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CHINA AEROSPACE STUDIES INSTITUTE

AIR-TO-AIR MISSILES
CAPABILITIES AND DEVELOPMENT IN CHINA

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PREFACE

"Good enough", this is how I often describe China's short-term ambitions. They don't need to have a world-class / global-leader military, not yet; what they need is something that is 'good enough'. This has implications for how China pursues its program of military modernization and its goal to increase its comprehensive national power. They don't need to have a navy that can go toe to toe with the U.S. Navy, they need a military which is 'good enough' to keep the U.S. Navy occupied or distracted, hence developing the idea to use ballistic missiles against aircraft carriers, this is a 'good enough' solution for now, at a much lower cost. So too in the realm of aviation. China is working very hard to modernize their fleet of aircraft and striving to improve their aerospace forces, but it takes time and money. So where do they focus? On getting to 'good enough'. Air-to-air missiles are a perfect example of this. Their newest fighter, the J-20, is stealthy-ish, may soon be able to supercruise-ish (if they solve their engine problems), and is a modern fighter. Is it as good as an F-35, no, but if you can develop air-to-air missiles that can outreach American and allied missiles, then a decent J-20 is good enough to keep the U.S. aviation forces, particularly the tanker bridge on which we heavily rely, at arm's length. Thus 'good enough' (for now). Make no mistake, China has goals to create a 'world class military' by 2049 (the centenary of the founding of the PRC), and they have the plans to get there. But in the interim, finding creative ways to fight asymmetrically will be 'good enough' to achieve their aims.

Drawing on Chinese-language sources, this report is the next in the series of studies by the China Aerospace Studies Institute that seeks to lay the foundation for better understanding the Aerospace Sector of the People's Republic of China (PRC). This report describes China's air-to-air missile capabilities and development. It reviews the history of the PRC's acquisition of air-to-air missiles and production capabilities, describes the missiles and associated airborne sensors that China has produced or is currently developing, and provides an overview of China's air-to-air missile research and development (R&D) ecosystem, including profiles of key organizations and individuals. It concludes with an assessment of the outlook for China's air-to-air missile capabilities and their implications for the United States.

We hope you find this volume useful, and look forward to bringing you further details on the foundations of Chinese aerospace in this series.

Dr. Brendan S. Mulvaney
Director, China Aerospace Studies Institute

Abbreviations

AECC	Aero Engine Corporation of China
AESA	Active Electronically Scanned Array (radar)
AEW&C	Airborne Early Warning & Control
AAM	Air-to-Air Missile
ASW	Anti-Submarine Warfare
AVIC	Aviation Industry Corporation of China
BVR	Beyond Visual Range
BVRAAM	Beyond Visual Range AAM
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CASC	China Aerospace Science and Technology
CASS	Chinese Academy of Social Sciences
CAST	China Academy of Space Technology
CATIC	China National Aero-Technology Import & Export Corporation
CCP	Chinese Communist Party
CETC	China Electronics Technology Company
CFD	Computational Fluid Dynamics
COMAC	Commercial Aircraft Corporation of China
CMC	Central Military Commission
CNC	Computer Numerical Control
ECM	Electronic Countermeasures
EDD	Equipment Development Department
EODAS	Electro-Optical Distributed Aperture System
EW	Early Warning
GAD	General Armament Department
HALE	High Altitude Long-Endurance
HMD	Helmet-Mounted Display
IFF	Identification Friend or Foe
IRST	Infrared search and tracking system
ISR	Intelligence, Surveillance, and Reconnaissance
MAWS	Missile Approach Warning System
MCF	Military-Civilian Fusion
MIIT	Ministry of Industry and Information Technology
MOST	Ministry of Science and Technology
NDU	National Defense University
NDRC	National Development and Reform Commission
NUAA	Nanjing University of Aeronautics and Astronautics
NUDT	National University of Defense Technology
PD	Pulse Doppler radar
PESA	Passive Electronically Scanned Array
PLA	People's Liberation Army
PLAAF	People's Liberation Army Air Force
PLAN	People's Liberation Army Navy
PRC	People's Republic of China
ROCAF	Republic of China (Taiwan) Air Force
RWR	Radar Warning Receiver
SAR	Synthetic Aperture Radar
TCAF	Theater Command Air Force
TISEO	Target Identification System Electro-Optical
UCAV	Unmanned Combat Aerial Vehicle
VLRAAM	Very Long Range AAM

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INTRODUCTION

On the morning of September 24, 1958, 32 days into the artillery duel at Kinmen (Quemoy) that triggered the Second Taiwan Strait Crisis, 18 Chinese Nationalist Air Force (ROCAF) F-86F fighters from the 11th Fighter Group took off from the Hsinchu Air Base some 40 miles west of Taipei and headed for the skies over Wenzhou Bay [温州湾] on the coast of Zhejiang province. Officially, their mission was to provide escort for the two unarmed RF-84F reconnaissance aircraft surveilling the mainland coast for signs of any pending invasion. But unofficially, as Gen. Leng Peishu – then-commander of the 11th Fighter Group – recounted many years later, the real purpose of the mission was to test the ROCAF's newly-received AIM-9 Sidewinder missiles under actual combat conditions. As Leng expected, the F-86s were intercepted by PLAAF MiG-17 fighters off the coast of Zhejiang. The ensuing battle, subsequently described as the largest air battle ever fought over the Taiwan Strait, saw the first use of air-to-air missiles (AAMs) in combat, and Lt. Col. Li Shuyuan (李叔元) of the ROCAF became the first pilot to shoot down an enemy aircraft with an AAM. The technological and training superiority of the ROCAF carried the day, and the battle ended with the Taiwanese claiming 10 kills with no loss of their own. According to Taiwanese records, a total of 6 AIM-9 missiles were fired during the battle, downing 3 MiGs and damaging another one. (U.S. advisors attached to the ROCAF confirmed 9 kills, including 2 missile kills.)[1] With the efficacy of the new weapon proven in combat, the U.S. began supplying the AIM-9 to Taiwan in large numbers in 1959, and the ROCAF would maintain a clear technological edge over their adversaries across the Taiwan Strait until well into the 1990s.

This report analyzes Chinese AAM and guidance system development. Drawing upon Chinese-language government publications, academic studies, and news articles, it reviews China's progress in air-to-air weapons development, including early attempts to copy and reverse-engineer foreign missile and fire control systems as well as more recent efforts at indigenous innovation. Throughout, it pays special attention to China's defense technology R&D plans and the technical characteristics of known systems.

The study is organized into five main sections:

- An overview of the basic components of air-to-air missiles and the different types of guidance systems they employ.
- A brief history of Chinese air-to-air weapon systems development
- Profiles of China's air-to-air weapon systems
- Profiles of relevant research institutes, manufacturers and scientists
- A conclusion summarizing the state of Chinese research into AAMs and its implications for the United States

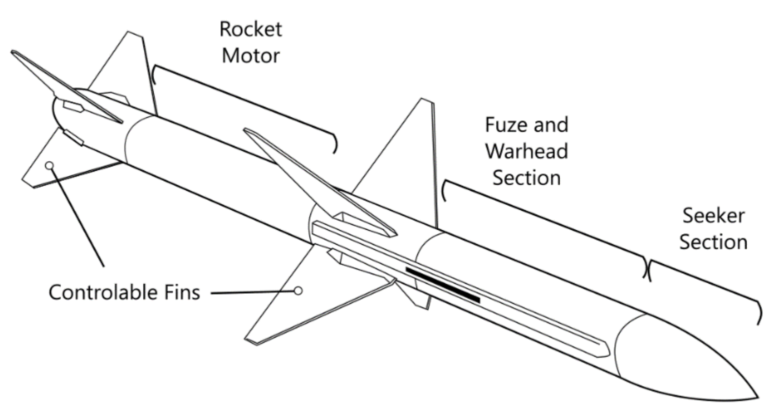
Types of Air-to-Air Missiles and Guidance Systems

Little more than a century has passed since the first casualty in air-to-air combat yet the nature of air war would likely be hardly recognizable to its earliest practitioners.

While the earliest air-to-air combat was conducted first with handguns and later machine guns and cannon, radar- and IR-guided AAMs have largely replaced guns as offensive systems. Radars were first installed in aircraft to allow them to find their targets at night. The first AAMs, such as the Soviet K-1, "rode" a radar beam from a fighter toward target. Later, the "Sidewinder" (AIM-9) missile developed by the U.S. Air Force incorporated sensors capable of detecting infrared heat. Advances in electronics and radar technology allowed missiles to incorporate their own small radar emitters. These systems are supplemented by large radars or infrared systems mounted in the front of an aircraft.

Before examining the specifics of China's AAM and guidance system research and development programs, an introduction to the essentials of AAM design and an overview of the state of these systems is necessary.

Basic Components of an Air-to-Air Missile



RANGES

Range Terminology for AAMs	
Range of modern airplane-mounted cannon[2]	<0.9 km
Normal human vision[3]	Eyes can only see effectively up to 2 km
Within Visual Range/Short Range	<10 km
Beyond Visual Range/Medium Range	10-100 km
Long Range	>100 km
Very Long Range	>300 km

While modern air-to-air gun systems are assisted with radar, their practical range is less than one kilometer (km).[4] Due to limitations on their sensor's capabilities, early AAMs hardly improved on this distance and relied on rear aspect attacks to take advantage of the large heat signatures of jet engine exhausts.

More powerful radars both within the aircraft and later on the missile itself allowed for beyond visual range (BVR) attacks for radar-guided systems, and later, through development of powerful infrared and TV-sensors, for optically-guided missiles.

Increasingly, there has been a push for systems capable of achieving successful kills beyond 100 kilometers through the use of advanced propulsion and guidance systems. The most advanced of these, which usually require a two-stage rocket motor, are envisioned as flying over 300 kilometers. For comparison, the combat radius of an aircraft (i.e., the distance an armed aircraft is capable of flying in one direction before needing to return to refuel) is typically below 1,500 kilometers.

GUIDANCE SYSTEMS

Air-to-Air missiles can be broadly categorized as using optical or radar guidance systems. Optical guidance systems are generally passive guidance systems, meaning that they neither emit energy nor receive commands from an external source, "homing in" instead on the infrared or visible light signature coming from the target itself. Typically, passive homing systems required target identification and lock-on by a human operator prior to launch. Optical guidance systems include sensors that track targets' infrared (IR) emissions, typically jet exhausts, and visual spectrum trackers that identify the shape of targets from a distance. Radar guidance systems come in the form of powerful radars installed in the nose of an aircraft, sometimes supplemented by smaller radar emitters in the front portions of missiles. While missiles equipped with their own onboard radars are said to possess "active guidance," other missiles, with "semi-active" radar-homing systems, are only equipped with radar receivers to detect radar energy beamed from an external source (typically the launch aircraft) and reflected off the target, requiring the launch aircraft to maintain radar illumination of the target for the entire duration of the missile's flight.

Infrared guidance is by far the most common for short-range AAMs, while radar guidance is typically employed for medium- and long-range AAMs. However, AAMs incorporating multiple forms of guidance systems are also becoming more common in contemporary AAM designs, due to the challenge of stealth and the increasing sophistication of other countermeasures employed by modern combat aircraft. This insight is not lost on Chinese missile engineers, who have likewise attached high priority to developing effective multi-mode seekers as a means to achieve true all-weather capability.[5]

Propulsion and Maneuverability

Most air-to-air missiles use solid propellant rocket motors. Liquid propellant is almost never used in air-launched missiles except in a few air-to-ground missiles, such as the YJ-91 anti-radiation missile derived from the Russian Kh-31 missile, which uses a liquid fuel ramjet. Work is also underway to develop gelled propellants that have advantages over solid and liquid propulsion, including higher performance and easier maintenance.[6] Low-smoke propellants are a priority as they are a significant cue for enemy aircraft that a launch has taken place.

Air-to-air missiles intended for very long-range engagements have adopted ramjets for propulsion. Ramjets use the missile's forward motion to compress air before combustion, providing jet propulsion with a very simple, lightweight engine. These missiles typically need a rocket booster to achieve the necessary speeds before the ramjet can achieve sufficient air compression. The addition of controls to the inlet allows such missiles to maximize their range across a range of altitudes (and air densities). A prominent example of these missiles is the Meteor beyond-visual range air-to-air missile (BVRAAM) developed by European conglomerate MBDA, capable of speeds over Mach 4 and range in excess of 130km. Some images of AAMs produced by AVIC suggest that development of a missile using ramjets is underway, though available information is scarce.

Most AAMs use a combination of fixed and moveable fins to maneuver the missile toward its target. Since the mid-80s, some AAMs, such as the Russian R-73 and advanced variants of the U.S. AIM-9, have used thrust-vectoring technology to further improve their maneuverability. Thrust vectoring involves using guide vanes to alter the direction of thrust (see inset). China's PL-10E AAM, profiled in a later section of this report, appears to incorporate thrust vectoring.

More recently, a new generation of AAMs have appeared which employ Divert Attitude Control Systems (DACS). These use thrusters arranged in a ring around the missile body to achieve rapid response and precision attitude control. Much like a satellite, such systems provide short bursts of thrust to adjust the missile's attitude (i.e., the missile's orientation about its center of gravity) in mid-air. These systems have been discussed in the context of "over the shoulder" [越肩发射] AAMs (missiles capable of reorienting toward the rear after launch, homing in on targets behind the launching aircraft).[7]

AAM WARHEADS

Air-to-air missiles typically employ blast, fragmentation or continuous rod warheads which damage enemy aircraft through explosive force, explosively formed shards of hard metal, or an expanding ring of linked metal pieces. These can be detonated either through contact or radar or laser proximity fuses.

History of Chinese AAM Development

The PLAAF's first encounter with air-to-air missiles occurred during the 1958 Taiwan Straits Crisis, when ROCAF fighters flying combat air patrols over Jinmen Island began to carry the newly-developed AIM-9 Sidewinder missiles supplied by the U.S..[8] The efficacy of the new missiles prompted the PLA to issue an urgent request for equipment upgrade, and before the year's end China's first AAM trial production line [试制生产线] had been set up at the 331 Factory in Zhuzhou, Hunan Province to license-produce the K-5 AAM, the first Soviet AAM to enter mass production, as the PL-1.[9] The following year, China set up its first missile test range in a desert area in western Inner Mongolia, the Northwest Combined Guided Missile Test Base [西北综合导弹试验基地] (which subsequently evolved to become the Jiuquan Satellite Launch Center), to conduct live-fire testing of AAMs. Initially, Lavochkin La-17 UAVs and modified MiG-15 drones were used as test targets.[10]

Although the K-5/PL-1 was a groundbreaking weapon, it was unsatisfactory in many ways. The PL-1's beam-riding system required the launching aircraft to maintain its relative orientation toward the target for the entire duration of the missile's flight, while the fan-shaped nature of the guidance beam greatly reduced the accuracy of the missile at any distance beyond four to five kilometers. These limitations meant that the missile was only moderately effective against slow-moving, large aircraft such as bombers, and was wholly inadequate against more agile fighters. Soviet missile designers were aware of the advantages of alternative guidance systems such as passive IR-homing, but progress on these other systems was slow.

Official Chinese histories, such as a single-volume month-by-month chronology of "key events" in the Chinese aviation industry published by AVIC, make little acknowledgment of foreign inputs into Chinese AAM development outside of initial Soviet assistance in the 1950s.[11] In fact, the Chinese AAM program, and the Chinese military aviation industry in general, benefited extensively from Western as well as Soviet technological input from the earliest days. While Soviet engineers struggled to come up with a satisfactory infrared-homing seeker, the PLA received an unexpected gift on 28 September, 1958, when a Sidewinder missile fired by a Taiwanese Saber failed to detonate after hitting its target during a skirmish over the Taiwan Strait. The PLAAF J-5 was able to land with the unexploded missile lodged in its fuselage, giving the PLA an intact example of the Sidewinder. Subsequently the Chinese transferred the missile to the Soviets, but only after attempting unsuccessfully to copy the missile on their own, and extracting a promise from the Soviets to share the reverse-engineered product. The result was the K-13, an almost exact copy of the AIM-9 Sidewinder.[12] Keeping their end of the bargain, in 1961 the Soviets sent China examples of the K-13, along with the relevant technical documentation. This became the basis for a new PL-series missile, the PL-2.

While the PL-2/K-13 is the best-known example of a Chinese air-to-air weapon system successfully reverse-engineered from captured U.S. technology, there were likely many other lesser-known instances where China benefited from captured/recovered U.S. technology, especially during the U.S.'s long involvement in the Vietnam conflict. For example, similarities between early Chinese airborne radars and those used on American aircraft during the Vietnam War is a possible indication that early Chinese designs were informed by radars recovered from crashed American aircraft. Likewise, some evidence suggests that the design of the PL-4 AAM, China's first semi-active radar-homing AAM, was informed by insights from recovered American AIM-7D "Sparrow" wreckage.

Nonetheless, relying on bits and pieces of salvaged Western technology and "indigenous innovation" had its limits, and Chinese progress in AAM development was slow and unsatisfactory throughout the 1960s and 1970s. Work on the aforementioned PL-4, for example, began in March 1966; but ground tests on the prototype were not completed until November 1980, and the entire program was terminated four years later for failing to meet the PLA's requirements. As the development of the PL-4 had been tied to the development of the new J-8 fighter, the missile's cancellation seriously disrupted the J-8 program as well.[13] By the mid-1980s China still lacked a credible all-weather fighter aircraft and the accompanying missile systems. The PLAAF continued to rely on the MiG-19-derived J-6 fighter, a 1950s' design built for traditional gun-based dogfights, as the backbone of its fighter force well into the 1980s,[14] some two decades after it had been retired from Soviet service.

Partly because of the technological inferiority of the PLAAF, air power did not play a part in any of China's major border conflicts, such as the Sino-Indian War of 1962 or the Sino-Soviet clashes at Zhenbao Island in Northeast China or near Tielieketi in Western China in 1969. While China's February 1979 incursion into northern Vietnam is typically mentioned as the last time China fought a "real war," it is notable that the PLAAF did not fly combat missions during the conflict, nor did it participate in any of the subsequent border clashes during the decade that followed.[15] In fact, China's last real experience with air-to-air combat since the Taiwan Strait Crisis of 1958 occurred during the U.S. involvement in Vietnam, when PLAAF fighters shot down several American aircraft that strayed too close to Hainan Island between 1965 and 1967.[16] In 1984, an internal U.S. government assessment called China's air defenses against Soviet forces – both in the air and on the ground – "probably the least credible aspect of the PLA's preparations."[17]

By this time, Soviet qualitative superiority had become a grave concern to Chinese security planners. Following the normalization of U.S.-China diplomatic relations in 1979, China eagerly sought Western assistance for the upgrade of its military aviation technologies, including jet engines, avionics, fire control systems, and air-to-air missiles.[18] In particular, China hoped to develop the J-8 fighter, its first indigenous fighter design, into a capable all-weather day/night fighter with look-down/shoot-down capabilities. At the same time, it sought technological upgrades to extend the service life of the basic J-7 design, a copy of the MiG-21 that China first obtained in the early 1960s. Access to Western missiles such as the French R.550 Magic and the

Israeli Python 3 in the early 1980s played a large role in the accelerated development of Chinese AAM technology.[19] By 1988, China had begun producing the Python 3 under license as the PL-8.

***Note on aircraft and missile variants*:** Chinese sources alternately use roman letters (A, B, C, etc.) and the "ten heavenly stems" [十天干] (甲, 乙, 丙, 丁, 戊 etc.) for "Mk 1, Mk 2, or A, B, C etc. when discussing weapon variants. For consistency, roman letters are used. Confusingly, this can also refer to missiles produced at the same time, but with different seeker heads, as in the PL-4A and B variants, which respectively use active radar and passive infrared seekers. In some cases, development

Since the 1980s, Chinese avionics development has been driven at least in part by arms exports. When China decided to offer the J-8 on the international arms market, the J-8's design was significantly modified and the central air intake was replaced by dual side intakes to accommodate a more powerful radar system in the nose capable of BVR engagements.[20] While the resulting J-8II fighter failed to attract any foreign orders, improved avionics allowed China to sell other aircraft, such as export variants of the J-7 (a Mig-21 derivative) upgraded with the Italian FIAR Grifo-7 radar,[21] to countries such as Pakistan, Egypt, Bangladesh, and Sri Lanka. While China did not receive the 52 AN/APG-66V2 PD radars that the United States had planned to transfer, due to post-Tiananmen sanctions, introduction to the technology and eventual access to the Israeli EL/M-2032 radar paved the way for later work. The J-10 variant sold to Pakistan is believed to have incorporated upgraded radars. The same is true for the smaller JF-17.[22]

PRC Air-to-Air Missile Development Timeline	
1956	Institute of Electronics of the Chinese Academy of Sciences established at the direction of the State Council as part of the first 12-year Long-term Science and Technology Development Plan (1956 – 1967)
1957	China signs agreement with Soviet Union on the transfer of “new technologies for national defense” to China, including the K-5 AAM[23]
1958	September – At least two PLA J-5s shot down by ROCAF Saber jets using U.S.-supplied “Sidewinder” AAMs during air battle over Wenzhou Bay. However, during a subsequent battle days later, a Sidewinder failed to detonate after hitting its target, allowing the J-5 to land with an intact missile lodged in its fuselage. This missile was subsequently replicated by the Soviets as the K-13.[24]
	First AAM trial production line [试制生产线] set up at the 331 Factory in Zhuzhou, Hunan Province to replicate the Soviet K-5 AAM as the PL-1[25]
1959	Northwest Combined Guided Missile Test Base [西北综合导弹试验基地] (now Jiuquan Satellite Launch Center) set up for ballistic and air-to-air missile tests
1960	March – First PL-1 successfully copied from K-5M[26]
	May – Zhuzhou in Hunan province chosen as a center for AAM development[27]
	July – Soviet technical advisors withdrawn from China due to Sino-Soviet ideological dispute. Target testing of AAMs suspended due to withdrawal of Soviet help and domestic economic difficulties (likely in part due to the Great Leap Forward)[28]
1961	Luoyang Optoelectronic Technology Development Center [洛阳光电技术发展中心], a.k.a. 613 Institute, established in Luoyang[29]
	February – Soviet Union transfers plans and technical information on Mig-21 fighters, aeroengines and K-13 AAMs during a brief thaw in bilateral relations
	July – Ministry of Defense 6th Academy establishes the 605 Institute (now AVIC Special Vehicle Research Institute) [航空工业特种飞行器研究] and gives it responsibility for replicating AAMs.[30] Factory 844 [844 厂] in Xi’an given primary responsibility for missile production.[31] Aviation Ordnance Research Institute (AORI) [航空兵器研究所] (predecessor to the Airborne Missile Academy) established in Xi’an.
1962	Replication of the K-13 AAM (designated PL-2) begins[32]
	June – Preliminary R&D begins on the PL-3, an improved variant of the PL-2
	August – AORI moved to Luoyang, Henan
1964	AORI and CAS Institute of Electronics [中国科学院电子学研究所] begin joint development of the Type 645 3cm band single-pulse airborne radar[33]
	Work on SL-4 (Type 204) radar for the new J-8 fighter begins at 607 Institute in Neijiang, Sichuan Province [四川内江] and Factory 780 [780 厂] in Mianyang, Sichuan [四川绵阳]
	331 Factory [331 厂] in Zhuzhou, Hunan sets up K-13/PL-2 AAM production line
	April – PL-1 final design approved and enters small batch production in Zhuzhou
	July – SL-1 (Type 201) radar begins flight testing
1965	605 Institute [605 所] given responsibility for design of the PL-3 missile, with Factory 331 given responsibility for manufacturing
1966	March – J-7 (MiG 21) reportedly uses PL-2A to shoot down U.S. “Firebee” UAV, claimed to be the first aerial kill by a Chinese AAM[34]
	April – R&D of PL-5A (SARH), PL-5B (IRH) begin at AORI in Luoyang[35]

	May – R&D on the PL-4, a SARH missile, begins in Luoyang, intended to equip the planned J-9 fighter[36]
1967	March–July – PL-2 live-fire testing completed
	November – PL-2 design approved, enters series production at Factory 331 in Zhuzhou
	December – AORI successfully tests an infrared guidance system
1968	March – Airborne Radar Research Institute [机载雷达研究所] established in Zhuzhou, building on previous work by the AORI Radar Research Office [雷达研究室]. Later moved to Neijiang, Sichuan [内江四川省]
	June – the first batch of PL-3 begins ground and flight testing
	November – SL-2 (Type 645) radar successfully flight-tested, begins batch production
1969	PL-1 ceases production
1970	Aviation Ordnance Research Institute (AORI) in Luoyang reorganized as China Airborne Missile Academy (CAMA) [中国空空导弹研究院]/612 Institute [612 所], also known as Base 014 (014 基地), replacing 605 Institute as the primary developer of AAM's
	May – Aviation Fire Control Research Institute [航空火力控制研究所] established in Luoyang
	November – PL-2 production transferred to the Nanfeng Machinery Plant [南峰机械厂], a.k.a. Factory 202, in Hanzhong, Shaanxi Province
1971	July – PL-5A begins flight testing[37]
1974	PL-3 live-fire test from J-7
1975	PL-6 R&D begins on the basis of the PL-5B, intended to possess high-G maneuverability[38]
1976	R&D of the PL-2B begins based on AIM-9E[39]
1977	PL-7 development initiated, believed to be a reverse-engineered copy of the French R.550 Magic missile, valued by the PLA for its high maneuverability
1979	China imports fire control systems from the UK for use on the J-7M fighter[40]
	PL-6 air-launch tests
1980	R&D begins on the JL-7 airborne radar[41]
	April – PL-3 final design approved,[42] intended for use on the J-8
	November – PL-4 prototype ground test completed[43]
1981	July – PL-4 begins second phase development
	August – PL-5 aerial testing against targets[44]
	October – final design of PL-2B approved, enters mass production[45]
1982	PL-7 program approved by the Ministry of Aviation Industries , R&D begins in Zhuzhou[46]
	PL-4A, intended for use on the J-8II, listed among 23 key conventional weapons R&D projects
	Israel signs Python 3 licensed production deal w/ China, giving access to key technologies
	PL-8 project approved with the goal of producing the Python-3 with 100% local components
	Ground testing for the JL-7 radar begins
	June – Luoyang Aviation Fire Control Research Institute successfully tests the first fire control system using an electronic display on a modified J-6A[47]
1983	Environmental and vibration testing on the JL-7 completed[48]

	Work on airborne continuous-wave irradiator (CWI)-A airborne radar begins, meant to fulfill requirements of Type 202 radar for the J-8II.[49]
	March – Ministry of Aviation Industries cancels the PL-6 and PL-5A (SARH version) projects
	July – PLA rejects the PL-3 due to continued problems with the proximity fuses; PL-3 production ceases
	September – CAMA begins work on the PL-8 project
1984	CW1-A airborne radar prototype completed[50]
	PL-7 aerial live-fire tests begin[51]
	R&D of PL-8B, an improved variant of the PL-8 using all domestic components, begins
	February – PL-2A ceases production
	October – Work on PL-4A ceases due to its inability to meet operational requirements[52]
1986	PL-7 successful live test
	PL-2B ceases production
	PL-9 program initiated;[53] the missile is believed to be based on the PL-7 airframe but fitted with a new IR seeker derived from Israeli Python-3 technology[54]
	PL-8 enters service
	China buys Italian Aspide BVRAAMs, likely for use with J-8II. Later becomes PL-11[55]
	September – PL-5B (IRH version based on PL-2 technology) design approved by the Central Military Commission[56]
1987	PL-5B enters small batch production
	March – flight testing of the JL-7 radar completed[57]
	April – PL-7 passes review, begins batch production[58]
	August – "Peace Pearl" Agreement signed with the U.S. for planned upgrade of 50+ J-8II aircraft with improved avionics, including AN/APG-66 fire-control radar.[59]
1988	Exports of the PL-7 begin
	January – CWI-A radar passes technical certification[60]
	February – The design of the SL-5 airborne fire control radar developed by Changhong [长虹] approved and enters production.
1989	PL-9 enters batch production[61]
	PL-8 R&D completed
	The first batch of PL-11s completed using Italian-produced parts, agreement canceled after the crackdown in Tiananmen Square
	July – "Peace Pearl" program canceled after Tiananmen Square crackdown
1990	Sino-Israeli agreement leads to EUM-2034 fire control radar being adopted for the J-8 II[62]
	Independent development of the PL-11 begins
	September – JL-10 full-waveform mechanical pulse DP radar completes first aerial flight test of high-frequency speed search[63]
1991	China purchases Soviet/Russian R-27 ("AA-10") BVR AAMs from Russia and Ukraine[64]
	PL-5C program initiated as upgrade to PL-5B
	May – PL-5B accepted for use by the PLA

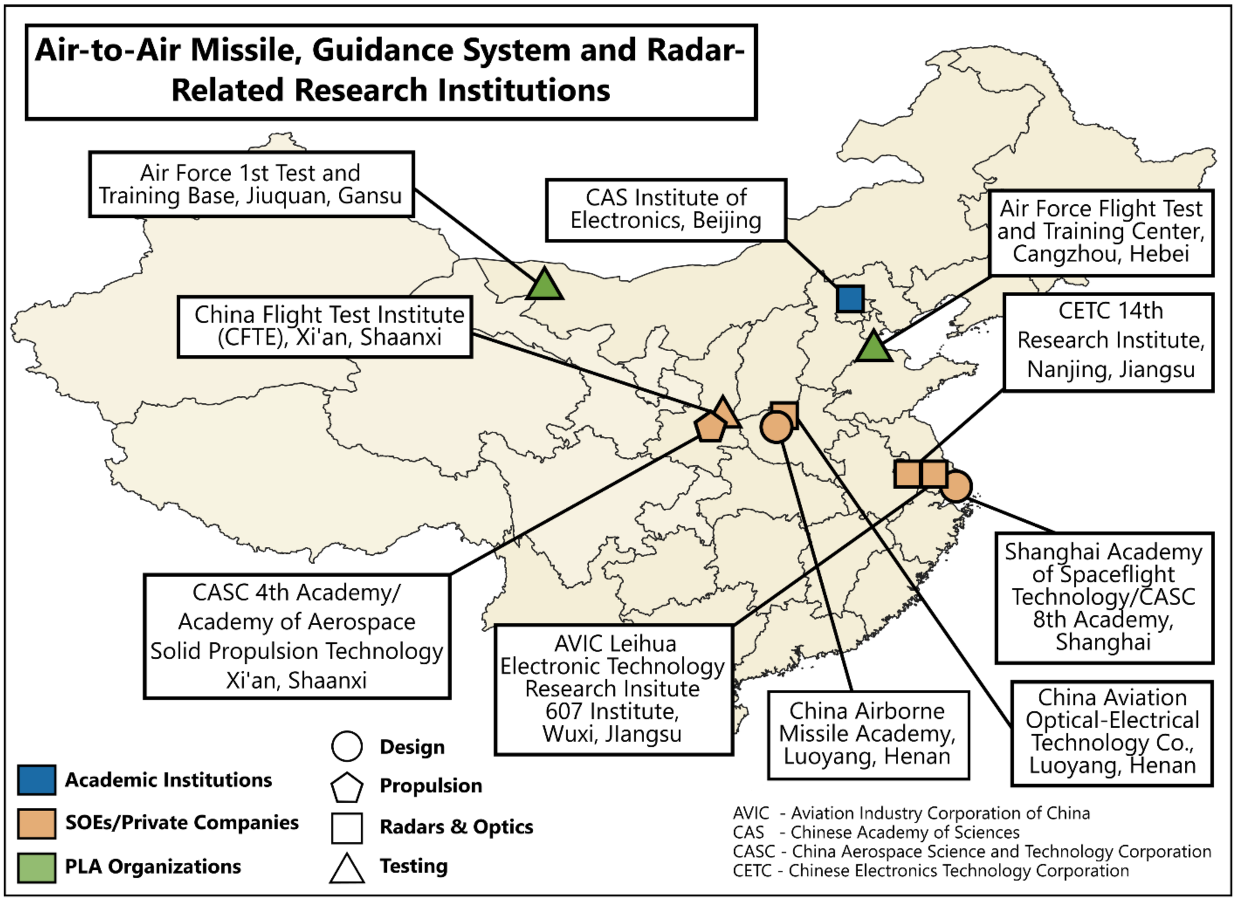
1992	PL-9B passes external inspection
	PL-11 live-fire test from J-8IIB
1993	August – PL-8A first successful firing test, enters service later that year
1994	Condor PD radar first successful flight test[65]
	March – PL-8A passes review, enters mass production
1995	China buys Russian R-73 (“AA-11”) SRAAMs and places a large order for R-73 missiles from Ukraine[66]
1997	SD-10/PL-12 begins development,[67] intended to be an active radar-homing BVR missile comparable to the U.S. AIM-120 and the Russian R-77 (“AA-12”)
1998	March – China develops universal AAM pylon
1999	CAMMRI conducts first successful interception and tracking test of an unidentified AAM in Zhengzhou
	PL-5C design finalized, enters service
2000	TY-90 anti-helicopter AAM program initiated
2001	China purchases the Russian Zhuk-8 radar for upgraded J-8II[68]
	August – China Airborne Missile Academy (CAMA) [中国空空导弹研究院] reorganized following merger with the Nanfeng Machinery Plant, which was relocated to Luoyang from Hanzhong, Shaanxi
2002	PL-9C design finalized, exports begin
	PL-9D program established
2004	PL-10 program initiated, intended to be a high maneuverability IR-homing AAM capable of +/-90 degree off-boresight angles. The missile seeker can be slaved to a helmet-mounted display (HMD), offering “look and shoot” capability beyond the radar scan envelope. The missile is believed to have thrust-vectoring capability[69]
2005	September – CAMA completes testing of the PL-12;[70] PL-12 adopted by the PLA
2006	TY-90 enters service[71]
2010	PL-10 design approved
2011	Unidentified missile believed to be PL-15 VLRAAM passes live fire tests[72]
2013	PL-10 enters production
2015	September – Successful air-to-air test of the PL-15 against a target drone[73]
2016	November – Successful test of a VLRAAM, possibly the ramjet-powered PL-21, launched from J-16 against a drone[74]

China's Air-to-Air Missile and Guidance System R&D Ecosystem

Development and production of air-to-air missiles is a complex process involving myriad institutions ranging from research institutes in Shanghai to test bases in remote parts of western China. The graphic below highlights a few of the many organizations involved. Examination of researcher affiliations from relevant academic journals indicates that the National University of Defense Technology [国防科学技术大学] in Changsha and the Air Force Engineering University [空军工程大学], in Xi'an, Shaanxi Province appear to be the focus of the PLA's internal R&D on AAMs. Civilian academia is much more diverse but the Xi'an-based Northwestern Polytechnical University (NWPU), Beihang University in Beijing and Nanjing University of Aeronautics and Astronautics (NUAA) in Nanjing all appear to have significant relevant academic or R&D programs.[i] The Chinese Academy of Sciences' Institute of Electronics, in particular, has been a major part of the effort to develop airborne radars. While primary responsibility for producing air-to-air missiles and related systems falls to state-owned corporations such as AVIC, CETC, and CASC, a number of smaller private companies appear to have joined the industry in recent years, particularly in high-tech niche areas such as sensor development.

Significant disadvantages such as reliance on imported signal processing chips for AESA radars appear to have been addressed through indigenization in the past decade. While details are scarce, available data suggests increasing levels of automation and precision in the smart manufacturing [智能制造] of AAMs.[75]

[i] Harbin Engineering University announced in 2017 that Dr. Liu Daijun [刘代军], Chief Designer of the China Airborne Missile Academy [中国空空导弹研究院], and Dr. Bai Xiaodong [白晓东], Deputy Chief Designer, would be joining the university's faculty. Liu also serves as Vice President and Chief Technology Officer of the China Airborne Missile Academy and Director of the Infrared Sensor Technology Aviation Technology Key Laboratory [红外探测器技术航空科技重点实验室].



INPUTS TO THE R&D PROCESS

The Central Military Commission's Equipment Development Department (EDD) has professional groups [专业组] and expert groups [专家组] dedicated to topics of interest, such as precision guidance technology [精确制导技术专业组], "preliminary" (i.e. basic) research in aerodynamics [空气动力学预研专家组], etc. These groups include senior scientists and engineers working on these topics. This presumably helps feed information about new discoveries and research priorities into the pipeline for state sponsorship of R&D.[76]

Key Developer of Missiles

中国空空导弹研究院
CHINA AIRBORNE MISSILE ACADEMY

China Airborne Missile Academy
[中国空空导弹研究院]

Also known as: 612 Institute [612 所]; 014 Base [014 基地]

Location: Luoyang, Henan Province [河南省, 洛阳]

Website: http://www.camags.com.cn/

The China Airborne Missile Academy (CAMA) is generally considered China's premier developer of air-to-air missiles. The current iteration of CAMA was created through the merger of two organizations in 2001: the original China Airborne Missile Academy [中国空空导弹研究院], founded in 1961 in Xi'an, and the Nanfeng Company [南峰公司], formerly known as the Nanfeng Machinery Plant [南峰机械厂] (a.k.a. Factory 202), established in 1966 in Hanzhong, Shaanxi Province [陕西汉中]. The Academy is subordinate to AVIC.[77] Prior to the consolidation of AVIC in 2008, the Academy was under AVIC 1.[78] It is strongly connected to AVIC Optronics.

The Airborne Missile Academy appears to have many subsidiaries under the umbrella of CAMA Luoyang, including the CAMA Luoyang Gas Supply Company [凯迈（洛阳）气源有限公司], CAMA Luoyang Electromechanic Company [凯迈（洛阳）机电有限公司], and CAMA Luoyang Measurement & Control Equipment Company [凯迈（洛阳）测控有限公司]. While many of these subsidiaries appear to be engaged primarily in the civilian sector, they may still play an important role in the defense sector mission of their parent institution. For example, in 2017 the R&D Center of the CAMA Luoyang Gas Supply Company, a manufacturer of pneumatic devices for general industrial applications, announced that it had successfully developed a Divert Attitude Control system (a quick reaction propulsion system providing control over the positioning of missiles and rockets) for the Kunpeng-1B [鲲鹏-1B] sounding rocket.[79]

While primarily an R&D organization for AVIC, CAMA also offers several masters and doctoral programs and has sponsored various youth talent development programs since 2011. CAMA also holds an annual "Future Air-to-Air Missile and Derivatives Design Competition" [未来空空导弹及其派生武器设计大赛] for its junior staffers.[80]

KEY DEVELOPERS OF OPTO-ELECTRICAL SENSORS AND RADARS

A number of state-sponsored research institutions, as well as commercial enterprises, are involved in the development of opto-electrical sensors (including infrared sensors) and airborne radars used for the guidance systems of air-to-air missiles.

AVIC Optronics

[航空工业光电所]

Location: Luoyang City, Henan Province

Website: http://www.avicoptronics.com

Established 10 May 1970, AVIC Optronics (a.k.a. the 613 Institute [613 所], and sometimes rendered as the AVIC Luoyang Opto-electrical Technology Development Center [中国航空工业总公司洛阳光电技术发展中心]) produces a wide range of sensors, IR and visual spectrum cameras (including the "Dragoneye" ["龙之眼"] optical pods for attack helicopters and UAVs), night vision goggles, displays, and the "Sharp Sight" series of HMDs ["锐视"系列头显]. In addition to its military products, AVIC Optronics also produces a wide range of electro-optical applications for the dual-use and civilian markets, such as displays for the C919 passenger jet under development by COMAC.

Subsidiaries of AVIC Optronics include the company's primary Optoelectronics R&D Center in the Luolong District of Luoyang; an optoelectronic industrial park in Yibin, Sichuan Province [四川,宜宾]; and an innovation center recently established in Beijing.[81]

China Electronics Technology Group Corporation (CETC) 14th Research Institute [中国电子科技集团公司第十四研究所]

Location: Nanjing, China

Website: http://14.cetc.com.cn/

Typically referred to as the 14th Institute, the 14th Research Institute of China Electronics Technology Group Corporation was also known historically as Nanjing Radar Plant 720 and Nanjing Research Institute of Electronics Technology (NRIET).[82] Its civilian subsidiary, the CETC Guorui Group Co. [中电国睿集团], offers a range of civilian products and services including civilian radars, wireless telecom equipment, integrated circuits, logistics and urban transportation solutions, software applications, etc.[83]

Known as the birthplace of Chinese radar, the 14th Institute traces its origins to the "Special Telecommunications Equipment Repair Center" under the KMT-era Ministry of National Defense in 1946. It was taken over by the Communist authorities in April 1949 after PLA forces captured Nanjing.[84]

Considered China's premier producer of airborne radars, the 14th Institute played a crucial role in the development of China's first operational airborne pulse-doppler (PD) radar in the 1980s, developing the antenna and the processing unit of the radar indigenously due to restrictions on foreign imports.[85] A decade later, the 14th Institute also played a crucial role in the development of China's first high-power AESA fire control radar for the J-10B.

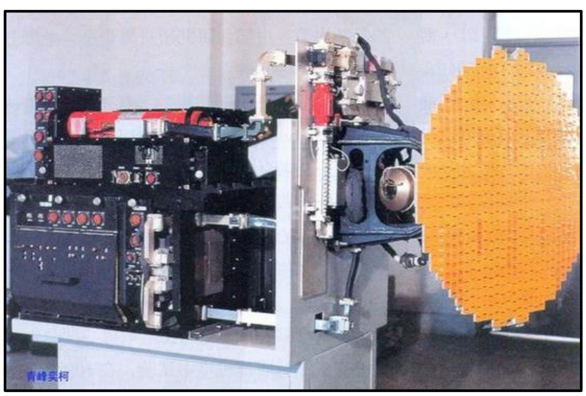
AVIC Leihua Electronic Technology Research Institute (LETRI) [航空工业雷华电子技术研究所]

Also known as: 607 Institute, AVIC Airborne Radar Institute [中航机载雷达所]

Location: Wuxi, Jiangsu Province, China

Website: www.chinaleihua.com

The 607 Institute, long-known as the AVIC Airborne Radar Institute [中航机载雷达所] before its rebranding as AVIC Leihua, was first established in Zhuzhou in Hunan Province. It was subsequently moved to Neijiang, Sichuan [四川内江] as part of the Third Front relocations, and later transferred to Wuxi in coastal Jiangsu province in the 1980s. The 780 Factory [780 厂] that worked in partnership with the 607 Institute was eventually transformed into the Sichuan Changhong Electric Co. [长虹电子], a large conglomerate that includes many military enterprises.[86] The 607 Institute developed the monopulse JL-7, often described as China's first successful airborne fire control radar, in the mid-1980s; although by this time monopulse radars were already obsolescent. In the 1990s it developed the full waveform mechanical pulse JL-10A PD Radar, one of the first airborne PD radars to enter Chinese service, although the type was not considered entirely successful and was relegated to the JH-7A fighter/bombers used by PLAN naval aviation units.[87]



LETRI continues to be a leading developer of airborne radar systems for the Chinese military as well as civilian end-users. In 2018 LETRI displayed an X-band AESA radar at the Zhuhai Airshow. Accompanying exhibits indicated that the radar is capable of detecting fighters 170 km away and can track 15 targets at the same time.[88]

LETRI's current director and Party Secretary is Cheng Yufeng [程宇峰]. He was previously the project leader for the C919 civilian airliner's "Thousand League Eyes" integrated surveillance system ["千里眼"综合监视系统], a core part of its situational awareness and safety system.[89]

China Electronics Technology Group Corporation (CETC) 38th Research Institute [中国电子科技集团第 38 研究所]

Also known as: Hefei Institute of Electronic Engineering

Location: Hefei, Anhui Province

Website: http://www.cetc38.com.cn/

Initially established in 1965 in Guizhou, the CETC 38th Institute is now based in Hefei. A leader in Chinese early warning radar and associated technological development,[90] the 38th Institute is also involved in a variety of dual-use and civilian sectors, with a range of subsidiaries including an integrated circuit design center and several important laboratories related to public health, automotive electronics, and the Beidou satellite navigation system.

The 38th Institute has developed an array of modern air defense radars such as the "Airborne Sentinel" [空中守望者] series, which include the JY-27A radar, JY-26 radar, and JYL-1A radar. According to Chinese media reports, China had been reliant on imported Digital Signal Processor (DSP) chips until the successful development of the Hunxin 1 [魂芯一号] chip by the 38th Institute in 2011, which was touted as a breakthrough that allowed China to break this reliance.[91] In 2016, the KJ-500 AEW&C aircraft, whose radar was built by the 38th Institute, appeared at the Zhuhai Airshow. The KJ-600, a shipborne AEW&C aircraft roughly similar to the U.S. E-2D aircraft under development for use on future Chinese carriers, will likely use the JY-26 AESA radar, believed to have a detection range of 500km.

CETC 50th Institute

[中国电子科技集团公司第 50 研究所]

Also known as Shanghai Microwave Technology Research Institute [上海微波技术研究所]

Location: Shanghai, China

Website: http://www.50.sh.cn

Established in 1977, and located in Shanghai's Putuo district, the 50th Institute is said to be focused on the development of tactical communications equipment and communication systems, detection equipment, microwave measuring equipment, telemetry systems, and terahertz communication systems. It employs some 1200 people and has eight scientific R&D departments and three subsidiary manufactories.[92][93] While the institute is regularly listed with the CETC 14th and 38th Institutes as a major developer of airborne radars, little public information is available about its role in radar development.

Institute of Electronics of the Chinese Academy of Sciences
[中国科学院电子学研究所] (IECAS; simplified as 电子所)
Location: Haidian District, Beijing
Website: http://www.ie.cas.cn

The Institute of Electronics originated with an exploratory committee established by the State Council in September 1956 as part of China's first long-term (12-year) S&T development plan. Work on airborne radars is carried out by subordinate research units including the State Key Laboratory of Microwave Imaging Technology, the State Key Laboratory of Electromagnetic Radiation and Detection Technology, and the Department of Airborne Microwave Remote Sensing Systems [航空微波遥感系统部].[94]

Beijing "A-Star" Science and Technology Co.
[北京中陆航星科技有限公司]
Location: Changpin District, Beijing
Website: N/A

One of the companies that appear to be a leader in Chinese airborne sensor technology is Beijing "A-Star." Founded in 2000, it is based in Beijing's Changpin S&T Park. Primary products include the Eagle Eye [鹰眼] series photoelectric pods. Its marketing materials boast of "strategic partnerships" with companies in Russia, Ukraine, Britain, France, Italy, Japan, and the United States. The Jiangsu branch of the company, Jiangsu A-Star [江苏中陆航星], was established in 2013 and appears to have primary responsibility for airborne sensors and aircraft manufacturing. In 2014 it was granted permission by the Jiangsu Provincial Development and Reform Commission (the Jiangsu provincial branch of the powerful National Development and Reform Commission (NDRC)) for the production of the EA400 and EA500 general aviation aircraft, the design rights of which were purchased from Germany.[95]

Its other products include the EORD-31 Forward Facing IRST System, pictured left, and the FS-69 and FS-99 infrared sensors.

In 2016 the company also signed an agreement with Ukrainian aerospace company Antonov to purchase two An-178 short-range medium-airlift military transports and produce the aircraft under license in China.[96]

A-Star produces the 290 kg Advanced Unified Electro-Optical Detection and Guidance System (AUEODS). Designed for use by itself or connected to other aircraft sensors, the system provides "missile/bomber guidance, searching/tracking reconnaissance, target position tracking, long-range panoramic IR searching, and battlefield situational awareness." The goal appears to be to upgrade existing second and third-generation aircraft into effective fighters.

No information regarding the company's ownership structure can be found in available open sources. However, given the privileged access that the company apparently enjoys, the company is likely a subsidiary of a major Beijing-based SOE or some other state entity directly subordinate to the Chinese Central Government.

Key Developers of Propulsion Systems

CASC Fourth Academy
[中国航天科技集团公司四院]

Also known as: Academy of Aerospace Solid Propulsion Technology (AASPT) [航天动力技术研究院]; Shaanxi Aerospace Science and Technology Corporation [陕西航天科技集团有限公司]

Location: Xi’an, Shaanxi

Website: http://www.aaspt.net

Established as the Solid Fuel Engine Research Institute of the Fifth Research Institute of the Ministry of National Defense on 1 July 1962, the CASC Fourth Academy is the oldest and largest specialized solid rocket engine research institute in China. Through the years it has been relocated several times to different locations throughout China. Since the 1990s, however, it has been continuously based in Xi’an.[97] It includes six research institutes, two production plants, and 18 civilian companies.

The Fourth Academy has conducted extensive work on solid-fuel rocket engines for AAMs. In 2017 *S&T Daily* reported that the academy had carried out successful tests of a variable-flow solid-fuel ramjet. The article indicated that the Fourth Academy was working on a longer-range AAM engine. Work apparently began on solid-fuel ramjets as early as 2000.

According to Chinese reports, the combination of thrust vector control and variable-inlet technology allows the missiles to achieve both longer range and greater maneuverability.[98]

CASC Eighth Academy
[中国航天科技集团公司八院];

Also known as: Shanghai Academy of Spaceflight Technology [上海航天技术研究院]

Location: Shanghai, China

Website: http://www.sast.spacechina.com/

Founded in 1962, the CASC Eighth Academy was charged with solid-rocket engine R&D.[99] Some of its major responsibilities include the development of launch vehicles, strategic and tactical ballistic missiles, satellites, and manned spacecraft. An unidentified institute under the Eighth Academy may be involved in the development of an unspecified long-range AAM.[100]

One of the Academy’s subordinate entities, the 803 Research Institute [八〇三研究所], also called the Specialized Control Institute [控制专业所], is involved in R&D of tactical missile infrared guidance and flight control systems, launch vehicle control systems, satellite control systems, and aircraft control systems. In 2013 it established a "Joint Laboratory on Ultra-Precision Manufacturing Technologies [超精密制造技术联合实验室] with the Nanjing University of Aeronautics and Astronautics.[101]

In 2013 its director, Zhang Chunming [张春明], gave a lecture at NUAA on "Microsatellite Development and Their Application in Practical Space-Based Attack and Defense." [102]

NOTABLE CHINESE AIR-TO-AIR MISSILE AND GUIDANCE SYSTEMS DESIGNERS AND ENGINEERS

Some of the most prominent Chinese AAM designers include:

Liang Xiaogeng
[梁晓庚]

Chief Weapons System Designer at Aviation Industry Corporation of China

In his decades-long career with the Chinese defense industry, Liang Xiaogeng, chief weapons system designer of AVIC and former deputy chief designer of China Airborne Missile Academy, was involved in designing multiple types of AAMs, in particular their guidance and control systems.[103] Specifically, he presided over the research and design of six missile models either as the chief designer or deputy chief designer. The weapon systems he worked on include China's third and fourth-generation infrared-guided AAMs,[104] the latter of which is said to be the PL-10E.[105]

For over 30 years, Liang has been working on AAM guidance and control technologies as well as their engineering applications. For example, he is said to have developed the technology that enables a recent AAM model to defeat adversarial jamming during its entire flight.[106] In an effort to increase a certain AAM's maneuverability, he helped develop a type of digitalized brushless motor for an AAM servo system.[107] In developing a "generation-skipping" AAM model, he led a team in achieving three challenging technical and tactical capabilities for AAMs, specifically: over-the-shoulder-launch capability; high angle of attack flight capability; and high G-load endurance capability.[108] During his long career, Liang is said to have led various development teams in overcoming many such "universal" challenges.[109]

Liang has spoken publicly about the designs and capabilities of China's latest AAMs such as the PL-10E. In a 2018 *Global Times* interview, Liang told the government-controlled media outlet that the PL-10E, as an AAM with outstanding performance capabilities, is comparable to the U.S.-developed AIM-9X Sidewinder missile.[110] At another public event, he noted that the Chinese-made SD-10, with its long-range, high maneuverability, outstanding anti-jamming capability, and active radar-homing capability, is competitive against fourth-generation medium-range AAMs from around the world.[111] Speaking about Chinese-developed fourth-generation AAMs' combat applications during the aforementioned *Global Times* interview, Liang said that under a complex electromagnetic environment, a fourth-generation Chinese AAM, like the PL-10E, with its high speed and maneuverability in close-range aerial combat,[112] may have an advantage over a fourth-generation stealth fighter.

Born in June 1960, Liang majored in missile control systems at Northwestern Polytechnical University as an undergraduate and received a masters and then doctorate from the same institution in 1995.[113] During his career, he has published over 60 papers and received 11 patents. [114] He also presided over the writing and publication of a book titled "*Design of Air-to-Air Missile Guidance and Control*," considered a classic by Chinese missile designers.[115]

Lin Youquan
[林幼权]

Chief Scientist at China Electronics Technology Group Corporation (CETC) [中国电子科技集团公司] and chief expert at the CETC 14th Research Institute.

A native of Zhejiang, Lin graduated from the Nanjing University of Aeronautics and Astronautics (NUAA) in 1986, before completing a Master's degree in signal and information processing at the same university in 1989. He then went on to complete a doctorate in signal and information processing at the Xi'an Electronic S&T University [西安电子科技大学].[116]

Under Lin's leadership, the 14th Institute, China's top radar technology developer and radar equipment manufacturer, has purportedly been able to overcome international embargos of critical defense technologies. Lin and his team designed an effective payload plan for a distributed satellite constellation's synthetic-aperture radar (SAR) system and conducted research on the positioning, navigation and timing (PNT) of the distributed satellite constellation's SAR systems. The satellite-borne SAR system the 14th Institute developed is believed to be a milestone in China's efforts to improve its military reconnaissance methods and capabilities.[117]

During the 9th, 10th, and 11th Five-Year Plans (1996-2010), Lin led a team developing a type of X-band aircraft-borne AESA fire control radar for the Chinese military.[118] The new-generation fire-control radar was later used to equip China's fourth-generation stealth fighter, the J-20. The radar's technical benchmarks are said to have exceeded the U.S.-developed AN/APG-77, which is installed on the F-22 Raptor fighter.[119] Moreover, the technologies developed for the program have been extensively applied to other national defense programs in aerospace, aviation and missile defense. Lin has received some of the PRC's most prestigious S&T prizes for his contributions.[120]

Lin is the author of *New Satellite-Borne SAR Radar Technology* and a co-author of *Development of Surveillance Radar Technology for Near-Space Hypersonic Vehicles*, published on 25 December 2010.[121]

THE PILI [霹雳] (THUNDERBOLT) SERIES OF CHINESE AIR-TO-AIR MISSILES

PL-1

The PL-1 was derived from the early Soviet beam-riding Kaliningrad K-5 AAM.

Due to the nature of its beam-riding guidance system, the missile had very limited range, was only moderately effective against large, slow-moving targets such as heavy bomber aircraft, and was impractical as a dogfighting missile. It never equipped the J-7 and J-8 fighters and was employed only experimentally on the J-6 fighter.[122]

PL-2

In 1958 China recovered an intact example of the newly-developed AIM-9B Sidewinder missile, when a missile fired by a Taiwanese Saber jet hit a PLAAF J-5 fighter without detonating, allowing the J-5 to return to base with the missile lodged in its fuselage. The missile was subsequently transferred to the Soviet Union, and was reverse-engineered as the K-13/AA-2 missile. Per an agreement reached before the transfer, in 1961 the Soviet Union delivered examples of the K-13 and the relevant technical documentation to China. The new missile became the basis for a new PL-series missile, the PL-2, although due to disruptions caused by the Cultural Revolution series production did not begin until 1970.

PL-3

Billed as China's first "indigenously-designed" AAM, development on the PL-3 began in 1962 as a follow-on to the PL-2 with major improvements in speed, range, maneuverability, and reliability. However, the original objectives of the program proved to be too ambitious for China's technological capabilities at the time, and the program was further disrupted by the onset of the Cultural Revolution. After the delivery of the first batch of prototypes for ground-testing in 1968, the new design did not receive its final state certification until 1980. However, during subsequent evaluations by the PLAAF, the new missile was assessed to be only marginally superior to the PL-2 in performance, while suffering protracted problems with its proximity fuse. The program was eventually cancelled in 1983.

PL-4

China's first semi-active radar-homing (SARH) AAM, the PL-4 was developed in the 1960s and was intended for the proposed J-9 interceptor. Work began in March 1966. Designed by the 612 Research Institute (now the China Airborne Missile Academy) and what is now the Zhuzhou Aeroengine factory, ground tests of the PL-4 prototype were completed in November 1980. In addition to the original SARH variant of the missile (known as the PL-4A), an IR-homing variant known as the PL-4B was also produced.

Although ground tests of the prototypes were completed in 1980, meeting the program's original design requirements, by that time those requirements were nearly 20 years old and were no longer adequate for the PLA's operational requirements. The J-9 interceptor, for which the PL-4 was originally intended, was cancelled in 1980. Although the missile was then repurposed for the relatively more successful J-8II program, with the normalization of U.S.-China relations China was given access to modern Western missiles such as the American AIM-7 Sparrow and the Italian Aspide, rendering the PL-4 unnecessary. The program was formally terminated in October 1984.[123]

Some evidence suggests that the PL-4's design was informed by insights from recovered AIM-7D wreckage obtained during the Vietnam War. Protracted issues with the Type-208 radar developed for the J-8II meant that the PL-4's SARH capability was never fully realized.

PL-5

A contemporary of the PL-4, the PL-5 program was also initiated in 1966 at the 612 Institute, although it is not clear whether the PL-5 program was launched simultaneously as the PL-4 as a separate, competing solution; or it was spun off the PL-4 program at a later date. Once again, two variants of the missile with two different seeker heads were eventually produced following the typical Soviet practice of the period – a SARH variant known as the PL-5A, and a passive infrared-homing variant known as the PL-5B.

Flight testing of both variants began in the early 1970s, although progress was generally slow. In 1983, the SARH "A" variant was cancelled by the Ministry of Aviation Industries, for much the same reason that the PL-4 program was cancelled as discussed previously. However, the IR-homing "B" variant, which was essentially an improved version of the PL-2, demonstrated sufficient promise to be retained, and the design was formally approved by the Central Military Commission in 1986. Small-batch production commenced in 1987.

Since then, the PL-5B has been continuously upgraded, and the third-generation "E" variant was offered for export beginning in 1999 by the China National Aero-Technology Import & Export

Corp. (CATIC) [中航技进出口有限责任公司]. It boasts all-aspect attack capability with maximum off boresight angle of ±25° before launch, and ±40° after launch. It also claims a maximum lateral acceleration of 40G.[124] The latest variant, the PL-5EII, is fitted with a dual band, multi-element detector as well as a laser proximity fuse found on other modern Chinese air-to-air missiles.[125] While the PL-5 is not the most advanced AAM in the Chinese arsenal, due to its relative light weight and compact size it continues to be the dogfighting missile of choice carried by smaller Chinese aircraft.

PL-6

Development of the PL-6 IR-homing short-range air-to-air missile (SRAAM) began in 1975, to meet a PLAAF requirement for a high-maneuverability dogfighting missile comparable to the third-generation missiles then entering service with foreign air forces, such as the Matra R.550 Magic.[126] Work began on the basis of the PL-5B, and the new missile was ready for flight-testing in 1979. By this time, however, access to Western technology such as the French R.550 had become available, and in 1983 the Ministry of Aviation Industries opted to cancel the PL-6 in favor of the technologically more sophisticated PL-7 (see section on PL-7 below).

PL-7

The IR-guided PL-7 SRAAM is believed to a reverse-engineered copy of the Matra Magic R.550 AAM,[127] which entered French service in 1975. According to one official Chinese history, preliminary research on the missile began in 1977, although the PL-7 program was not officially initiated until 1982.[128] Responsibility for the new missile was assigned to Factory 331 in Zhuzhou, which by then had been renamed the Southern Aero-Propulsion Machinery Company [南方航空动力机械公司] (now AECC South Industry Co. [中国航发南方工业有限公司]). Decades earlier, Factory 331 had been likewise tasked with the licensed production of the Soviet K-5 as the PL-1, and the copying of the K-13 as the PL-2. The third-generation PL-7 offered a much-improved seeker with automatic target detection and tracking abilities, and was capable of attacking targets at significantly greater off-boresight angles than earlier Chinese AAMs.

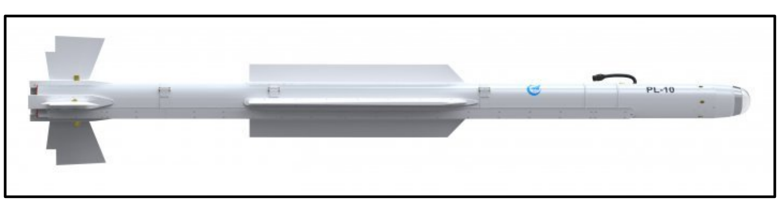
PL-8

A capable IR-homing SRAAM employed by the PLA in large numbers, the PL-8 is another example of a direct transfer of AAM technology through licensing. China acquired the design of the PL-8 through a licensing agreement signed with Israel in 1982 for the domestic production of the Rafael Python-3 missile, whose performance during the 1982 Lebanon conflict reportedly impressed PLAAF observers.[129]

The IR seeker of this missile has a wide off-boresight targeting envelope and can be linked to a helmet-mounted display, giving the pilot "look and shoot" capability. The missile's dual-thrust solid rocket motor can propel it to speeds of over Mach 4, and it can maneuver at over 38Gs with a guidance precision level of 1 meter or less.[130]

PL-9

PL-9 is a short-range IR-homing missile with an airframe derived from the PL-5 and PL-7, but fitted with the seeker from the Python-3/PL-8. Some analysts believe that the missile was developed primarily for the export market, to bypass export restrictions in the PL-8's licensing agreement.[131] Work began in 1986. It was designed by the 612 institute (later known as the China Airborne Missile Academy) and manufactured by the Xi'an Eastern Machinery Factory [西安东方机械厂]. Huang Bingyin was credited as the lead designer. In addition to the seeker, the PL-9 also integrated the PL-8's use of rollerons (spinning wheels that can be seen on the far right of the rear fins) to improve aerodynamic stability. An improved version, the PL-9B, was displayed for the first time in 2002 and adopts an improved automatic search function and off-axis launch capability and higher G tolerance. Another variant, the PL-9C, was introduced in 1997 and features reduced weight, a larger warhead, and greater maximum speed and range.



PL-10

The PL-10, and in particular the PL-10E variant, is currently China's most advanced SRAAM. The missile was developed by the

Shanghai Academy of Science and Technology, with Liang Xiaogeng [梁晓庚] (profiled below) credited as the missile's chief designer. The missile appears to have been partially based on the South African Denel A-Darter AAM. The design of the original "A" variant was finalized in 2010 and entered production in 2013. The latest "E" variant was first unveiled at the 11th China International Aviation and Aerospace Exhibition in Zhuhai in 2016. The PL-10E weighs 105 kg and has a range of 20 km. The missile can be slaved to a helmet-mounted sight, giving the pilot "look and shoot" capabilities. The design incorporates thrust vectoring technology to help it achieve high maneuverability and the missile can withstand 60 Gs and achieve high angles of attack. According to its designer, the PL-10E has superior anti-jamming abilities.[132]

Importantly, the PL-10E can attack targets at significant off-boresight angles "several times" greater than the 30 degrees typical on missiles of the previous generation. For comparison, the AIM-9X-2 Sidewinder's IR sensor is capable of tracking targets up to 90 degrees off-bore. The missile also incorporates a more advanced IR sensor that images the entirety of its target, rather than focusing on a specific salient IR source, giving it true all-aspect targeting capability. Reports also indicate that the missile can be mounted on second- and third-generation fighters with modifications.

In simulated air combat, the PL-10E hit a target at a range of 20 km and bearing [方位] of 38 degrees off boresight. It was reportedly able to "turn at nearly a 90-degree angle and was not fooled by infrared decoys."[133]

The PL-10 was first shown being used in live-fire exercises in 2016 during the "Red Sword" exercise.[134]

PL-11

The PL-11 was the mainstay medium-range AAM of the PLAAF until the more advanced PL-12 (see below) began entering service in significant numbers. Developed by a subsidiary of Shanghai Academy of Spaceflight Technology from the Italian Aspide AAM, which was itself derived from the U.S. AIM-7 Sparrow, accounts differ as to whether the PL-11 was a licensed copy or simply reverse-engineered.[135] Some sources suggest the PL-11 was originally intended to be a licensed local version, but the licensing agreement was terminated after the initial batch was completed using European parts in early 1989, due to the imposition of an arms embargo against China following the Tiananmen Square crackdown. This forced the PLA to begin independent development in 1990. The missile completed its first live-fire test in 2002. The same missile has also been developed into the HQ-61 series of SARH surface-to-air missiles (SAMs).

PL-12

The PL-12 is China's current mainstay medium-range AAM. Offered for export under the SD-10 designation, the missile is equipped with active radar-homing.[136] In a probable reference to this type, then-Director of the Airborne Missile Academy, Rong Yichao [荣毅超], told the Chinese magazine Ordnance Knowledge [兵器知识] in 2006 that Chinese fourth-generation radar-guided AAMs adopted a composite guidance approach that employs both mid-course and terminal guidance.[137] (Mid-course guidance is likely provided via data link updates from the launching aircraft.) The PL-12 uses a dual-thrust solid rocket motor and can exceed Mach 4 and endure 38 Gs. Chinese media accounts claim that the missile's omnidirectional sensors are accurate within one meter.[138] Its active radar-homing guidance system has a range of 25-30 kilometers and offers "fire-and-forget" capabilities. It has a 24 kg warhead and uses a radio proximity fuse.[139]

While mock-ups of the SD-10 made their first public appearance as early as 2002 at a trade show in Pakistan,[140] the first known live-fire test of the missile did not occur until 2005. According to official media accounts, during the test two PL-12s launched against two targets successfully downed both targets.

According to several reports, Russia aided China in the development of the PL-12. This includes both engineering assistance from missile manufacturers such as the Tactical Missile Corporation, as well as the provision of Russian components.[141] Specifically, the PL-12 is reported to have used the Russian-made Agat 9B-1348 seeker head. This was developed for the Russian R-77 (RVV-AE) air-to-air missile produced by Vympel NPO. However, current assessments suggest that China is no longer reliant on Russian components for the production of this missile.[142]

PL-15

The PL-15 is China's most capable long-range active radar-homing AAM currently deployed. Although the first explicit reference to the missile in (quasi-)official Chinese media appeared in September 2015,[143] implicitly confirming a *Popular Science* report regarding a successful live fire test of the PL-15 against a target drone on 15 September,[144] the missile might have been tested as early as in 2011, when the *People's Daily* reported a successful test of an unidentified "key model" of "next-generation air-to-air missile", with all seven missiles hitting their targets.[145] While the *Popular Science* report identified Institute 607 (a.k.a. China Leihua Electronic Technology

Research Institute - LETRI) in Wuxi, Jiangsu Province as the PL-15's developer, Chinese reports identified the missile's developer as the Luoyang-based CAMA.

Image-analysis of published photos of the PL-15 suggests that the missile is "about four meters long and 200 mm in diameter," about the same dimensions as its predecessor, the PL-12/SD-10 BVRAAM. However, the PL-15 is believed to have a greater range than the PL-12's estimated 100 km, reaching up to 150-200 km according to USAF estimates. The range and speed of the PL-15 is enhanced through the use of a dual-pulse solid rocket motor, possibly in conjunction with ramjet engines. However, current versions of the missile do not appear to employ thrust-vectoring.[146]

The PL-15 is believed to be equipped with an improved AESA radar seeker and upgraded jam-resistant datalinks. Like the PL-12, the PL-15 is also expected to employ a composite guidance system that features both mid-course and terminal guidance. Its mid-course guidance capability would enable the missile to receive course correction information in flight from a standoff AEW&C aircraft such as a KJ-2000, without requiring the missile's launch platform, such as a J-31 stealth fighter, to turn on its own radar and risk giving away its position.[147]

According to Janes Defense Weekly, the PL-15 might have already entered PLAAF service as of July 2017.[148]

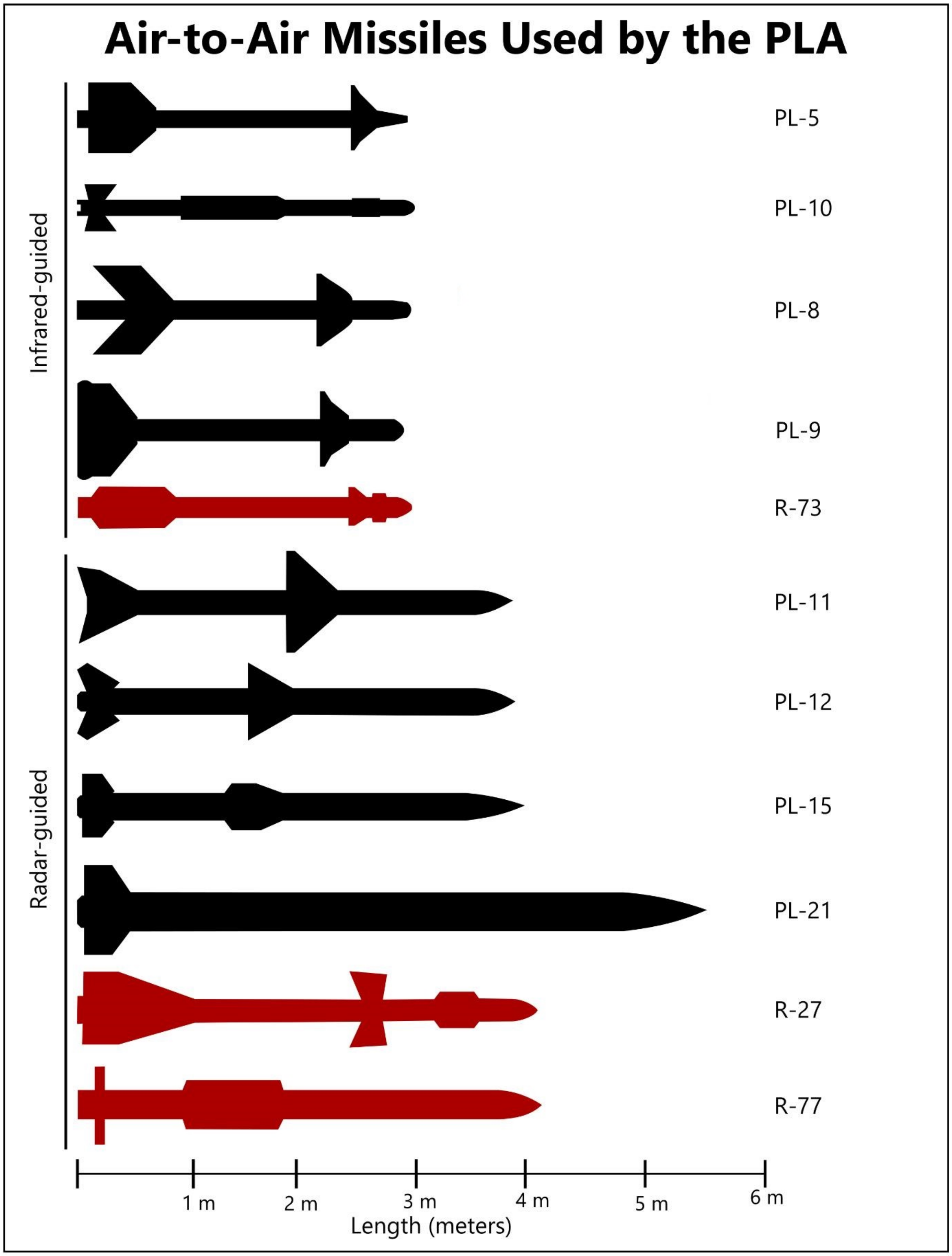
PL-21 (PL-XX)

The PL-21 (also referred to as the PL-XX, since the missile's actual designation, or even its existence, cannot be confirmed) is said to be a ramjet-powered active radar-homing very long-range air-to-air missile (VLRAAM) under development with performance characteristics roughly comparable to the American AIM-120 AMRAAM, DARPA's Triple Threat Terminator (T3), Europe's MBDA Meteor, and the Russian Vympel R-77. The existence of the missile has never been confirmed in reliable Chinese sources, although there are strong indications that China had been making serious efforts to develop a ramjet-powered AAM. In May 2017, for instance, the state-owned *Science and Technology Daily* newspaper reported that the 4th Research Institute of the China Aerospace Science and Technology Corp. (CASC) had successfully tested a ramjet engine designed to power air-to-air missiles. In a separate *Global Times* report, the engine was claimed to be hypersonic (Mach 5+), which would make it a scramjet. Moreover, the new engine was said to be able to more than triple the range of existing Chinese BVRAAMs, to over 300 kilometers.[149]

Notably, a display graphic at the 2014 Zhuhai Airshow appears to show a J-31 fighter carrying four unidentified missiles fitted with ramjet engines. The new missile appears significantly larger than any known Chinese AAM, such as the PL-12 or the PL-15.[150]

Air-to-Air Missiles by Generation *(as classified in Chinese literature)*					
	First	Second	Third	Fourth	Fifth (?)
Infrared Guided	PL-2	PL-5B	PL-6#	PL-10	
	PL-3#		PL-7		
			PL-8		
			PL-9		
Radar Guided	PL-1*	PL-4#	PL-11	PL-12	PL-15
		PL-5A#			PL-21
*: Beam-riding; #: Cancelled w/o entering production					

Summary of Chinese Air-to-Air Missiles					
	Length (meters)	**Total weight (kg)**	**Engagement Range (km)**	**Max speed (kph)**	**Guidance**
PL-1[151]	2.5	82	6	2,880	Beam-riding
PL-2A[152]	2.83	85	7.6	3,062	IR-homing
PL-3[153]	2.1	N/A	11.5	2,450	IR-homing
PL-4[154]	3.2	N/A	18	2,695	Semi-active radar-homing
PL-5A[155]	3.23	150	16	2,695	Semi-active radar-homing
PL-5EII[156]	2.89	83	14	N/A	IR-homing
PL-6[157]	2.12	93	11.5	2,450	IR-homing
PL-7[158]	2.75	90	14	2,450	IR-homing
PL-8[159]	2.9	115	15	N/A	IR-homing
PL-9	2.9	123	15[160]	2,500	IR-homing
PL-10	3.0	105	20	N/A	IR-homing
PL-11 (Aspide Mk.1)	3.7	220	75	4,680	Semi-active radar-homing
PL-12/SD-10[161]	3.93	199	>70	>4,900	Active radar-homing
PL-15	3.8[162]	180-230[152]	>300[163]	~4,900[153]	Active radar-homing
PL-21	>5.5[140]	Unknown	Up to 400[164]	>6,170[165]	Active radar-homing
TY-80[166]	N/A	N/A	<6	N/A	IR-homing
TY-90[167]	1.86	20	6	2,252	IR-homing
R-27 ET2	N/A	N/A	N/A	N/A	IR-homing
R-73/74[168]	2.9	105	40	2,815	IR-homing
R-77-1[169]	3.6	174.8	90	3,378	Active radar-homing

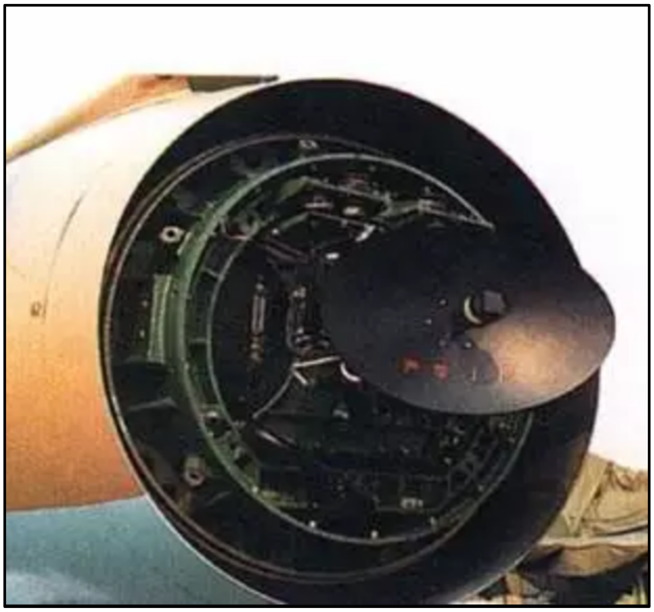


Note: Red indicates Soviet/Russian-designed missile in service in the PLA

RADARS AND IR SENSORS

Airborne radars in Chinese service

Until the 1990s Chinese airpower suffered significantly from the lack of effective all-weather fighters, which in turn was due primarily to the lack of capable airborne radars.



Although China had access to radar rangefinders and received some components of the MiG-21's fire-control radar in 1961, Chinese engineers did not have access to modern airborne interception radar technology. Early efforts to develop an airborne radar indigenously were slow and unsatisfactory. In 1964 the 607 Institute (predecessor to the AVIC Leihua Electronic Technology Research Institute) in Neijiang, Sichuan Province was tasked with developing an interception radar for the proposed J-8 interceptor, with the goal of making the J-8 a true all-weather fighter.[170] However, the new radar – known as the Type 204 (a.k.a. SL-4) – was a relatively primitive single-pulse radar with a detection range of less than 21km, considered inadequate by the PLAAF since it was less than the detection range of the RP-21 Sapfir radar used on the Soviet MiG-23 and upgraded versions of the MiG-21 that the new fighter was expected to face. Moreover, the bulkiness of the Type 204 made it impossible to fit into the MiG-21-derived J-7, with its very limited space within the shock cone.[171]

Once again, help arrived in the form of an unexpected infusion of American technology. In 1966, a relatively intact Autonetics R-14A radar set was recovered from the wreckage of an American F-105 fighter-bomber downed in Vietnam. According to one account, PLA Naval Aviation was particularly impressed with the R-14A's multi-mode capabilities, which included air-to-air, air-to-ground, and terrain avoidance functions. Eager to acquire similar capabilities for its own Q-5B torpedo bomber/naval strike-fighter, the PLAN threw its support behind the effort to reverse-engineer the R-14A. A prototype of the reverse-engineered copy, known as the Type 317, was completed in 1968, and flight-testing began in 1970 onboard a Lisunov Li-2 transport specifically allocated by the Navy. However, the PLAN's original requirements were not met until the appearance of the improved Type 317A in 1978, its most significant upgrade being the employment of transistor circuits in place of the vacuum tube circuits used on the original Type 317.[172]

Subsequently, the Type 317A was further developed into the JL-7 radar, which had a maximum detection range of 30km (for fighter-sized targets) and tracking range of 15km.[173] While the J-band single-pulse JL-7 was obsolete by 1980s' standards, according to at least one account its "American-descended" technology still proved superior to the RP-22 radar used by the MiG-21MF,[174] the upgraded version of the MiG-21 widely exported by the Soviet Union in the 1970s, which China had acquired an example of from Egypt in early 1979.[175]

By this time, however, pulse-Doppler (PD) radars have been widely adopted by the world's leading air forces. Unlike traditional single-pulse radars, which have major limitations in their resolution and ability to distinguish a low-flying target from ground clutter, PD radars combine the ability of pulse radars to determine the range to a target using pulse-timing techniques, with the ability of continuous-wave radars to use the Doppler effect of the returned signal to distinguish a moving target from stationary ground clutter. Although China had initiated preliminary research on PD radars in 1973, very little progress was made during the first subsequent decade. Indeed, by 1986 COSTIND (Commission for Science, Technology, and Industry for National Defense – often characterized as "China's DARPA") was so dissatisfied with the 607 Institute's lack of progress on the JL-10 PD radar project, that it cancelled the JL-10 (before reviving the project a few years later for the export market) and asked the 14th Institute, which had been known mostly for ground-based radars up until then, to take over airborne PD radar development.[176]

According to one Chinese aviation analyst, the major bottleneck facing Chinese engineers at the time was their lack of familiarity with digital circuit design. Supposedly, Chinese engineers trained in Soviet engineering methods of the 1950s and 60s spent much of their time wrestling with analog circuits, not realizing that an all-digital circuit was needed to perform the Fast Fourier Transform operations required of PD radars. The analyst credited the induction of three Western radar systems in the 1980s and early 90s for "finally setting Chinese radar design on the right path" – these include the technology for the Westinghouse AN/APG-66V2 radar inducted under the Peace Pearl program of the 1980's, which gave Chinese engineers the first "clear and comprehensive" understanding of the principles and practice of modern PD radar design;[ii] the Israeli EL/M-2032 radar, which taught Chinese engineers "how to build a reasonably capable radar using commercial off-the-shelf components"; and the Italian Grifo-7/s radar, a simplified, miniaturized PD radar which taught Chinese engineers how to strip a PD radar down to its bare essentials and get the most out of a radar with a weak transmitter and low antenna gains.[177]

[ii] Although the sale of the radars was cancelled in the aftermath of the Tiananmen Square crackdown in 1989, a large amount of the related technical documentation had been transferred ahead of the delivery of the radar sets.

Nevertheless, even with much enhanced understanding of the principles of PD radar design, limitations in Chinese manufacturing technologies during the 1990's reportedly delayed the appearance of China's first "successful", "practical" airborne PD radar until the early 2000's, when the Type 1473 developed by the CETC 14th Institute began entering service with the J-8F and early blocks of the J-10. In particular, the aviation analyst identified three components as critical to the eventual breakthrough: the successful development of planar slotted array antennas; the appearance of high speed digital processing chips; and the development of high-speed analog-to-digital converter chips. According to his account, simply upgrading the chip sets in the receiver and digital processor of the Type 1473 was sufficient to nearly double its detection and tracking ranges, making it vastly superior to the Russian N001 radars that originally equipped the imported Su-27's.[178]

Since the turn of the century, Chinese radar development efforts have turned to Active Electronically Scanned Array (AESA) systems that characterize the state-of-the-art in airborne radar technology today. Unsurprisingly, early Chinese efforts in the area were slow and halting, so much so that both the 607 Institute and the 14th Institute were instructed to develop a Passive Electronically Scanned Array (PESA) system based on the Russian NIIP Irbis-E radar (which China had acquired from Russia at some point in the early 2000's), as a fallback option for the J-10B if AESA development should prove unsuccessful. However, while the PESA system offered the ability to track multiple targets simultaneously, it suffered from a poor detection range, reportedly inferior even to the PD radar that it was meant to replace. PLAAF dissatisfaction with the performance of the PESA system is said to have delayed the induction of the J-10B by almost a decade, until a satisfactory AESA system was finally completed, obviating the PESA option.[179]

A number of CETC research institutes were involved in the development of AESA technology, including the CETC 38th, 14th, and 50th Institutes (all of which are profiled in a later section). The research organizations involved were said to have invested "almost everything they'd got" into the development of an AESA production line [几乎是倾家荡产的打造 AESA 生产线], starting with the development of separate transmission and processor chips when MMIC (monolithic microwave integrated circuit) chips proved beyond Chinese capabilities in the beginning. However, thanks to the rapid advances made by the Chinese telecom equipment industry, and in particular progress in gallium arsenide IC fabrication technology, the MMIC challenge has now been overcome, facilitating a significant reduction in the cost as well as the size of AESA transmitter-receiver sets.

Modern radar systems are increasingly incorporating the use of gallium arsenide chip sets, due to their better performance at high temperatures than silicon. The latest-generation Chinese AESA systems are said be based on gallium nitride MMIC chips, which are said to offer even better performance and lighter weight. These latest AESA systems are said to have been developed specifically for China's stealth fighters, and offer "special signal transmission and processing capabilities which make it impossible for current aircraft to detect their search and tracking emissions."[180] These claims likely refer to the Type 1475 (KLJ-5) AESA radar, which is believed to have been developed for the J-20 fighter.[181] According to Hu Mingchun [胡明春], director of the CETC 14th Institute [中国电子科技集团公司第十四研究所], the latest Chinese AESA radars are on par with those used in the F-22 and the F-35.[182]

Chinese radars for the export market

In addition, Chinese research institutes have displayed a number of advanced radars intended for the export market at international defense exhibitions in recent years. While many if not most of these systems will never enter Chinese service, they can still provide some useful insights on the state of Chinese radar technology today, even if these systems undoubtedly do not represent the Chinese state of the art. Some of these systems include:

KLC-7 Silk Road Eye

As described by CETC 14th Institute's Hu Mingchun, the KLC-7 combines a mechanical scanning system with AESAs, and features the latest digital technology and processing capacity, making it much more robust than previous models.[183] With state-of-the-art electronics, the system boasts better anti-jamming functions, a longer detection range, and stronger target-tracking ability and optimized algorithms.

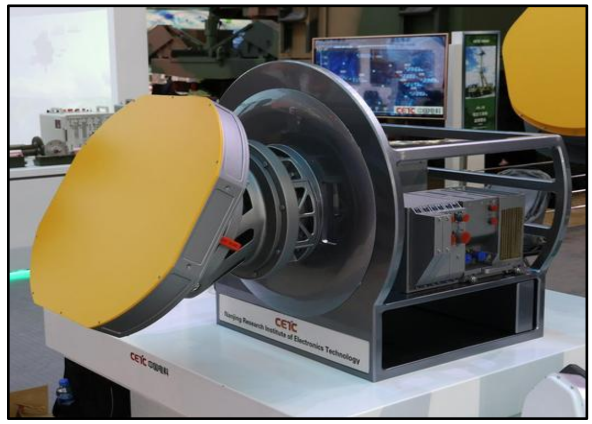
KLJ-7A Active Phased Array Radar

The KLJ-7A or Type 14789 is an X-band airborne fire-control radar produced by the CETC 14th Research Institute. China is upgrading JF-17 fighter aircraft it co-produced with Pakistan with new radars, and the KLJ-7A would "tremendously extend the fighter's detection range."[184]

This might have been the same radar shown being flight-tested on a Y-7 aircraft in a 2017 CCTV news report. In the CCTV segment, the radar being tested was described as intended for the JF-17. Zang

Weiwang [藏伟旺] was identified as its chief designer at the 14th Institute. The radar was said to be capable of detecting multiple targets at a range of 100km, at an altitude of 3,000 meters.[185] The KLJ-7A was first displayed at the 2017 Paris International Aerospace Exhibition, along with the KLC-11 airborne multi-function surveillance radar.[186] Its design appears to have been informed by the imported Russian Zhemchoug (Pearl) radars.

The latest variant of the KLJ-7A uses a new "three-sided" [三面阵] design that has smaller arrays on either side of the primary array. According to its designers, this variant can detect multiple targets within a 300-degree field and would allow fighter-sized aircraft to have limited "early warning" capabilities.[187]

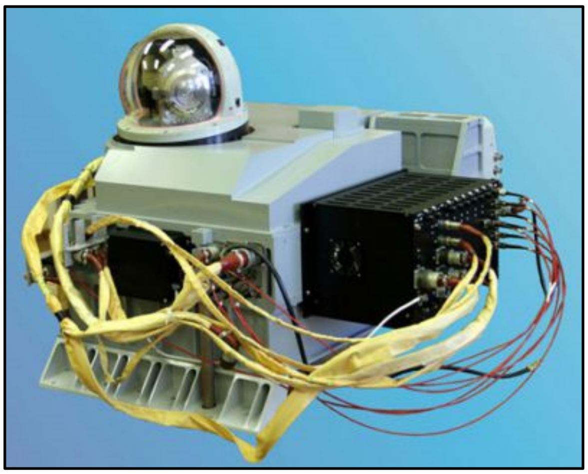


Airborne Air-Cooled Two-Dimensional AESA Fire Control Radar

In May 2017, AVIC's Leihua Electronic Technology Research Institute [中航工业雷华电子技术研究所] (a.k.a. 607 Institute) announced the successful development of "the world's first airborne air-cooled 2-D AESA fire control radar [机载风冷二维有源相控阵火控雷达]". The key innovation involved in the new radar appeared to be the development of a new "high efficiency air-cooled heat dissipation technique [高效风冷散热技术]", which reportedly provided a solution to the "world-class challenge" of replacing the PD radars in older combat aircraft with AESA systems without significant modifications to the environmental control systems, power supplies, and structures of existing airframes. According to AVIC, the new radar would significantly reduce both the time requirement as well as the costs of AESA upgrades, greatly enhancing the competitiveness of Chinese AESA systems in the export market.[188] However, it should be noted that some Chinese military experts have expressed skepticism, claiming that in practice, due to databus compatibility issues, the system can only be installed on the J-11B or -D variants, and that the upgrade would still be quite costly.[189]

Infrared Search and Tracking Systems

Active fire control radar systems emit radio waves that can reveal an aircraft's presence and location. In contrast, passive infrared sensors, such as the Russian OLS-series of infrared search and tracking systems (IRST) [红外搜索跟踪] first used on the MiG-29, incorporate sensitive IR cameras to detect the infrared emissions given off by enemy aircraft and missiles without alerting the enemy aircraft of their own presence.



An example of such a system can be seen in the image below of a J-15 carrier-based fighter. The IRST is housed in the small bubble just forward of the canopy. Older Flanker variants, such as those purchased from Russia (Su-27SK, Su-30MKK) or derived from Ukrainian aircraft (J-15), use the OLS-27 IRST, or its Chinese-produced equivalent. The newer Su-35 uses an updated IRST, the OLS-35 (see left inset) produced by JSC Scientific and Production Corporation Precision Instrumentation Systems, that is capable of detecting a Su-30-size aircraft 90km away from a rear aspect, and at 35km head-on. [190] Notably, while the IRST systems currently in Russian service are all based on mid-wave infrared (MWIR) sensors, some of the more recent Chinese aircraft (e.g. the J-10B/C and the J-16) are believed to employ IRST systems based on long-wave infrared (LWIR) sensors, which are said to offer detection ranges 50%-100% greater than the equivalent MWIR sensors. Other modern combat aircraft which employ LWIR-based IRST systems include the Dassault Rafale and the Sukhoi Su-57 still under development. The Electro-Optical Targeting System (EOTS) used on the F-35, on the other hand, is believed to be based on MWIR, as a compromise to optimize the system's TV camera, laser rangefinder, and laser designator capabilities. [191]

An EOTS system similar to that used on the F-35 is said to be under development by the Beijing "A-Star" Science and Technology Co. [北京中陆航星科技有限公司], profiled in a later section. Beijing "A-Star" has shown its own EOTS-86 system, which the company claims can detect stealthy aircraft such as the B-2 bomber from over 100km away.

Another company, the Wuhan Gaode Infrared Co. [武汉高德红外], appears to be involved in developing similar technologies. In 2016 the company announced that it had completed China's first uncooled infrared focal plane detector, after eight years of development.[192] The company claimed a "sensitivity level 30%-50% higher" than comparable systems produced in France. It also claimed that its system, called the "Super Cat's Eye" [超级猫眼], can detect and track aircraft in the air at 300-400 km.

Helmet Targeting Systems

China appears to have made progress in developing helmet targeting systems, or Helmet-mounted Displays (HMDs), which track eye movement to allow lock-on of targets and provide other flight information. With the introduction of the Su-27 to the PLAAF in the early 1990s, Chinese pilots were able to use the Shchel-3UM HMD (see left) to target the R-73 missile. In recent years the number and sophistication of these systems have multiplied. To improve pilots' ability to see targeting data and make more rapid targeting decisions, the Chinese defense industry has been investing in the further development of helmet targeting systems. For example, AVIC Optronics [中航工业光电所], also known as the AVIC Luoyang Optronics Equipment Development Institute [洛阳电光设备研究所], produces the "Sharp Vision" ["锐视"] series of HMDs.[193]

On 9 May 2018, the PLAAF's official Weibo account published photos showing what are believed to be the first images of the HMD used by J-20 pilots. The new helmet appears to be an upgraded version of the TK-31 helmet already in use, produced by AVIC Huadong Optoelectronics [中航华东光电(上海)有限公司]. The new helmet features integrated wireless communication, image recognition, and voice controls. Raised bumps (see inset) are used to help determine the position of the pilot's head for integration with sensors. To keep weight manageable,

the helmet does not incorporate night vision sensors.[194] The helmet system can be used to lock and fire PL-9 or PL-10 AAMs.

These systems accompany more general improvements to pilots' visibility and displays. The J-10, which entered service with the PLA in 2006, was the first Chinese fighter to adopt a "bubble" canopy that gives pilots much greater visibility. The adoption of "glass cockpits" has given modern fighter pilots unprecedented levels of situation awareness and control. However, it has also presented them with what can be an overwhelming amount of data. Chinese pilots transitioning from second, third or fourth-generation aircraft to the latest fifth-generation models (J-7s, J-8s to J-16, J-20) have described themselves as being overwhelmed by the influx of additional data points.[195] China's investment in systems such as HMDs demonstrate the Chinese aviation industry's growing awareness of the importance of ergonomics and human factors in the effectiveness of modern combat aircraft.

Conclusion

China's air-to-air missile design and production capabilities have made significant progress in recent decades. Until the late 1980s, the most advanced Chinese missile factories were capable of producing was a reverse-engineered copy of the original AIM-9 Sidewinder, which entered service in the USAF in the mid-1950s. China is now capable of producing missiles that appear to be comparable in capability to the AIM-9X and AIM-120 AMRAAM. In combination with more capable fighter aircraft and improvements in training, Chinese air-to-air missiles are providing the PLA's aviation forces with a hitherto unseen level of combat capability. In addition, China is developing very long-range air-to-air missiles with ranges of 300 km or more. Such missiles would provide the PLA with a capability that the U.S. military does not currently possess.

As a result of these advances, the United States can no longer assume that it has a dominant advantage over China in air-to-air missiles. Maintaining the U.S. lead in this area will require continual investment in new and more capable systems.[iii] In addition, countermeasures may become increasingly important, such as the capability to blind, "dazzle," or even shoot down missiles with airborne lasers.[iv]

China's advances in air-to-air missile technology may result in greater exports of Chinese missiles and fighter aircraft. Air-to-air missiles have already become a significant export item, with Pakistan, Bangladesh, and Nigeria all purchasing Chinese missiles to arm Chinese-built aircraft. The PL-10 and PL-12, in particular, appear to be meant as rivals for the AIM-9 and AIM-120 series IR- and radar-guided AAM families that dominate global markets. While it is unlikely that China's missiles will be adopted by U.S. allies, their increasing sophistication may help drive sales of Chinese-built fighter jets and related systems to other countries.

A key issue in the future may be China's ability to overcome increasingly stringent U.S. technology transfer restrictions, which Chinese media describes as a "foreign technology blockade" [国外技术封锁]. Restrictions on foreign technology, for example, were cited as a primary reason that China needed longer than planned to develop modern AAMs with anti-jamming capabilities, such as the PL-12 and PL-9. Were it not for sales of airborne radars, licensed production, and

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[iii] For a discussion of some the air-to-air missile systems currently under development, see John A. Tirpak, "Air Force Seeking Faster, Longer-Range Air-to-Air Missiles, *Air Force Magazine*, May 6, 2020, https://www.airforcemag.com/air-force-seeking-faster-longer-range-air-to-air-missiles/.

[iv] For example, on 23 April 2019, the Air Force Research Laboratory (AFRL) Self-Protect High Energy Laser Demonstrator (SHiELD) Advanced Technology Demonstration (ATD) Program successfully shot down multiple air-launched missiles in flight. The eventual goal of the program is to be able to neutralize SAMs and AAMs. See "Air Force Research Laboratory completes successful shoot down of air-launched missiles," Wright Patterson AFB, 3 May 2019. https://www.wpafb.af.mil/News/Article-Display/Article/1834836/air-force-research-laboratory-completes-successful-shoot-down-of-air-launched-m/.

transfer (legally or illicitly) of high-tech materials science, China's air-to-air missile program would likely be significantly behind where it is today. The question now is whether China's domestic capabilities to design and manufacture components such as microprocessors are sufficiently advanced that it is no longer dependent on foreign technology or inputs. In the near-term, however, China's air-to-air missile capabilities present a significant challenge to U.S. air dominance.

Appendix: English-Chinese Glossary of Technical Terms

Due to the technical nature of the study and with the hope that other researchers will find this useful, we have included a list of some of the technical vocabulary we encountered in the writing of this report.

Active Electronically Scanned Array (AESA) radar	有源相控阵雷达 /有源电子扫描阵雷达
Active Radar Guidance	主动雷达制导
Air Combat	空战
Air superiority	制空权
Advanced Medium-Range Air-to-Air Missile (AMRAAM)	先进中程空空导弹
Angle of Attack	攻角
Anti-stealth	反隐身
Automatic search and interception	自动搜索和截获
Beyond Visual Range (BVR)	超视距
Close Air Combat	视距内空战
Combat Air Patrol	空中战斗巡逻
Divert Attitude Control Systems	姿态控制系统
Dogfight	空中格斗
Fire control radar	火控雷达
G-force	G 力
Gallium Nitride	氮化镓
Gallium arsenide	砷化镓
Gelled Propellants	凝胶推进剂
Helmet-mounted Targeting	头盔显示器
Hypersonic	高超声速/ 高超音速
Identification friend or foe (IFF)	敌我识别系统
inertial navigation system (INS)	惯性导航系统
Infrared-guided	红外制导
Infrared search and tracking system (IRST)	红外搜索跟踪系统
Interception	拦截
Missile Approach Warning System	导弹逼近告警设备
Over the Horizon Combat	超视距空战
Passive infrared search	被动式红外搜索
Passive Guidance	被动式制导
Passive Electronically Scanned Array (PESA) radar	无源相控阵雷达
Propellant	推进剂
Proximity fuse	近炸引信
Pulse-Doppler radar	脉冲多普勒雷达

Radar-guided	雷达制导
Scramjet engine	超音速冲压喷射装置
Semi-active Radar Homing	半主动雷达制导
Short Range AAM	近距空空导弹
Solid fuel	固体药柱
Synthetic Aperture Radar SAR	合成孔径雷达
Thrust Vector Control	推力矢量控制
Towed Decoy	拖曳诱饵
Variable Thrust	可调喷管

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