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Overview of Low Observable Technology and Its Effects on Combat Aircraft Survivability

John Paterson*
Northrop Grumman Corporation, Pico Rivera, California 90660-3783

The introduction of low observable (LO) technology on combat aircraft has produced a leap in aircraft survivability, but it has also raised some difficult questions. How do you quantify survivability, and because new technology tends to be expensive, how LO does an aircraft need to be to accomplish its mission? This paper will show how low observability dramatically improves combat aircraft survivability by reducing an air defense's ability to detect, track, intercept, and destroy an LO aircraft. Important aircraft signatures that can be detected such as radar, visual, infrared, and intentional emissions are discussed in detail as well as methods to reduce those signatures. LO and mission planning tactics' impacts on threat system capabilities are examined and examples of LO aircraft penetration of a notional hostile air defense are shown. The conclusion is that through the use of mission planning tactics and low signature, LO aircraft can survivably penetrate heavily defended air space with little support to accomplish their mission.

Nomenclature

C^3 = command, control, and communication
P_d = probability of detection
P_k = probability of kill
P_s = probability of survival

Introduction

ON January 17, 1991, the first wave of F-117s flew through some of the most dangerous Iraqi air defenses to attack key command posts, communications centers, and air defense centers in Baghdad and southern Iraq. This exposed the F-117s to a modern and effective air defense including early warning (EW) and ground control intercept (GCI) radars, advanced surface-to-air missles (SAMs), antiaircraft artillery (AAA), airborne interceptors, and the Kari C^3 system that tied these systems together to form an integrated air defense system (IADS). The Iraqis had overlapping EW radars called Nanjing, Flat Face, Spoon Rest, and Squat Eye, which could detect nonstealthy aircraft up to 150 miles at high altitude and 30 miles at low altitude into Saudi Arabia.[1] High-altitude strategic SAMs included Soviet SA-2, SA-3, and SA-6 missile systems. To counter aircraft approaching at low altitude, the Iraqis used Russian SA-7, SA-9, SA-13, and SA-16 infrared (IR) missiles; SA-6 and SA-8 Soviet radar-guided missiles; French Roland missiles; and 23, 37, 57 mm, and larger AAA.[1]

In the 1970s, the Kari C^3 system was the best technology that a third-world country could buy. Kari was made up of hundreds of observation posts and radars that automatically fed tracking data, giving the heading, altitude, and quantity of hostile aircraft. This information was used to enhance the effectiveness of Iraq's belts of SAMs and to vector airborne interceptors to intercept hostile aircraft.

Because of the high threat, conventional [non-LO (low observable)] aircraft were directed to avoid Baghdad while F-117s continued to attack each night. This was the first true test of LO combat aircraft penetrating a modern air defense. Even after hundreds of sorties into areas where other combat aircraft were denied, no stealth fighters were lost.

The F-117s demonstrated that LO aircraft are highly survivable in a hostile air defense. This paper will show how low observability dramatically improves combat aircraft survivability by reducing an air-defense's ability to detect, track, intercept, and destroy an LO aircraft. Important aircraft signatures that can be detected such as radar, visual, IR, and intentional emissions are discussed in detail as well as methods to reduce those signatures. LO and mission-planning tactics' impacts on threat-system capabilities are examined and examples of LO aircraft penetration of a notional hostile air defense are shown.

Radar Detection

Radar is one of the most effective methods of locating, identifying, and tracking aircraft at long ranges. Radar works by transmitting an electromagnetic wave and using the echo returned to the receiver to locate, identify, and track the aircraft. Typically, radars fall within the standard frequency bands shown in Table 1. These band designations were developed during World War II and because of their utility have come into standard usage. Generally, the bands were divided by similar power sources, propagation effects, and target reflectivity within a band. Low-frequency radars, very high frequency (VHF) and ultrahigh frequency (UHF), are used for long-range surveillance but are not as effective at determining aircraft location. To get fine angular resolution at the low frequencies, very large antennas are required. S-, C-, X-, and Ku-bands are used for search and tracking because narrow beamwidths can be obtained using much smaller antennas than the low-frequency radars.

Table 2[2,3] lists radar systems that can impact aircraft survivability by threat type and radar band. Early warning radars will provide airborne target information out hundreds of miles, but cannot always provide accurate target location. GCI radars operate in the S-band because noise is at a minimum and an accurate target location can be provided. At low altitudes, multipath propagation can occur where two echo signals are received from a target.[4] One signal is reflected directly from the target and the other is reflected from the ground. This can result in large elevation angle errors and can be great enough to cause the radar to break track. Using an antenna with a very narrow beamwidth, so that it does not illuminate the ground,

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*Engineer Specialist, Program Survivability and Mission Effectiveness, Military Aircraft System Division, 8900 East Washington Boulevard.

Table 1 Radar frequency bands and their uses

Band designation	Frequency range, GHz	General usage
HF[a]	0.003–0.03	Over-the-horizon surveillance
VHF	0.03–0.3	Very long-range surveillance
UHF	0.3–1	Very long-range surveillance
L	1–2	Long-range surveillance, enroute air traffic control
S	2–4	Medium-range surveillance, terminal traffic control
C	4–8	Long-range tracking
X	8–12	Short-range tracking, missile guidance, airborne intercept
K_u	12–18	High-resolution mapping
K	18–27	——
K_a	27–40	Very high-resolution mapping
Millimeter	40–300	——

[a]High frequency.

Table 2 Radar threats[2,3]

Radar system	Band	Frequency, GHz	Wavelength, in.
Early warning	VHF	0.15–0.2	70–80
	S	3–4	3–4
Ground-control intercept	S	2–3	3–5
Height finders	S, C	2–7	1–5
Airborne early warning aircraft	UHF	0.3–1	12–40
	S	2–4	3–6
	X, K_u	8–18	0.6–1.5
AAM	X	9	1
SAM strategic			
Acquisition	VHF, L, S	0.15–3	3–70
Tracking	C, X, K_u	5–13	0.9–2.4
SAM tactical			
Acquisition	S, C	2–6	2–5
Tracking	C, X	5–13	1–2
Radar-guided AAA	K_u	14–16	0.6–0.7

Table 3 Maximum radar detection range[a9]

RCS, m^2	R_{max}, n mile
0.001	32
0.01	57
0.1	101
1	180
10	320
100	569

[a]As a function of RCS.

Table 4 Radar cross-section magnitudes[9]

Examples, m^2 (dBsm)					
Ships	Large aircraft	Small aircraft	Man	Birds	Insects
10^4	10^3	10^2, 10^1	10^0	10^{-1}, 10^{-2}	10^{-3}, 10^{-4}
(40)	(30)	(20, 10)	(0)	(−10, −20)	(−30, −40)

can eliminate this problem. Most fighter aircraft operate in the X- and Ku-bands because accurate target locations can be provided with less power and in a much smaller package. Many fighters operate in the 1.2-in. (3-cm) wavelength of the X-band because atmospheric attenuation is reasonably low and very good angular resolution can be achieved with an antenna small enough to fit in a fighter nose.[2] LO aircraft should be designed with careful attention to C-, X-, and Ku-bands because that is where most of the lethal threats lie. Even if a radar can detect an LO aircraft, it is not much of a threat if it cannot get a good track and launch a missile or accurately vector an airborne interceptor to the LO aircraft's position.

The simplest form of the basic radar range equation can be expressed as

$$R^4_{max} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 P_{min}} \tag{1}$$

where R_{max} is the maximum range at which an aircraft can be detected, P_t is the transmitted power, G is the antenna gain, λ is the wavelength, σ is the RCS of the target (defined later), and P_{min} is the minimum level of received signal based on a signal-to-noise ratio (S/N_{reqd}). An important thing to note from Eq. (1) for LO aircraft is that maximum detection range varies with the fourth root of radar cross section. R_0 is the maximum detection range of a radar against a one square meter (1 m^2) target, and so Eq. (1) can be rewritten as

$$R_{max} = R_0 \sigma^{1/4} \tag{2}$$

Assuming a change in RCS does not alter other radar performance parameters, Eq. (2) can be used to calculate maximum detection ranges for different RCS. The ARSR-2 is a surveillance radar used by the Federal Aviation Administration (FAA) to provide control of air traffic, and it has a maximum range of 180 n miles against a 1-m^2 target. Using the ARSR-2 detection range for the R_0 value, Table 3 shows the detection ranges for different radar cross section (RCS) conditions using Eq. (2). The values in Table 3 assume a free-space detection range and do not take into account antenna patterns' ground effects' clutter. Table 3 also shows that for each magnitude in reduction of RCS the radar detection range is reduced by about 44%.

To express the ratio between widely different power levels, a decibel scale is often used. The ratio of power levels can be expressed in decibel form by the following equation:

$$\text{dB} = 10*\log_{10}(\text{ratio}) \tag{3}$$

When square meters are expressed in decibels, dBsm is used. Typically for aircraft, an isotropic scatterer of 1-m^2 echoing area is used as reference for RCS. Table 4 demonstrates the use of Eq. (3) against a wide range of targets that a radar might illuminate.

The signal to noise ratio discussed in Eq. (1) plays a large role in determining radar detection range. For a jet aircraft, a 20 to 1 S/N_{reqd} (13 dB) might be required for a search radar.[5] Values for S/N_{reqd} and radar losses are difficult to obtain analytically and should use test data for verification. S/N values are applied based on detection probability and on false alarm rate (FAR). P_d is the probability for a target return exceeding the detection threshold on any one pulse. FAR is the average rate at which noise exceeds the detection threshold on any one pulse. A compromise FAR value for search radars is 10^{-7} and a P_d of 0.5.[5] A compromise FAR value for track radars is 10^{-8}

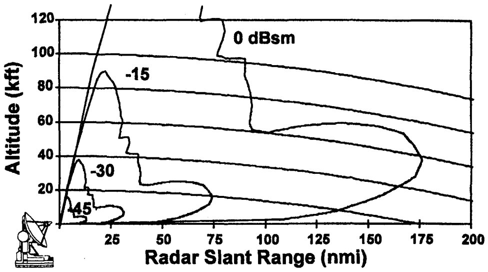

Fig. 1 ARSR-2 radar system coverage against varying RCS.[6]

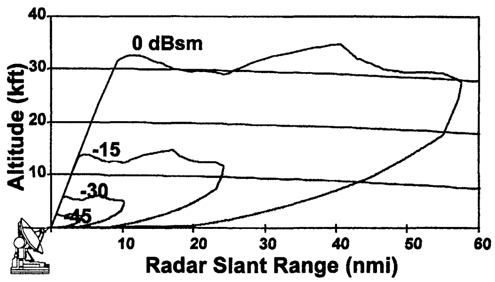

Fig. 2 ASR-7 radar system coverage against varying RCS.[6]

and a P_d of 0.9. Search radars may use a higher FAR because they can detect a target at longer range and they have more time to reject false alarms. Tracking radars need to lock on as quickly as possible to vector fighter intercepts or SAM launches and, therefore, need a low FAR. Search radars direct tracking radars to azimuth and elevation bins to speed up the detection process.

Applying Eq. (2) to a radar coverage diagram graphically shows how much impact LO can have on aircraft detectability. Figures 1 and 2 are the radar coverage diagrams for the ARSR-2 and ASR-7, respectively (see Ref. 6). The 1-m^2 antenna patterns and pointing direction for the ARSR-2 and the ASR-7 are used to compute slant detection range at different altitudes. Coverages are shown for 0-, −15-, −30-, and −45-dBsm cases that correspond to 1-, 0.03-, 0.001-, and 0.00003-m^2 targets, respectively. For Figs. 1 and 2, the target is an isotropic scatterer that has a constant RCS in all directions and is scaled using Eq. (2). The P_d used is 0.5, assuming both the ARSR-2 and ASR-7 are being used as search radars. There are a few interesting things to note about Figs. 1 and 2. As the RCS is lowered, the radar detection range and altitude coverage decrease significantly. A −30-dBsm target could fly undetected over an ARSR-2 at 40,000 ft and fly over an ASR-7 at 7000 ft. A huge amount of airspace opens up for lower RCS targets. Another thing to note is that if a −15 to −45 dBsm target can be detected, so can birds and insects, as shown in Table 4.[7] Some of these undesired targets may be removed by applying moving target indication techniques that use Doppler to separate targets from clutter or by using sensitivity time control (STC) to reject target returns below a certain threshold at given ranges. This increases the complexity of the radar and results in poorer sensitivity. Also, moving target indication (MTI) may be less effective for speeds above 30 kn, and with winds it is not unusual for birds or swarms of insects to exceed this velocity.[8]

Radar Cross Section

As shown in the previous text, the RCS of a target is a very useful tool for measuring the impact of radar reflection. The RCS of a target is proportional to the far-field ratio of reflected to incident power density as shown next:

$$\sigma = \left[\frac{\text{Power reflected back to receiver/unit solid angle}}{\text{Incident power density}/4\pi}\right] \tag{4}$$

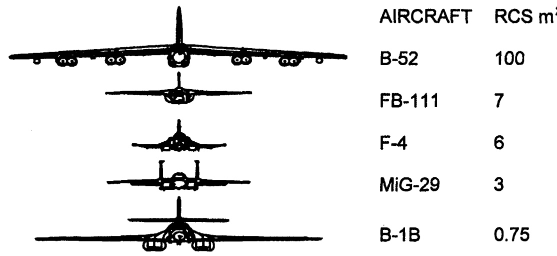

Fig. 3 Notional RCS of military aircraft.[9]

Using Eq. (4) as a definition, the RCS of any reflector may be thought of as the projected area of an isotropic reflector that would return the same power per unit solid angle.[7] When a radar signal strikes an aircraft, a large portion of the energy will be scattered, a portion will be absorbed as heat, a portion may pass through, and the portion that is reflected to the receiving antenna is known as the aircraft echo. This radar echo expressed as the equivalent isotropic scatterer is the aircraft's RCS.

RCS for an aircraft, sometimes called aircraft signature, depends on the direction of the radiated signal and on the direction of the receiving antenna. (A monostatic radar is assumed for this paper.) The radar polarization and radar wavelength are important when computing aircraft detectability. The size and shape of an aircraft and the electromagnetic properties of its materials determine the magnitude of its RCS. Large aircraft that were not designed to reduce RCS may have signatures of over 100 m^2. Typical small fighters/interceptors may have signatures of around 2–8 m^2, and aircraft that consider RCS reduction techniques may fall below 1 m^2.

Howe (see Fig. 3) represents typical frontal RCS signatures by familiar military aircraft. The figure indicates that even large aircraft can have small RCS signatures.

For conventional aircraft, large contributions to RCS can be expected from[9] 1) engine compressor faces and turbines, 2) engine air inlets, 3) external weapon stores, 4) wing leading edge, 5) corner reflectors at intersections of horizontal and vertical tails, 6) wings from directly above/below, 7) radome, if transparent to illuminating radar, 8) cockpit including cavity effects, 9) powerplant exhausts from rear, and 10) fuselage when viewed from the side. Smaller contributions to aircraft RCS can be expected from 1) fuselage when viewed from the front, 2) wing leading and trailing edges, 3) control surface gaps, 4) local air inlets, 5) surface protuberances, 6) vertical and horizontal tails, 7) long thin fairings or missiles, and 8) small antennas or external lights.

Aircraft RCS reduction can be accomplished through the following four techniques: shaping, radar absorbing material (RAM), passive cancellation, and active cancellation.[8] Shaping and RAM are the most practical and tend to provide good results.

Shaping must be performed in the initial aircraft design and should take precedence over most other aircraft design features in very low observable aircraft designs. Shaping is used to orient aircraft surfaces and edges to deflect energy away from radar receivers. One technique is to use a smoothly blended external geometry to achieve a continuously varying curvature, e.g., SR-71, Tacit Blue, B-2 bomber. Another technique is to use a faceted geometry, with flat surfaces to minimize normal reflections back to the receiving antenna, e.g., F-117A, DASA Firefly.[3] The following is a list of shaping design guidelines[8,9]:

1) Define mission and threat sectors (frontal sector tends to be the most important).
2) Minimize aircraft size.
3) Use an aircraft planform shape with a minimum of specular returns, place surface, and edge returns well away from threat sectors.
4) Use shallow surfaces viewed toward grazing angles.

5) Cant vertical surfaces to avoid right-angle corner reflectors. Eliminate vertical surfaces if possible, e.g., vertical tail.

6) Use swept leading edges.

7) Align all unavoidable body lines to place their specular spikes into a common direction (away from major threat sectors).

8) Use internal weapons storage.

9) Blend or eliminate crew stations, air inlets and exhausts, antennas, external lights, and sensors.

10) Engines should be buried with air intakes and exhausts located over the upper portion of the airframe.

11) Curved S-shaped inlet ducts or screens over the engine intakes should be used to reduce cavity effects.

RAM materials reduce reflected radar energy by absorbing some of the energy.[8] RAM may be used to attenuate a signal's intensity, which is useful against a wide range of radar frequencies. Another way RAM may function is to generate internal reflections of the received signal. This interferes with the signal reflected from the outer surface and it applies to a particular frequency. RAM can be tailored to a specific threat but it is very difficult to generate internal reflections over a wide band of threats. RAM tends to add significantly to aircraft weight and, in some cases, it is difficult to maintain.

The idea behind passive cancellation techniques is to introduce an echo source whose amplitude and phase cancels another echo source; similar to an antireflection coating commonly used in optics.[8] This is very difficult to design because aircraft are subject to numerous frequencies and have many echo sources.

In active cancellation, a repeater system produces a return pulse whose amplitude and phase cancels the reflected energy from the aircraft body.[8] The aircraft must have accurate sensors to determine signal arrival angle, intensity, frequency, and waveform. This repeater must then generate the proper waveform, frequency, and amplitude signal at the correct time and phase to cancel the incoming signal.

Visual Detection

The visual signature of an aircraft is an important factor in determining overall aircraft detectability. AAA may be visually directed, particularly low-altitude systems. Short-range, low-altitude SAM systems may require visual acquisition before launch. Airborne interceptors, particularly older systems, at close ranges visually acquire an aircraft to fire their cannons and to launch IR missiles. Modern detection systems, such as that on the F-14 fighter, may use automatic optical trackers to detect aircraft at long ranges.

The visual signature is determined by the contrast of the aircraft with the background as well as the angular extent of the aircraft from the observer's location. However, a rule of thumb is that 6–12 arc minutes is required for visual acquisition and recognition.[10] The aircraft may be observed or other things such as a contrail or engine smoke may reveal its presence. At night, engine exhaust glow, external lighting, and cockpit lighting may provide visual cues. Nighttime aircraft detectability is increased if the observer uses night-vision goggles. The aircraft's luminescence, color, clutter, and movement are the principle factors in visual signatures.

Paints of different reflectivity may be used to reduce the contrast of the airframe. It is also important to minimize the visual signature of the aircraft from important aspect angles. Glint may be reduced by using flat surfaces because they can only be viewed over a small incident angle and the duration of the glint will be brief. If the aircraft's mission is a deep strike or reconnaissance, flying at night can greatly reduce visual detection range. Paints that match the principle mission of the aircraft are important. High-altitude aircraft that fly principally at night should be painted shades of black, and low-altitude ground attack aircraft might be painted to match the ground terrain.

Special design of the engine combustion system should result in a smoke-free exhaust plume. The engine glow can be masked by placing the engines on the top of the airframe and burying the engines within the wings or fuselage. Contrails are caused by water vapor in the exhaust plume and can indicate an aircraft's presence for many tens of miles. Contrails can be suppressed by the use of fuel additives or avoided by changing altitudes when a contrail forms.[5]

Aircraft lighting should be masked in directions that threats might occur. During an attack portion of a mission, all lights should be turned off unless essential to the mission. Internal lighting should be masked.

Infrared Detection

At low altitudes, there are many IR threats that consist of short-range, hand-held IR SAMs. At higher altitudes and longer ranges, tactical IR SAMs can be significant threats. Some airborne interceptors have highly capable IR search systems that can be used to accurately locate aircraft.

Analysis of IR detectability is complex because it depends upon aircraft design as well as the environment through which the aircraft is flying. The IR signature presented to the sensor depends upon the environment through which the energy propagated as well as the infrared background against which the aircraft's IR signature is contrasted. Water vapor and carbon dioxide in the atmosphere absorb IR radiation, and so in clouds and fog, IR transmission is low. At higher altitudes, water vapor decreases, and so the IR transmits over a much larger distance. IR search systems can detect aircraft in either positive or negative contrast.

For most aircraft, the engines are the largest sources of thermal energy. Using heat insulation around the engine or cooling the outside shell of the nacelle can be used to reduce the temperature. Coatings can also be used to absorb IR radiation. Tail pipes that are masked or cooled can be used to mask the thermal energy of the engine.[9]

Jet-engine exhaust plume is a small contributor to aircraft IR signature in nonafterburning aircraft. The largest IR source will be at the tail pipe. Curved exhaust pipes will mask the radiation from the hot turbine blades. Two-dimensional rather than circular exhaust nozzles helps by increasing the area where gas flow mixing occurs. Cold air from the atmosphere can be ducted to flow around engine parts and be used to mix with the exhaust to provide cooling.

The airframe can contribute significantly to thermal signature caused by reflected energy from sunlight, aerodynamic heating, and from local heat sources such as avionics or air conditioning. Surface treatments/paints can be used to optimize the reduction of IR signature within a given threat waveband. Flat surfaces can be used to reduce the angles over which reflected energy may be detected. Masking can be used by radiating energy in areas that have less exposure to threats. Stagnation temperatures occur on sharp edges and corners where the airstream comes to a complete rest. Kinetic energy of the airstream is then converted into high temperature and pressure. By minimizing sharp edges and corners, the aerodynamic heating effects of stagnation can be reduced.[11] Improvements in detector technology and cooling now focus on the detection of aerodynamically heated bodies at long ranges. This inherently puts larger aircraft at greater risk of detection (by IR sensors) than detection technology of 15 or even 10 years ago.

Intentional Aircraft Emissions

An aircraft can reveal its location by radiating signals for purposes such as communication, navigation, target locating, weapon aiming, determining altitude, etc. When in a threat area these radiated signals can be detected by electronic support system (ESM) and tracks can be formed by triangulation methods. All transmitting communication should be eliminated or compressed into short data pulses that are unlikely to be intercepted. Navigation should be performed through passive means such as relying on an inertial navigation system with an occasional update from global positioning system (GPS), radar, etc. Target location should be performed using laser radar or low probability of intercept radar using low energy and intermittent emissions. Weapon aiming/target illumination should be performed by laser designation, forward-looking infrared (FLIR), GPS, or the weapon may have a terminal seeker. Laser designation and FLIR can be significantly impacted by clouds or dust. Radar designation and GPS locating may be required for all-weather targeting. Low-altitude flight may require a radar altimeter, which should only be used at very low altitudes to prevent inadvertent detection.

Antiaircraft Artillery

AAA is a very deadly threat and has damaged/destroyed more aircraft than any other threat type. AAA includes the category of guns that fire projectiles 23 mm in size and larger. Typically, the projectiles are either high-explosive or armor-piercing and are fused to explode either on contact or at a particular altitude.[12]

AAA is limited by its ability to detect an approaching aircraft and by its ballistic range. If the AAA sensor detection range is reduced because of the signature of an LO aircraft, then fewer projectiles will be fired, increasing the survivability of the aircraft. If AAA location/type is a known quantity then it can be avoided by flying outside of its detection range or above the capability of its guns.

Surface-to-Air Missiles

SAMs vary from small IR-guided hand-held shoulder launch tubes to permanent facilities containing radars, command centers, and numerous launchers. SAMs contain a guidance system, one or more sensors, a propulsion system, and a warhead. Some SAMs are guided from the ground and others have terminal seekers allowing them autonomous operation. SAMs typically contain HE warheads of one of the following types: blast or pressure warheads, fragmentation warheads, continuous rod warheads, or shaped charge warheads. Most of these warheads are deadly to all aircraft types.

SAMs are limited by their tracking and missile-launch envelopes and fuzing capability. If the SAM sensor track range is reduced because of the LO aircraft's signature it will be unable to fire a missile until the aircraft enters its tracking capability. The "lethal envelope" of a SAM is defined as the area where a target is within both the launch and track envelopes.

Small IR SAMs have very small lethal envelopes in both range and altitude and can be defeated through the use of surprise or flying above their known capability. Because of the quantity and uncertain location of these hand-held SAMs they can be very deadly to low-flying aircraft.

Strategic SAMs typically are radar guided, have long ranges, high-altitude capability, and can effectively deny large amounts of airspace to attacking aircraft. If the SAMs location/type is a known quantity then it can be avoided by flying outside the smaller of its detection capability or the missile flyout range. Figure 4 shows a typical strategic SAM lethal envelope and the impact of LO aircraft radar signature on it. As the target's RCS is lowered, more area is opened up.

If an aircraft enters the lethal envelope of a SAM, there is some chance that when the missile is launched it will not explode at the correct time because of the aircraft's LO signature. A SAM warhead detonates through either ground control or missile terminal seeker direction. Typical SAM doctrine is that multiple missiles are launched against a hostile aircraft. The number of missiles launched is dependent on the cost and quality of the missiles. This greatly increases the P_k for the SAM, and so an aircraft should remain outside the lethal envelope if it is only relying on its low observability. A mixture of LO, high maneuverability, tactics, and countermeasures can be used to increase P_s within the SAM launch envelope.

Airborne Interceptors

Airborne interceptors are aircraft whose purpose is to engage hostile penetrating aircraft. They are highly maneuverable and have an array of sensors and weapons designed to give them a high probability of killing airborne threats. Many modern airborne interceptors have look-down/shoot-down radars, IR sensors, optical magnification devices used to target threats, and air-to-air guns and missiles for attacking those threats. Airborne interceptors are particularly dangerous because they are commanded by skilled pilots trained in air-to-air combat and are not easily fooled by countermeasures or tactics, and airborne interceptors can make multiple passes until the airborne threat is destroyed.

The best way to survive an encounter with an airborne interceptor is to avoid the encounter altogether. If a hostile airborne interceptor cannot detect a penetrator, it cannot attack it. Airborne interceptors are usually directed by ground-based C^3 systems, which detect penetrators through an extensive radar network. If an LO penetrator can avoid detection, then airborne interceptors will not be launched. If the C^3 system can track the penetrator, it must direct an airborne interceptor to an intercept location close enough so that the airborne interceptor's sensors can detect the penetrator. Figure 5 shows the radar detection envelope of an advanced Russian airborne interceptor. The airborne interceptor has a coherent pulse Doppler look-down/shoot-down engagement radar that has a range of 54 n miles against a MiG-21 sized aircraft (RCS ~ 4 m^2). This is a very capable system but the radar range is significantly reduced for LO targets. Without accurate ground vectoring an airborne interceptor would have a very difficult time finding an LO target. Less advanced airborne interceptors would have much less capability to find and attack LO aircraft.

If the penetrating LO aircraft is a fighter it most likely will get in the first shot and will be much more difficult to shoot down than a conventional fighter. In a study performed by the British Defence Research Agency, the F-22 (an LO fighter) is projected to have an exchange ratio of 9 to 1 against an upgraded Russian Su-27 (Su-35).[13] The exchange ratio is defined as quantity of enemy aircraft shot down per friendly aircraft. The F-15E (non-LO aircraft) in the same study is projected to have an exchange ratio of 1.3 to 1 (F-15E is currently the

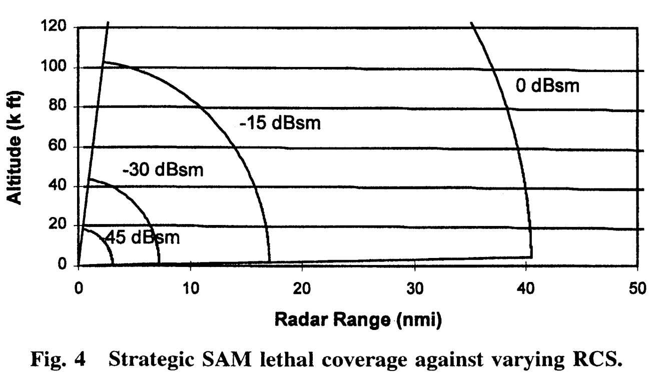

Fig. 4 Strategic SAM lethal coverage against varying RCS.

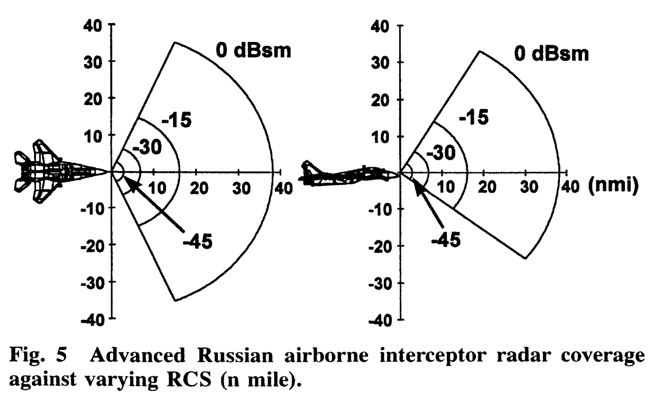

Fig. 5 Advanced Russian airborne interceptor radar coverage against varying RCS (n mile).

U.S.'s most advanced air superiority fighter). If this kill ratio is valid, then an air defense not equipped with LO airborne interceptors would be rapidly wiped out.

Because of the mobile nature of airborne interceptors, LO airborne penetrators should have passive sensors able to detect airborne interceptors, enabling them to either stay out of their detection envelopes or to maneuver into a first strike position.

Command, Control, and Communication Network

The air defense C^3 network is vital in intercepting airborne penetrators. The C^3 net takes detection data from radar sites, ESM sites, observation posts, and other sensors, and compiles these data to destroy or cause a penetrator to abort its mission. The sensors are the air defense's eyes and ears and the C^3 net is its brain.

A typical C^3 net may contain numerous radar sites and observation posts that record penetrator location, altitude, heading, velocity, and type. A radar site will require multiple detections, called blips, to develop a track. The quality of the track will depend on the radar types at a site that are able to acquire the penetrator and strength of target return. An EW radar will usually detect a penetrator first and provide a rough bearing, range, and azimuth. GCI radars will then point to that location in space and try to acquire the target. Tracking radars will provide accurate penetrator location, heading; and range; height finder radars will provide altitude. Observation posts use visual, infrared, and acoustic means to detect penetrators and provide rough estimates of location, altitude, velocity, and type. Observation posts are useful but they provide detection data in tens of miles, whereas radar can provide detection data in hundreds of miles.

The tracking data from radar sites and observation posts can be fed into the C^3 net through a filter center (FC).[5] Typically an FC will combine data from several radar sites and observation posts within a geographic area and generate a single track file for each detected penetrator. The tracking data are combined from all of the sites within the FC's control to develop a much more accurate penetrator fix. A FC will use a radar site track as a starting point and will maintain that track by adding detection information from other radar sites. This track can be maintained even if the original radar site loses track by combining blips from other radar sites within its control.[14] If the FC loses track then the whole process starts over.

Multiple FCs within a geographic area, called an air defense zone (ADZ), report to an air defense weapons operation center (ADWOC). An ADWOC controls airborne interceptors, SAM sites, and AAA sites within the ADZ, and uses them to attack a penetrator. Once an ADWOC has a verified track, a decision is made as to how to attack the penetrator. If the penetrator is within a SAM/AAA lethal zone, and the SAM/AAA can acquire the penetrator, they may be ordered to attack. Once a SAM is launched, the SAM fire control radar must effectively vector the missile toward the penetrator or the missile may have its own seeker to acquire the penetrator. At farther ranges or in areas not otherwise covered, an airborne interceptor may be vectored to the penetrator until the airborne interceptors sensors are able to lock on. If an airborne interceptor is on strip alert it will receive an order to launch and will then be vectored toward an intercept point with the penetrator. Time is required to launch and fly the airborne interceptor to an intercept point and then search for the penetrator. Once the airborne interceptor locates the penetrator it will attempt to maneuver into a position where it can effectively attack it with guns or launch air-to-air missile (AAM). The AAM must also be able to acquire the penetrator and fuse properly to destroy or damage the penetrator. If the airborne interceptor is on combat air patrol (CAP), airborne alert, it can be vectored toward a penetrator much more quickly.

Each element of the C^3 net has time delays and errors that can make it difficult to stop an incoming penetrator. The time from first radar detection to intercept can be minutes for a SAM or tens of minutes to vector airborne interceptors to a distant intercept point. SAMs have range and altitude limitations and are ineffective if they do not detonate within close range of the penetrator. Airborne interceptors have a longer search time, limited by fuel or air defense doctrine, and can attack multiple times with different weapon types if needed.

Air defense C^3 network performance can vary greatly from country to country. To accurately detect, track, and assign defensive assets, numerous calculations, decisions, and communications are required. One of the more primitive systems is essentially a manual system similar to the British air defense system of World War II. Once a radar tracked a group of German aircraft for a period of a few minutes, an estimate of the number of aircraft, heading, location, and altitude was telephoned into a control center that recorded the data on a map. Once enough tracking data was acquired, an airfield was called and a squadron of aircraft was vectored to intercept. This system, although very effective for the time, required a large amount of time for intercept and the intercept solutions were inaccurate. During the Gulf War, Iraq had a much more modern 1970s-vintage C^3 system, as described in the Introduction. The Iraq C^3 net was a centralized system that used computers to combine multiple penetrator detection data into intercept solutions. One of the most advanced C^3 systems would probably be the U.S. Joint Surveillance System, which can track very small and fast penetrators and generate quick intercept solutions.

LO penetrators wreak havoc on C^3 systems. Because of their small radar signatures, it takes much longer to detect them; for every reduction of 12 dB, the radar range is cut in half. Once the LO penetrators are within detection range, the echoes are very difficult to distinguish from background noise, and gaps between detection echoes occur. When tracks are established they are frequently lost before defensive assets can be allocated. This is dependent upon how small the penetrator radar signature is and the quality of the C^3 net. A manual C^3 system would probably be unable to effectively engage any level of LO penetrator. A highly computerized C^3 system might be able to distinguish an LO penetrator from radar clutter and develop an accurate intercept solution, depending on how small the LO signature is. Also, highly trained radar operators experienced with identifying LO aircraft can improve the tracking accuracy of the C^3 net.

Mission Planning

It is vital to prepare a mission plan before any aircraft combat mission to ensure mission success with the available resources. Combat missions usually have one or more of the following as a primary goal: close air support; attacks against fixed, relocatable, and moving targets; air-to-air combat; suppression of enemy air defenses (SEAD); and battlefield interdiction.[6] Each of these combat missions involves a large amount of risk, and survival within enemy airspace is a critical factor.

Mission planning resources include the aircraft, weapon payloads, weapon types, range, performance, supporting facilities, and supporting aircraft. An attacking aircraft must have the range to reach a target, maneuver, and return to base. This range may be affected by weather (winds, thunder storms, etc.), altitude, speed, and unexpected maneuvering to account for threat avoidance. Fuel may be conserved by flying at an aircraft's best cruise altitude/speed, but in high-threat areas, flying above or below threat capabilities may be required. The location of the takeoff base and refueling aircraft can significantly impact aircraft range. For short-range missions, large weapon payloads, including externally mounted weapon stores, might be carried. For long-range missions, the weight penalties and drag associated with external stores may require additional refueling or reduced weapon carriage. The use of external weapon stores for very low observable (VLO) aircraft must be carefully considered, the weapons will have signatures larger than the aircraft itself.

Aircraft weapons may include offensive and defensive weapons, depending on the mission objective. Air-to-air missions include an array of weapons that are deadly to other aircraft and give a high probability of survival with encounters with enemy aircraft. Air-to-ground missions typically include aircraft that have very little defensive weapons to protect against other aircraft, their weapons are designed for specific ground targets. SEAD weapons such as the Shrike or Harm (antiradiation) missiles may be used to attack radar or SAM sites at safer distances. Standoff weapons such as standoff land attack missiles (SLAM), joint standoff weapon (JSOW), and conventional air launched cruise missile (CALCM) can be used to attack objective targets in dense threat areas, thus protecting the penetrating aircraft. Direct attack weapons can be used against targets that are in low-threat environments or can be used against targets in high-threat environments if the threats have little capability against the penetrating aircraft.

LO aircraft typically fly alone or in small groups of the same type of aircraft. Survival of LO aircraft is ensured because of their low detectability and use of threat-avoiding tactics, hence their title, *Stealth*. Tactics such as flying at night or in inclement weather dramatically reduce the ability of airborne interceptors to find LO aircraft. High-altitude flight minimizes exposure to low to medium altitude SAM and AAA coverage. Very low-altitude flight uses ground clutter and terrain features to reduce detectability. Flying at the greatest speeds possible in high-threat areas minimizes the time at risk. LO aircraft should not generally penetrate with onboard jammers or have escort jammers accompany them, as this may draw attention to the LO aircraft's location. Standoff jamming may be useful in certain situations; corridor jamming is not a good thing for LO aircraft. LO aircraft rely on tactical surprise and, in general, jamming should be used only as a last resort if surprise cannot be achieved (no multiple passes on the same target and do not enter SAM lethal zone if SAM can achieve radar lock).

By considering the factors discussed in the preceding text, the mission planner can plan a survivable route. Because of the complexities of LO aircraft signature, quantity of threats, and aerodynamic performance, a computer autorouter is typically used by the mission planner to plan routes. A target tie-up is usually generated first; this is where targets are selected, pre- and poststrike bases are chosen, refueling needs are considered, and major threats are noted. An autorouter then plans out a route that avoids all SAM and AAA lethal zones, minimizes radar detection, strikes selected targets, and returns to base. This tends to be an iterative process. If certain threats cannot be avoided, they may need to be suppressed, or certain targets may be attacked later when the threat is reduced. Suppression can be lethal as in the destruction of air-defensive assets, or nonlethal as in concurrent jamming, to prevent air-defensive assets from attacking the penetrator. After the route is generated, the mission planner must review the route to make sure the computer autorouter did not plan something that is operationally infeasible. If an aircraft must enter a SAM or AAA lethal envelope, then the probability of survival may be impacted. Countermeasures, tactics, jamming, and aircraft speed can be used to enhance aircraft survivability in these lethal zones and should be considered by the mission planner.

Because LO aircraft have much smaller signatures than other aircraft, the SAM and AAA lethal zones are much smaller and easier to avoid, but this does not mean they are invulnerable to these defenses. Countermeasures such as flares and chaff can be used and are more effective for LO aircraft because they are masking small LO signatures rather than conventional aircraft signatures. LO aircraft are much more survivable, but because of their survivability, they are used for the most dangerous and important missions. LO aircraft can penetrate deep into an enemy air defense and destroy vital resources with little chance of loss of aircraft. A single B-2 Bomber can penetrate deeply into a heavily defended country and destroy up to 16 different targets with 16 precision-guided munitions.

Aircraft Penetration of a Hostile Air Defense

An air defense represents a combination of overlapping radar and SAM coverage used to protect vital assets. EW radars are designed to give information about the approach of hostile aircraft long before they reach the country's borders. SAM sites are used to protect important facilities and to cover likely aircraft attack approaches. Airborne interceptors are used to identify unknown aircraft and attack them if hostile, and also to attack known hostile aircraft outside SAM lethal envelopes. Figures 6–11 show a notional threat laydown of a highly defended country vs LO penetrators (0, −15, and −30 dBsm) flying at 30,000 ft. The country is roughly 500 by 600 n miles and has 11 long-range ARSR-2 EW radars, 33 shorter-range ASR-7 EW radars, 47 strategic SAM sites, and 21 high-value targets. Each of the increments in both North–South and East–West is 100 n miles. The dashed outer line represents the combined radar coverage and the solid inner line represents the combined SAM coverage. The targets are represented by

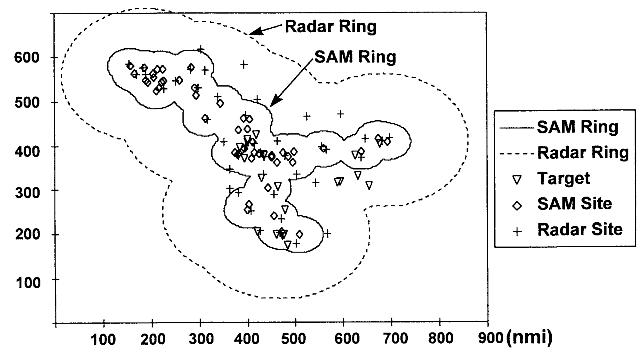

Fig. 6 Air-defense radar and SAM coverage vs 0-dBsm target at 30,000 ft.

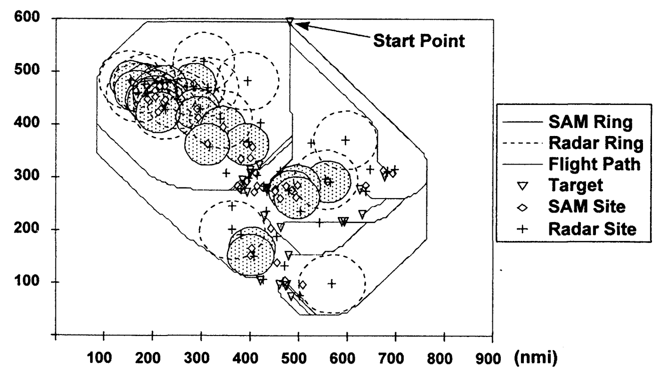

Fig. 7 Air-defense radar and SAM coverage after SEAD vs 0-dBsm target at 30,000 ft.

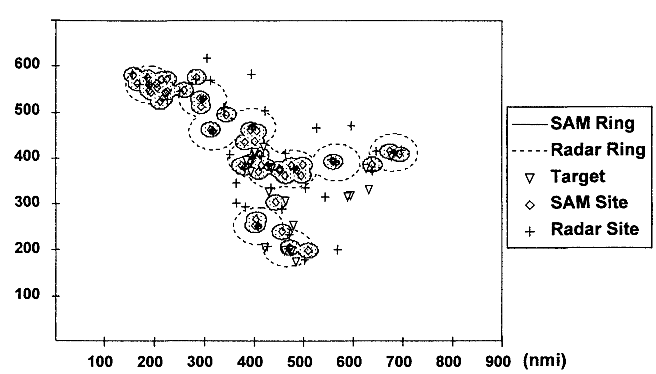

Fig. 8 Air-defense radar and SAM coverage vs −15-dBsm target at 30,000 ft.

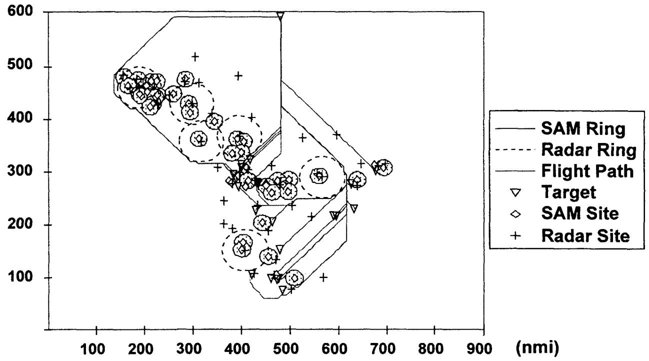

Fig. 9 Air-defense radar and SAM coverage after SEAD vs −15-dBsm target at 30,000 ft.

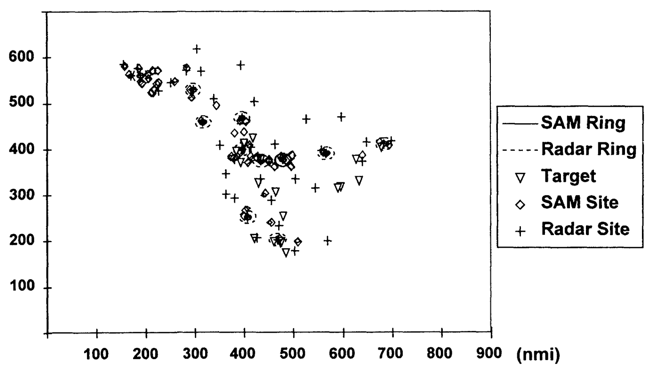

Fig. 10 Air-defense radar and SAM coverage vs −30-dBsm target at 30,000 ft.

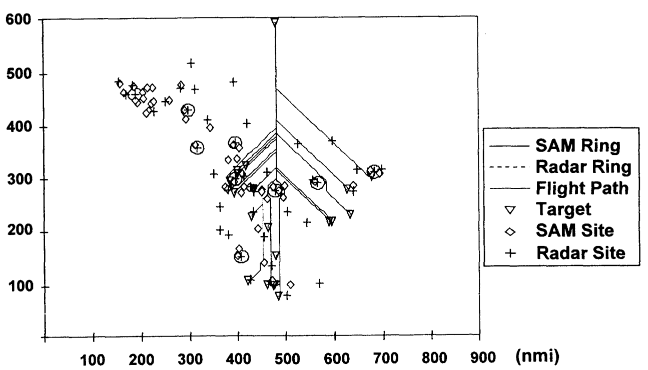

Fig. 11 Air-defense radar and SAM coverage after SEAD vs −30-dBsm target at 30,000 ft.

triangles, SAM sites are represented by diamonds, and radar sites are represented by crosses.

Figure 6 shows the air-defense coverage against a 0-dBsm attacking aircraft (a smaller RCS signature than most conventional attack aircraft). There is significant overlapping radar coverage extending over 200 n miles from most of the targets, and all but three targets have SAM coverage. To attack any of the targets would require a large aircraft strike package including fighters for air-to-air protection, jamming aircraft to reduce the radar, and SAM capability and Wild Weasel aircraft to destroy SAM sites. To attack all targets would require 28 radar and 21 SAM sites to be suppressed to ensure high survivability of the strike aircraft.

Figure 7 shows the routes of attacking aircraft after the minimum number of radar and SAM sites have been suppressed to strike all targets. All routes start at the triangle on the North side of the map. Each individual route is planned to minimize the number of suppressions required to attack a single target (routes are not optimized to take advantage of suppressions required for other targets). If all targets are to be struck, an average of 12 suppressions are needed for each individual route, as shown in Table 5. Fewer suppressions are needed to keep a smaller number of the targets at risk; an average of 10 suppressions/route are needed to keep 70% of targets at risk. Table 5 shows how useful LO aircraft are when planning survivable routes. There is an order of magnitude fewer suppressions required between a 0-dBsm aircraft and a −15-dBsm aircraft, and again between −15 dBsm and −30 dBsm. Not only does LO technology increase survivability, it dramatically reduces the support aircraft required to successfully attack a target.

Table 5 Air-defense suppressions required to strike targets for different levels of aircraft RCS signature

	Average number of suppressions per route, dBsm			
Targets struck, %	0	−15	−30	−45
70	9	0.8	0	0
80	10	1.0	0	0
90	11	1.2	0.1	0
100	12	1.4	0.2	0

Figures 8 and 9 show the air-defense coverage and suppression required for a −15-dBsm aircraft. Because the ASR-7 has no capability against a −15-dBsm aircraft at 30,000 ft (see Fig. 2), it can be overflown with little chance of detection. The ARSR-2 radar coverage is reduced to a circular area with a diameter of 80 n miles and the SAM coverage is reduced to a diameter of 35 n miles. Eight of the targets are in the open and can be attacked without any suppression. Figure 9 shows the planned routes used to attack all targets after four radar and nine SAM sites have been suppressed.

Figures 10 and 11 show the air-defense coverage and suppression required for a −30-dBsm aircraft. The ARSR-2 radar coverage is reduced to a circular area with a diameter of 25 n miles and the SAM coverage is reduced to a diameter of 14 n miles. A weapon that has a range greater than 7 miles could be used to attack a SAM site or target within the SAM ring (guided direct-attack weapons can fall within this category). Seventeen of the targets are in the open, and only two radar suppressions are needed to attack the other four targets. An aircraft with a −30-dBsm signature could fly almost anywhere within the threat laydown shown, with little impact to its survivability.

The threat laydown against a −45-dBsm aircraft was not shown because the ASR-7, ARSR-2, and the SAM systems described in this paper have no capability against it at 30,000 ft. The threat laydowns and aircraft routes shown in Figs. 6–11 show operationally how much low observability can improve aircraft survivability. LO aircraft make much of the world's air defenses obsolete or at the least significantly reduce their capability. Long-range LO aircraft can penetrate deep into a hostile country and attack assets that are vital to its ability to wage war. LO aircraft need far fewer support aircraft to carry out strike missions. A strike package that would require over 70 conventional aircraft can be accomplished by eight F-117 stealth fighters or one B-2 bomber.†

Summary and Conclusions

LO aircraft are much more survivable and require orders of magnitude less support than conventional (non-LO) aircraft. LO significantly reduces radar detection range; for every 12 dB of RCS signature reduction maximum radar detection range is halved. Because of the reduced radar detection volume, radar-guided SAMs, and airborne interceptors are much less likely to locate LO vehicles. Reduction of visual and IR signatures makes it much more difficult for AAA, airborne interceptors, and IR SAMs to acquire and attack LO aircraft. The

†Secretary of the U.S. Air Force testimony to the Senate Armed Services Committee, June 1991.

level of RCS signature needed to penetrate an air defense is driven by the quality and quantity of threats. For the notional air defense shown, a −15-dBsm aircraft with minimal SEAD assistance would be adequate for penetration. Through the use of mission-planning tactics and low signature, LO aircraft can survivably penetrate heavily defended air space with little support to accomplish their mission.

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