dual band or two color seekers—using either two bands in the IR spectrum or a combination of IR and a band from a completely different spectrum, like ultraviolet (UV) radiation, millimeter waves (mmW) or visible light.

The seeker range is closely related to the material used to detect IR radiation. Early MANPADS used lead sulfide (PbS) detectors which were uncooled (Lyons, Long and Chait, 2006, p. 10; Yildirim, 2008, p. 40). Later models used indium antimonide (InSb) or mercury cadmium telluride (HgCdTe), which need to be cooled to around -200°C to achieve sufficient sensitivity, as well as cadmium sulfide (CdS), which covers part of the UV spectrum (Lyons, Long and Chait, 2006,

p. 10; Yildirim, 2008, p. 40; Kopp, 1982; Macfadzean, 1992, p. 243; Jane's, 2012b).

Another characteristic of IR seekers is the size and shape of the area they scan, as well as the pattern in which they scan it. The first generation of IR seeker heads had a rotating rectangular field of view (FOV) with a single detector element, leading to increasing inaccuracy in close proximity to the target (Kopp, 1982). The second generation of IR seekers used a conical scanning technique which eliminated these inaccuracies. Third generation seeker heads used a very narrow FOV that moved in a rosette pattern to improve the information available to the guidance system. This technique is also called 'quasi-imaging', as an image is assembled from several data points. The latest generation of seekers use imaging IR, which work similar to a digital camera. They are more easily capable of distinguishing between the target and countermeasures such as flares or decoys (see Chapter 6 for a discussion of countermeasures).[4]

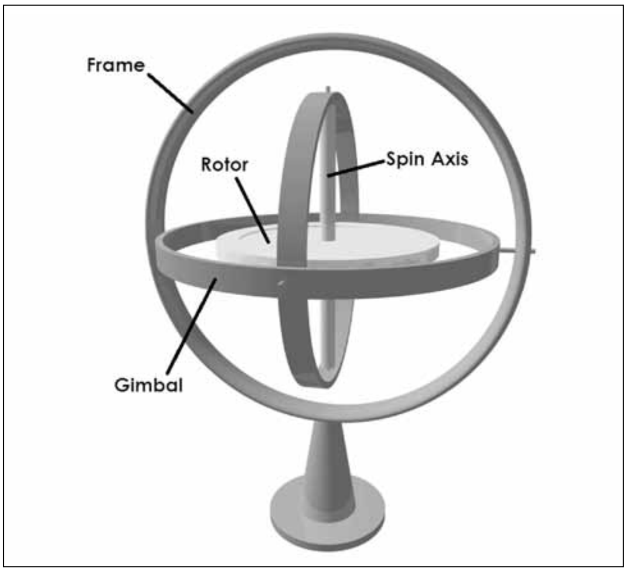
The central role of the seeker section in a MANPADS is highlighted by the fact that IR homing missiles are classified into different generations according to the seeker technology they employ. Table 5 provides an overview of the four generations of passive homing MANPADS and their defining characteristics.

As some of the intended targets of MANPADS are very maneuverable, it is impossible to keep them directly 'in front of' the missile. The seeker head, which has a very narrow FOV, must therefore be able to move independently from the missile's orientation. In order to achieve this, the seeker head is gimbal-mounted and stabilized by a gyroscope (see Figure 8). Once the rotor has gained sufficient momentum, the spin axis will remain stable regardless of gimbal movement.

Seeing that most missiles rotate at a frequency of between 10 and 20Hz (cf. Lyons, Long and Chait, 2006, p. 15; Fiszer and Gruszczynski, 2002, p. 47), precise gyro-stabilization is crucial to missile accuracy. The seeker head is covered by an IR-transparent dome to protect it from aerodynamic drag without distorting or degrading the incoming IR radiation.

[4] See Yildirim, 2008, p. 39f for a summarizing overview of scanning patterns, detector materials and seeker range of different generation MANPADS.

Figure 8: Schematic representation of a gyroscope



Source: Adapted from Wikimedia Common, Public Domain.

Guidance

The guidance section of the missile translates the information from the seeker as well as information on attitude and speed of the missile into concrete guidance commands for the steering section.

There are different algorithms available for this process, the most important one being proportional navigation (PN), a guidance method developed in the 1940s (Dyer, 2004, p. 16; Siuris, 2003, p. 194). As opposed to pure pursuit navigation, in which the missile keeps its velocity vector aligned with the line of sight (LOS) between missile and target, PN keeps the missile's acceleration proportional to the LOS turn rate (Siuris, 2003, pp. 166, 194; Frieden, 1985, p. 451). This effectively steers the missile to a predicted future position of the target. PN has proven so effective that it is used in virtually all modern guided missiles, even though in some cases in an altered configuration (Siuris, 2003, p. 161).

Conceptually, a MANPADS flight can be divided into the boost phase, the mid-course phase, and the terminal phase (Frieden, 1985, pp. 432–34, 54). The boost phase serves to get the MANPADS into a position with LOS to the target and to accelerate it to maximum speed. The mid-course phase usually is the longest part of the flight and serves to bring the missile as close to the target as possible. During the terminal phase, the missile is guided to a vulnerable part of the aircraft to maximize the chance of destruction. The terminal phase demands the highest performance

Table 5: Generations of IR homing MANPADS

MANPADS generation	Detector	Optical modulation	Characteristics
1st generation FIM-43 Redeye[5] SA-7A Strela-2 SA-7B Strela-2M HN-5A Anza Mk I CA-94	Uncooled PbS (lead sulfide) infrared (IR) detector	Spin-scan	• Tail-chase engagement only • High background noise • Increasing tracking error in close proximity to target • Vulnerable to flares • Single-shot kill probabilities between 0.19 and 0.53
2nd generation FIM-92A Stinger Basic Strela-2M/A SA-14 Strela-3 HN-5B Sakr Eye QW-1 FN-6 Anza Mk II Misagh-1 CA-94M	Cooled PbS, InSb (indium antimonide) or HgCdTe (mercury cadmium telluride) IR detector	Conical scan	• All-aspect capability • Reduced background noise • No tracking error • Some resistance to flares • Single-shot kill probabilities between 0.31 and 0.79
3rd generation FIM-92B Stinger POST FIM-92C Stinger RMP FIM-92E Stinger Block I SA-16 Igla-1 SA-18 Igla SA-24 Igla-S Grom-1 Grom-2 Mistral 1 Mistral 2 Chiron (Singung) QW-11 QW-18 QW-2 FN-16 Anza Mk III Misagh-2	Cooled dual channel IR or combined IR/UV detector	Rosette scanning (quasi-imaging)	• All-aspect capability • High resistance to flares • Better target discrimination under unfavorable conditions • Single-shot kill probabilities between 0.44 and 0.98
4th generation Kin-SAM Type 91 QW-4	Cooled imaging IR or combined IR/UV detector	Full imaging	• All-aspect capability • Very high resistance to flares and decoys • No data on single-shot kill probabilities available

[5] From Block II onwards, the FIM-43 Redeye used a gas-cooled PbS seeker (Cagle, 1974, p. 129). As it retained spin-scan optical modulation, the missile can arguably be placed between generations 1 and 2.

of the guidance system. While this does not necessarily imply that different seeker mechanisms or even different guidance algorithms are used during each phase, most IR passive homing MANPADS do switch to a different guidance algorithm for the final phase of the flight. During 'terminal guidance', as this phase is called, the missile guidance algorithm is usually biased towards the airframe proper of the aircraft rather than the jet engine exhaust (Lyons, Long and Chait, 2006, p. 13; cf. Jane's, 2012c).

Control

The guidance computer inputs the information on the target's position relative to the missile into the guidance algorithm and computes the appropriate acceleration to correct the missile's current velocity vector. This information is then translated into concrete commands for the missile's steering elements. Usually, there is a set of stabilizing fins at the rear end of the missile and a set of steering canards in the front third, in the vicinity of the guidance section.

Warhead

The warhead is the element of the MANPADS that serves to destroy or render inoperable the target aircraft. In all cases, this is achieved by means of an explosive, although the missile's pure kinetic energy (mass*speed) can exert an enormous destructive force on the target on its own.

In principle, there are two main strategies of exerting force on the target: The first consists of the shock wave created by the explosion, as well as a large amount of small fragments of the warhead casing which are rapidly accelerated. This design is called blast fragmentation. In its most basic form, the force of explosion is not directed anywhere specific and results in a spherical shock wave. A more refined form is annular blast fragmentation, where the explosion is directed in a ring shaped form to increase its effectiveness. The majority of MANPADS rely on some form of blast fragmentation to achieve the destruction of the target (Gander, 2011). Some of the latest systems have combined annular blast fragmentation with a projectile consisting of a series of short metal rods that have been welded together at alternating ends, much like a folding rule, to expand into a large circular metal ring upon explosion, which then cuts into the aircraft. This setup is called continuous rod and is employed by the Russian SA-24 (9K338 Igla-S) and allegedly by the Chinese QW-3 (Macfadzean, 1992, p. 277; Gander, 2011; Jane's, 2012a; NA, 2007; Fiszer and Gruszczynski, 2002, p. 52). The second way of exerting force on the target is by use of a shaped charge, which focuses

Figure 9: Stinger front section

Source: Adapted from Klaus Holtkamp, First Sergeant, Technische Schule Landsysteme und Fachschule des Heers für Technik, Bundeswehr.

As with the seeker head, missile flight control is a challenge due to the rapid missile roll. Quick mechanical implementation of the steering commands and precise information about the missile rotation are therefore crucial for steering the missile accurately. It comes as no surprise that Lyons, Long, and Chait have identified the improved servomechanism and dedicated laser gyroscope roll frequency sensor of later Stinger versions as key innovations to improve the MANPADS' accuracy (2006, pp. 12–13).

the energy of the explosion into a very small area. This technique is often used in armor-piercing warheads, where a cone-shaped piece of metal is condensed by the targeted explosion and heats up so quickly that it changes its aggregate state to plasma which then melts through armor plating. Only the Swedish RBS-70 MANPADS uses a shaped charge warhead, although the current Bolide missile combines both shaped charge and blast fragmentation in a single warhead (Jane's, 2011c).

To achieve the optimal destructive force of the warhead, it must be detonated at the right place at the right time. The guidance system is responsible for ensuring that the missile gets in a position that is as close as possible to the most vulnerable part of the target aircraft. A fuze then initiates the detonation of the warhead. Fuzes come in two types: proximity or impact. As the name says, a proximity fuze initiates detonation once a specific distance to the target is achieved, ranging from 0.5 (C-94M) to five (Igla-S) meters (Jane's, 2012d; Fiszer and Gruszczynski, 2002, p. 52). An impact fuze detects the first impact with the target and initiates detonation either immediately or after a time delay. The latter is utilized in cases where the missile can penetrate the target and explode there, as in the Starstreak missile projectiles, which reach a comparatively high maximum speed of between 1,020 and 1,150 meters per second (Jane's, 2011a; Jane's, 2012e; Gander, 2011). Most other MANPADS use an impact fuze or a combination of impact and proximity fuze.

Propulsion

As MANPADS are launched from the gunner's shoulder, it needs to be ensured that the latter is out of harm's way when the missile is accelerated to supersonic speed. All systems employ a dual stage propulsion system to solve this problem. First the missile is propelled out of the launch tube by a small launch (or eject) motor. The launch motor extinguishes before leaving the launch tube to protect the gunner and drops to the ground after some meters. After coasting a distance of between five and ten meters, depending on the MANPADS model, the flight (or sustainer) motor ignites and rapidly accelerates the missile to its maximum speed.

Conceptually, a rocket motor contains the fuel and an oxidizer, as opposed to a jet engine which uses air sucked in by the engine as an external oxidizer (Frieden, 1985, p. 465). Rockets can either run on liquid fuel, which is stored in a fuel tank separate from the oxidizer, or on a solid propellant which integrates these components. In most cases, MANPADS rocket motors use a composite solid propellant which consists of a binder, a fuel (for example aluminum), an oxidizer (usually ammonium perchloride), and a number of optional additives, such as a catalyzer or stabilizer. Generally, while the use of a solid propellant reduces the performance of the engine, its high density results in a more compact and lighter propulsion section which, in turn, leaves more room for other components, most notably the warhead (Thakre and Yang, 2010, p. 1). It is also very stable, which makes it easier to handle under battlefield conditions. The reactivity of the propellant depends on its exact composition and cannot be altered after production. MANPADS flight motors usually use two different 'grains' of propellant: a small amount of highly reactive booster propellant for rapid acceleration and a larger amount of less reactive sustainer propellant (cf. e.g. Jane's, 2011b; Jane's, 2012f; Jane's, 2011c; Jane's, 2012g). These burn in a combustion chamber and the exhaust is ejected through a nozzle at the rear to achieve forward propulsion.

While it is one of the simplest components of the missile, the rocket motor contributes most to size and weight of the missile. The rocket motor of the Redeye missile, for example, weighed 4.5 kg (10 lbs), with a total missile weight of 8.3 kg (18.3 lbs) (Cagle, 1974, p. 146). The Russian Strela-2M carries 4.2 kg of solid propellant fuel, while the missile weighs 9.6 kg (Jane's, 2011d).

Gripstock

The gripstock is the main interface between missile and gunner and mediates target acquisition and launch sequence (US Army, ND, p. 22). It enables the gunner to 'uncage' the seeker head (i.e. unlock it, so that it can move freely and acquire the target), start up the missile electronics and gyroscopes, initiate target lock, and trigger the missile launch. If desired and available, it also serves as an interface to the IFF interrogator. While gripstocks of early versions, namely the SA-7, merely contained the trigger mechanism, those of more advanced MANPADS have a more prominent role in the acquisition and launch sequence.

The gripstock has sometimes been classified as the actual weapon, while the missile round has been classified as 'merely' ammunition[6]. While this is a matter of definition, it is certainly true that the gripstock has a key function in a MANPADS system. Without it, a MANPADS missile cannot be fired and it is often shipped and stored separately from the missile rounds to limit the likelihood and impact of theft.

The missile round of a MANPADS is in many cases identical to those used in other, non-MANPADS setups. A prominent example is the Strelets multiple missile launcher for the Russian Igla-S missile, which is usually installed on a vehicle chassis. When, in the wake of the Libyan revolution, SA-24 Igla-S missiles which had been delivered with Strelets twin launchers were looted from government arms depots, they could not be used as a MANPADS as the gripstocks required to launch them were missing. This illustrates the key importance of tight gripstock control.

Other launch mechanisms

Classic gripstock setups are used in the American and Russian MANPADS series and all their descendants and copies. In addition, there are a number of passive homing MANPADS which use a different, bulkier launching mechanism in combination with a tripod. These include the French Mistral and the South Korean Chiron. This setup allows for assisted target tracking, as well as day and night sight devices. On the downside, these systems are substantially heavier and bulkier, and need to be transported by vehicle.[7]

Battery coolant unit

The battery coolant unit (BCU) is a disposable cartridge which is attached to either launch tube, gripstock or launcher unit, depending on the MANPADS model and it provides power to the system and cooling to the seeker head. Once activated, it provides power for start-up and launch of the missile for 30–90 seconds, again depending on missile type. If the missile has not been fired in this time period, the engagement will have to be aborted and the BCU will need to be replaced by a spare. With passive homing MANPADS, the BCU consists of two parts: a thermal battery and a tank with compressed gas for cooling.

The battery unit of the BCU is a so-called 'thermal' battery', even though 'thermally activated chemical battery' would be a more accurate term (see Guidotti and Masset, 2006). Like a conventional battery, it consists of an electrolyte and two electrodes. Unlike a conventional battery, however, the electrolyte is in solid state at room temperature and the battery is inert until the electrolyte is melted by a pyrotechnic device situated between the electrodes (Guidotti and Masset, 2006; Davidson, 2003; ASB Group, ND; Doughty et al., 2002, p. 357). The pyrotechnic device is activated by an impulse generator located in the gripstock (e.g. Stinger; Lyons et al., 2006, p. 11). Upon activation, the battery generates heat as a byproduct of the chemical reaction, leading to temperatures of more than 200°C at the surface of the BCU (US Army, ND, pp. 25, 54). The thermal battery supplies power for gyroscope spin-up, the activation of the on-board thermal battery or generator, eject motor ignition, as well as some less energy extensive pre-launch processes (Lyons et al., 2006, p. 11).

The second function of the BCU is to cool the infrared seeker head to its working temperature of around -200°C. This is achieved by the so-called Joule-Thompson effect, the rapid expansion of a gas, either argon (e.g. Stinger; see Jane's, 2012g), nitrogen (e.g. Strela-3, Igla, Igla-S; see Ochsenbein, 2008, p. 8) or compressed air (e.g. Mistral; see NA, ND).

Command guidance

Command guidance MANPADS share many components with their passive homing relatives. The missile itself, however, is lighter and cheaper, as the complicated seeker and guidance setups are outsourced to a launcher unit on the ground. A command guidance MANPADS thus consists of a missile round and a launcher unit, which is usually attached to a tripod assembly.

As with passive homing MANPADS, the missile is contained in a sealed, reusable launch tube. Together, these elements form a missile round. Once the missile has been fired, the now empty launch tube is replaced with a new missile round and the launch tube can only be reloaded in a factory setting. As the missile is guided from the ground, it does not require an on-board seeker. The weight and room that is

[6] The United Nations' Report of the Panel of Governmental Experts on Small Arms, A/52/298, of 27 August 1997 defines in §26 "Portable launchers of anti-aircraft missile systems" as light weapons, while "Mobile containers with missiles or shells for single-action anti-aircraft and anti-tank systems" are defined as an ammunition (UN, 1997). The International Tracing Instrument of 8 December 2005, A/CONF.192/15, uses the same definition for launching mechanisms, while ammunition is not covered by the agreement (UN, 2005).

[7] Jane's Land Warfare Platforms: Artillery & Air Defence 2012 states on the Mistral 1 that "[t]he basic assembly can be broken down into two 20 kg loads - the containerised missile and the pedestal mount with its associated equipment for carriage by the missile team commander and the gunner respectively. In operational use, the system will normally be transported in a light vehicle to the deployment area where it will be man packed to the firing site by the team."

freed up by the absence of a seeker section can be used for a more powerful rocket engine or warhead.

In addition to managing the missile launch, the launcher unit is also responsible for tracking the missile, calculating the required missile course, and transmitting guidance information to the missile.

Guidance architectures

The flight phase of command guidance MANPADS can be conceptually divided into two phases. First, the missile needs to be 'gathered' by the respective guidance mechanism, i.e. the missiles must be brought into the FOV of the gunner or into the guiding radio or laser beam (Kopp, 1989). Second, guidance information is transmitted to the missile until the target is hit. The way this is achieved has differed between models and generations of command guidance MANPADS.

In the early 1970s, the first two command guidance MANPADS were developed: the British Blowpipe and the Swedish RBS 70, which entered service in 1975 and 1976 respectively (Gander, 2011; Kopp, 1989). The Blowpipe was effectively a radio remote controlled missile, which was guided to the target solely by the gunner. Once the missile was automatically 'gathered' into the gunner's FOV, he had to track the missile and the target and steer the missile with the help of a thumb joystick. The RBS 70 used a 'beam riding' configuration, in which the gunner directs the missile to the target with the help of a laser beam. The gunner points the beam at the target and the missile uses sensors at the rear to ensure that it stays within the laser beam (Jane's, 2012h). This setup is semi-automatic, as the gunner only needs to track the target and keep the guiding beam aligned with it. The missile is again automatically 'gathered' into the laser beam and then continuously determines its position within the beam and corrects any deviations.

While both systems require very good operator training, the Blowpipe was so difficult to handle that even well trained gunners had a very low hit rate (Hillson, 1989; Freedman, 2005, p. 734). The Javelin, Blowpipe's successor, still stuck to command guidance but with automatic missile tracking. In practice, the gunner needed to only track the target and keep a stabilized aiming mark aligned with it. The system would track the missile via infra-red sensing, calculate the necessary guidance commands to keep the missile on the line of sight between gunner and target, and communicate them to the missile via a radio link (Kopp, 1989; Jane's, 2012i). With the introduction of the Starburst MANPADS in 1990, the radio guidance technique was abandoned in favor of a beam riding setup to avoid jamming (Jane's, 2012j). Since then, all modern command guidance MANPADS rely on laser beam riding.

Launcher unit

In command guided MANPADS, the launcher unit plays an even more crucial role than in passive homing models, as it is instrumental in guiding the missile to the target. Without it, the missile cannot be guided in any way. In fact, if the missile loses the guidance beam—and with it communication to the launcher unit—mid-flight, it will self-destruct (see e.g. Joshi, 2011b).

The launcher unit consists of two functional parts: the sighting unit and the control unit. The sighting unit enables the gunner to acquire and follow a target until impact. It consists of an optical sight, which is gyro-stabilized to facilitate target tracking, as well as an aiming mark, crosshair or aiming reticule, which the gunner needs to keep aligned with the target (Kopp, 1989). Modern command guided MANPADS, like the Starstreak II or RBS 70 NG, are also equipped with a thermal sight enabling engagements during night time (Saab Group, 2011; Thales Group, 2011). The control unit calculates initial lead angles and permits the gunner to follow the target with the help of a thumb joystick (Kopp, 1989).

The launcher unit is supported by a tripod stand, although there is a shoulder launched version of the Starstreak missile where the launcher unit is attached directly to the missile round.

Semi-active laser homing

In principle, semi-active laser (SAL) homing missiles resemble IR passive homing ones. There are, however, two major differences. First, the missile is equipped with a laser seeker head, which is immune to flares and highly resistant to jamming. It is also capable of locking on to low-signature targets, like attack helicopters or cruise missiles, at a much larger distance than a passive IR seeker. Second, the target needs to be illuminated by a ground-based laser rangefinder so that the missile can lock on to and track the target.

There is very little open source data available about how the technology is implemented in the Chinese QW-3 missile. According to Jane's (2012a) the QW-3 comes in an IR only, a SAL only, and a combined variant. It is not clear whether the SAL QW-3 is actually available in a MANPADS configuration or is only employed in a vehicle mounted multiple missile system, where it is designated FL-2000B. The fact that the SAL QW-3 is a two-stage missile with a weight of 23 kg suggests the latter, but it is not inconceivable that there is a tripod-mounted version as well.

Implications of technical aspects for MANPADS threat assessment

Seeker, guidance and control: In passive and semi-active homing missiles, the seeker and guidance section of a MANPADS is the single most important part of the missile to determine its accuracy. This does not only include the IR detector and guidance algorithm, but also other elements, such as the gyroscope that stabilizes the detector element and the roll frequency sensor that improves flight control. All other things being equal, the MANPADS with a more advanced seeker and guidance section will thus present a greater danger to civilian aircraft than earlier versions.

To reach maximum accuracy, the seeker head in particular must work under the right conditions. A gyroscope enables it to keep a stable position relative to the ground disregarding missile spin. A coolant keeps the temperature at around -200°C and an auto-tracker keeps the seeker centered on the target. As such, the seeker head is one of the most sensitive and vulnerable parts of an IR homing MANPADS and a forceful blow with a hammer to the seeker dome will render the missile useless.

First generation uncooled PbS seekers—apart from being easily distracted by background IR clutter—are only able to lock on to the engine of an aircraft, permitting tail-chase attacks only. Later generation seekers decrease interference of background radiation, allow to lock onto all aircraft surfaces and are all-around more reliable.

Warhead: Like all explosives, a MANPADS warhead is subject to degradation. Yet, as the warhead is a sealed unit, this happens very slowly. While even several decade-old warheads can continue to be functional, warhead degradation leads to a decrease in reliability of the MANPADS. Consequently, the older a MANPADS is, the higher the chance of warhead failure.

This trend is amplified by technological advances in warhead design. Early generation warheads, like that of the Russian Strela-2, had so little destructive power that not even a direct hit would reliably deal sufficient damage to down the target aircraft (Fiszer and Gruszczynski, 2002, p. 49). Later generations used more effective and more stable explosives as well as more functional warhead designs, leading to ever increasing single-shot kill probabilities (see Table 6 for details). Strategies to increase warhead lethality are manifold and include combining an increased area of impact with a proximity fuze, as employed by the Igla-S, as well as splitting the warhead into three separate darts to increase the hit probability, as used by the Starstreak MANPADS.

Rocket motor: Warhead and rocket motor rely on similar chemical processes, leading to some shared characteristics. The Russian Igla family (excluding the Igla-1E, which was mainly produced for export) even uses the leftover fuel as an additional explosive to enhance the destructive power of the warhead.

Like the warhead, a MANPADS rocket motor will slowly degrade, leading to an increase in failure and a decrease in consistency and uniformity of the reaction, both of which are crucial for accurate missile guidance.[8] Solid-fuel composition has changed and improved over time, with stabilizers being added to inhibit premature oxidation of the fuel. Consequently, later generation rocket motors are not only more reliable by design, but also by their lesser age and less advanced fuel degradation. In addition, one expert pointed out that the squib or electrical ignitors of both eject and sustainer motor need to be recharged or changed on a regular basis, which requires special equipment.[9]

Battery coolant unit: Thermal batteries are extremely robust and resilient against shock, extreme temperatures, and degradation. According to Guidotti and Masset, thermal batteries can withstand forces of 16,000 g and storage temperatures of between -55 and +75°C without significant degradation (2006, p. 1444). When protected from moisture and oxygen, they can stay operational for 25 years and longer (Guidotti and Masset, 2006, p. 1444). This makes them particularly suited for guided munitions and missiles, as well as space travel applications.

8 In an introductory presentation on MANPADS at a meeting of the Organization of American States on 8 March 2007, Chris Hughes of the United Kingdom Ministry of Defense stated regarding the rocket motor that "[…] when these things are manufactured the quality control of this part is very, very important because it has to burn evenly along the length of the motor to enable it to perform and fly in a straight line or as guided by the control" (7:38-7:54).

9 Personal email from a Mines Advisory Group (MAG) expert, 18 September 2012.

Nonetheless, the BCU has been identified as one of the weakest components in a MANPADS, concerning the life expectancy of the system, which indicates the overall robustness of MANPADS.[10] In addition, the short life span of the battery upon activation—a Strela-2 battery expires after 30 to 40 seconds—makes it harder for the gunner to conduct a successful engagement and may lead to a shortage of BCUs. Due to the high temperature of the activated thermal battery, the BCU has to be removed within minutes, or permanent damage to the BCU receptacle may render the weapon round inoperable (US Army, ND, p. 45).
Overall, the BCU clearly represents a limiting factor to successful attacks on civilian aircraft. It degrades more easily than other components, complicates the engagement process, can damage the MANPADS if handled improperly, and needs replacement once activated, even if the MANPADS cannot be fired.

IR vs. SACLOS: Contrary to the belief of some analysts (e.g. Wisotzki, 2007), command guidance MANPADS are not an evolution of, and therefore inherently better or more advanced than, passive homing ones. Rather, both have been used and developed in parallel, with newer models of both kinds, like the British Starstreak (command guidance) or Russian Igla-S (passive homing), being more capable than the early 'pioneers', like the British Blowpipe (command guidance) or US Redeye (passive homing) MANPADS.

Yet it is true that command guidance missiles of the beam riding type are immune to most currently available countermeasures, the majority of which have been developed to confuse passive homing missiles, as well as jamming devices which aim to disrupt communication between gunner and missile. While this makes them more dangerous for military targets, this quality is less relevant for civilian aircraft, most of which are not equipped with countermeasures anyway, so that passive homing missiles are not at a disadvantage against such targets. Yet, this point does require an important qualification: The analysis of attacks on civilian aircraft in Chapter 1 shows that MANPADS attacks have occurred near exclusively in active war zones. While it is not feasible to equip civilian airplanes worldwide with IR countermeasures, a focus on areas of armed conflict may reduce the risk of successful MANPADS attacks drastically. This is especially relevant in light of the finding that there is no evidence for attacks on civilian aircraft with command guided systems (see Chapter 1) and the near ubiquity of IR guided MANPADS worldwide (see Chapters 3 and 4).

Currently, however, only a very small amount of civilian airplanes is equipped with systems to counter the threat of MANPADS attacks. Therefore, for civilian airplanes the pure hit probability of a MANPADS is the deciding factor, assuming that the missile is fully functional and the gunner is familiar with its handling. All modern MANPADS, regardless of the type, have demonstrated a very high hit probability in testing (see Table 6), though many have not been used on the battlefield.

Some additional factors need to be considered regarding MANPADS performance:

Weather conditions: A weakness of laser beam riding missiles is their dependence on clear weather conditions, as water particles diffuse the laser beam and the gunner needs to be able to track the target visually. Even very advanced systems, like the British Starstreak II and the Swedish RBS 70 Bolide MANPADS suffer from this problem. Only the very latest RBS 70 NG operates independent of weather conditions.

Launch mechanism: Launch mechanisms, i.e. gripstocks and tripod-mounted launch units, have become more complex and their role in MANPADS has increased in importance. One expert reported that improvised gripstocks for SA-7 MANPADS have been found in Afghanistan.[11] Second generation and more recent IR homing MANPADS, however, are very unlikely to be fired without a gripstock. While a theoretical possibility of use with an improvised launching mechanism remains for IR homing MANPADS, a command guided MANPADS is completely useless without the launcher unit and it will self-destruct if communication with the launcher unit is lost during missile flight.

Ease of use: Even for early generations of IR homing missiles, operators were able to learn basic maneuvers relatively quickly. While a large number of hours is necessary to qualify as a MANPADS gunner in a military context, this time is substantially shorter from a purely practical perspective. One expert of the German Armed Forces estimated that a 30 minute introduction would be sufficient to perform the basic operations of a Stinger MANPADS. Precise and reliable operation of a MANPADS does, however, require a much larger amount of training. Command-guided MANPADS, on the other hand, gained a reputation of being very hard to operate, even with a good amount of training. The abysmal combat performance of the Blowpipe MANPADS, both in Afghanistan and in the Falklands

[10] Personal email from a Mines Advisory Group (MAG) expert, 18 September 2012.

[11] Personal email from a Mines Advisory Group (MAG) expert, 18 September 2012.

Table 6: Single-shot kill probabilities of different MANPADS.[12]

MANPADS	Claimed hit probability	Actual hit probability
Strela-2		0.19–0.25 (Fiszer and Gruszczynski, 2002, p. 49)
Strela-2M		0.22–0.25 (Fiszer and Gruszczynski, 2002, p. 49)
Strela-2M/A	0.42–0.45 ("Advantages when compared to the standard Strela-2M warhead are: […] A 0.2 per cent increase in the single-shot kill probability figure" (Jane's 2011e)[13])	
Strela-3		0.31–0.33 (Fiszer and Gruszczynski, 2002, p. 49)
Igla-1 (SA-16)		0.44–0.59 (Fiszer and Gruszczynski, 2002, p. 49)
Igla (SA-18)	0.45–0.63 (Ochsenbein, 2008 p. 7)	
	0.45–0.65 (Fiszer and Gruszczynski, 2002, p. 49)	
Igla-S (SA-24)	0.5–0.75 (Fiszer and Gruszczynski, 2002, p. 49)	
Stinger Basic (FIM-92A)		0.79 (Kuperman, 1999, p. 246)
Redeye (FIM-43)		0.403–0.53 (Cagle, 1974, p. 147)
FN-6/HY-6	0.7 (Jane's, 2011f)	
FN-16/HY-6	>0.8 (Jane's, 2012k)	
QW-3 (FL-2000B)	>0.85 (Richardson, 2003)	
Mistral 1	"very high" (Jane's, 2011g) 0.98 (Joshi, 2011a)	
Starstreak I	0.96 (Jane's, 2012e)	
RBS-70	0.93 (Pike, 2000)	
Chiron	0.9 (Jane's, 2012l)	

War, was a key factor for this reputation. In the past decades, however, command guided MANPADS have introduced a range of mechanisms that assist the gunner in operating the system, notably a stabilized sight and target auto-tracking. As a consequence, the gap between IR homing and command guided MANPADS regarding ease of use has become significantly smaller and other aspects, like mobility, price, and availability, have gained in importance.

Exploiting aircraft vulnerabilities: While an IR guided missile will always home in on the engine, a command guided missile can, in theory, be steered towards a more vulnerable part of the airpart. This does, however, require a very well trained gunner and adds to the existing difficulties in operating a command guided missile.

Overall, command guided MANPADS are thus still at a disadvantage compared to their IR homing relatives, even though the difference has decreased enormously. They are more difficult to use, more dependent on clear weather conditions, and cannot be used without the appropriate launch mechanism. Their main advantage, immunity to countermeasures, is of little relevance in the context of attacks on civilian aircraft which are not equipped with such mechanisms in the

12 Note that these numbers need to be taken with a grain of salt and are not fully comparable. It is often unclear under which circumstances and against which targets the hit probability was measured. The table serves merely as an illustration of the orders of magnitude of different MANPADS' hit probability.

13 As a 0.2 percent increase would be insignificant, we assume that the author actually means an increase of 0.2 in the kill probability, which would equal an increase of 20 percentage points.

first place. Their ability to target the most vulnerable part of an aircraft depends on a well trained operator.

System weight and setup: A number of MANPADS are noticeably bulkier and heavier than others, making them more difficult to smuggle and transport. They employ a setup where a launcher unit, attached to a tripod, is used rather than a gripstock. While the latter weigh between 15 and 19 kg, the former range from 24 to 35 kg. They need to be carried by a team of two or three people and require more time to set up than those of the gripstock variety. Overall, this makes them slightly less desirable for a clandestine attack on a civilian aircraft. MANPADS of this category include the RBS 70, Mistral I and II, Chiron, as well as the Lightweight Multiple Launcher (LML) version of the Starstreak.

Semi-active laser guidance: SAL MANPADS face similar restrictions to command guided missiles: they are more difficult to operate, heavier and bulkier than IR homing MANPADS, and are impossible to operate without a complete system. As such—apart from the near complete absence of such weapons from the world market—they do not represent the weapon of choice for an attack on a civilian aircraft.

Repair and spare parts: As many of the MANPADS in circulation are several decades old and often stored in less than ideal conditions, failure of or damage to parts of a MANPADS are increasingly likely to occur. In addition, MANPADS that were looted from state stockpiles or other sources are often incomplete, lacking either gripstock, BCU, or both. The question thus arises, whether a non-state armed group can realistically repair a damaged MANPADS with spare parts or with improvised craft components.

MANPADS missiles are compartmentalized and all components can in principle be replaced. This, however, is not a trivial enterprise without expert know-how and outside a factory setting. Even removing the missile from the launch tube requires the loosening of a number of connections between the tube and the missile which transfer power, information, and the coolant to the missile before launch. Another problem is aligning the components neatly after replacement. At production, each missile is tested electronically for imbalances. This is important, as the missile rotates at high speed and needs to be able to withstand high-g maneuvers. Outside a factory setting this level of precision is hard to achieve.[14]

[14] Hughes emphasized this point, stating: "I would like to make the point that this is not the sort of thing that a terrorist or an insurgent can manufacture in a workshop in his garage, in his basement, and put one of these things together. It's a very, very technical production." (2007, 6:03–6:17).

In principle, however, all missile parts can be replaced. According to one expert, the seeker and the rocket motor's electrical ignitors are the most sensitive parts and are likely to fail first.[15] Given the relatively low prices of MANPADS on the black market (see Chapter 3; cf. Silverstein and Pasternak, 2003), complicated and potentially dangerous repairs are likely as a last resort only, while acquisition of a functional MANPADS seems more feasible and likely.

Conclusion

From the above analysis, the following conclusions can be drawn regarding the threat of MANPADS for civilian aviation:

- Overall, MANPADS are very durable and can be functional after decades. Some components—including warhead, rocket motor, electrical ignition, and thermal batteries—degrade more quickly than others, leading to a decrease in reliability with greater system age.
- The seeker and guidance sections contribute most to a MANPADS' accuracy, but they are also the system's most sensitive elements. From a purely technical perspective, later generation MANPADS with their higher hit probability pose a higher risk to civilian aircraft. Destroying the seeker head of an IR passive homing or semi-active laser homing MANPADS will make the system unusable.
- IR passive homing MANPADS continue to be easier to use as they require less training and have a higher chance of a successful engagement than command guided MANPADS. Still, the latter have closed the gap significantly and in the not too distant future may be as easy to use as passive homing MANPADS.
- Tripod-mounted MANPADS are less mobile and more difficult to transfer clandestinely. Shoulder-fired systems pose a greater danger to civilian aviation.
- While repair or replacement of nearly all components is possible in theory, the technical difficulties of such a procedure make it very unlikely. Increasing complexity of later generation MANPADS, as well as low black market prices of complete systems, further decreases the likelihood of 'craft MANPADS'.

[15] Personal email from a Mines Advisory Group (MAG) expert, 18 September 2012.