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Conformal Load-Bearing Antenna Structure for Australian Defence Force Aircraft

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ABSTRACT

Conformal Load-Bearing Antenna Structure (CLAS) replaces separate aircraft structure and antennas such as blades, wires and dishes, with electromagnetic radiators embedded in the structure. This approach reduces weight, drag and signature, and enhances electromagnetic performance, damage resistance and structural efficiency. However the design, manufacture, certification and through-life-support of CLAS are more complex than for its non-integrated counterparts. The first half of this report describes the advantages and limitations of CLAS and the factors to be considered when deciding whether to incorporate CLAS into Australian Defence Force aircraft.

The second half of this report describes the state-of-the-art in CLAS technology through a review of the open-source literature. It focuses on United States Air Force CLAS programs where demonstrators for Very High Frequency/Ultra High Frequency (VHF/UHF) and X-band communication applications have been successfully designed, analysed, manufactured and tested. Current programs include demonstrator X-band and UHF radars. CLAS will form part of the load-bearing airframe structure of the F-35 Joint Strike Fighter. It is predicted that the ongoing completion of demonstrator programs and the performance advantages likely to be realised by operational systems will lead to a gradual acceptance of this technology and an increase in the number of aircraft types containing CLAS in the ten year timeframe.

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Executive Summary

Just as moving from fabric and wood to metal monocoque construction during the 1930's produced a quantum leap in aircraft performance, so the adoption of multifunctional aircraft structure (MAS) offers the potential to radically alter the capabilities of military air vehicles. Integrating airframe structure with functional systems that; monitor structural integrity, change shape at a gross and local level, transmit and receive signals across the entire electromagnetic spectrum, produce and store power and provide ballistic protection will eliminate many of the weight, volume and signature penalties associated with the current approach of designing, manufacturing and maintaining airframes and functional systems separately. Ultimately this will allow aircraft to be designed around mission requirements rather than platform limitations.

One type of multifunctional aircraft structure that shows promise is Conformal Load-Bearing Antenna Structure (CLAS). CLAS refers to load bearing aircraft structure, typically exterior skins manufactured from carbon fibre reinforced polymer composite, that also contain radiofrequency transmitters and receivers. This structure may be retrofitted to existing airframes or incorporated in new platforms.

The first half of this report introduces the field of MAS with a focus on CLAS, its advantages and limitations and the factors than must be considered when deciding whether to incorporate CLAS into Australian Defence Force aircraft. It concludes that relative to traditional blade, wire and dish antennas, CLAS can reduce substantially weight, volume, drag and signature penalties in addition to providing for enhanced electromagnetic performance, damage resistance and structural efficiency. However the design, manufacture, certification and through-life-support of CLAS will be more complex than for its non-integrated counterparts. Some of these performance benefits may be realised at lower cost and complexity by using conformal non-load-bearing antenna (CNLA).

The second half of this report describes the state-of-the-art in CLAS technology through a review of the open-source literature. It focuses on the United States Air Force CLAS programs because they are the most comprehensive and widely publicised. The highlights of these programs have been the successful design, analysis, manufacture and test of demonstrators for Very High Frequency/Ultra High Frequency (VHF/UHF) and X-band communication applications. Current programs include demonstrator X-band and UHF radars. CLAS will form part of the load-bearing airframe structure of the F-35 Joint Strike Fighter.

It is predicted that the ongoing completion of demonstrator programs and the performance advantages likely to be realised by operational systems will lead to a gradual acceptance of this technology and an increase in the number of aircraft types containing CLAS in the ten year timeframe.

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Contents

Acronyms

ADF	Australian Defence Force
AESA	Active Electronically Scanned Array
AEW&C	Airborne Early Warning and Control
AFRL	Air Force Research Laboratory
AFTI	Advanced Fighter Technology Integration
AGR	Anti-Jam Global Positioning Satellite Receiver
ARL	Army Research Laboratory
AWACS	Airborne Warning and Control System
BLA	Buffet Load Alleviation
CFRP	Carbon Fibre Reinforced Polymer
CLAS	Conformal Load-Bearing Antenna Structure
CLAAS	Conformal Load-Bearing Antennas on Aircraft Structures
CNI	Communications, Navigation and Identification
CNLA	Conformal Non-Load-Bearing Antenna
DAMA	Demand Assigned Multiple Access
DARPA	Defence Advanced Research Projects Agency
DoD	(United States) Department of Defense
DSTO	Defence Science and Technology Organisation
EM	Electromagnetic
GFRP	Glass Fibre Reinforced Polymer
GPS	Global Positioning Satellite
HALE	High Altitude Long Endurance
IEEE	Institute of Electrical and Electronics Engineers, Incorporated
ISIS	Integrated Sensor Is Structure
ISR	Intelligence, Surveillance and Reconnaissance
JASSM	Joint Air To Surface Standoff Missile
JSF	Joint Strike Fighter
J-UCAS	Joint Unmanned Combat Air System
LO	Low Observable
LOBSTAR	Low-Band Structural Array
MAS	Multifunctional Aircraft Structure
MAW	Mission Adaptive Wing

MESA	Multi-role Electronically Scanned Array
MMA	Multimission Maritime Aircraft
MUSTRAP	Radiofrequency Multifunctional Structural Aperture
NASA	National Aeronautics and Space Administration
NLR	National Aerospace Laboratory
OML	Outer Mould Line
ONR	Office of Naval Research
PHM	Prognostics and Health Monitoring
QFRP	Quartz Fibre Reinforced Polymer
R&D	Research and Development
RCS	Radar Cross-Section
RF	Radiofrequency
RWR	Radar Warning Receiver
Satcom	Satellite Communication
SAR	Synthetic Aperture Radar
SBIR	Small Business Innovative Research
S-CLAS	SensorCraft Conformal Low-Band Antenna Structure
SDL	Satellite Data Link
SHM	Structural Health Monitoring
SIXA	Structurally Integrated X-band Array
SRTM	Shuttle Radar Topography Mission
S^3TD	Smart Skin Structure Technology Demonstrator
STTR	Small Business Technology Transfer
T/R	Transmit/Receive
UAV	Uninhabited Aerial Vehicle
UHF	Ultra-High Frequency (300 MHz - 3 GHz)
US	United States
USAF	United States Air Force
USD	United States Dollars
USN	United States Navy
VHF	Very High Frequency (30 – 300 MHz)
VLO	Very Low Observable
XTRA	X-band Thin Radar Aperture

1. Introduction

This report is the result of a literature review conducted by the Defence Science and technology Organisation (DSTO) on the topic of conformal load-bearing antenna structure (CLAS) technology as it applies to aircraft for the Australian Defence Force (ADF).

The report consists of five sections in addition to this introduction. Section 2 describes the generic field of multifunctional aircraft structures, of which CLAS is a sub-set. Section 3 describes a typical CLAS, the benefits and limitations of this technology and the likely way that this technology will be introduced to operational service. Section 4 describes the application of CLAS technology to the ADF and Section 5 gives the conclusions. Appendix A provides the reader with additional background by describing the state-of-the-art in CLAS technology through a review of the open-source literature.

2. Multifunctional Aircraft Structure

Most airframe structure is analysed, designed, manufactured, operated, maintained and supported independently of functional systems such as condition monitoring, electromagnetic transmitters and receivers, electrical wiring, thermal management, power storage, armour and weapons. While this approach reduces complexity it does increase weight and limit capability. Ongoing research and development (R&D) does extract further performance improvements out of these stand-alone airframe structure and functional systems however the scope for additional performance decreases as each becomes more optimised.

It is hypothesised that many functional systems could contribute to structural integrity, and similarly, parts of the airframe structure could contribute to functionality. For example many of the constituents of ballistic armour would have sufficient mechanical stiffness and strength to act as load-bearing structure. Thus, multifunctional aircraft structure (MAS) is airframe structure that serves the dual purpose of providing for structural integrity and at least one of the functional systems listed in the previous paragraph. In this way the airframe structure enhances aircraft capability and/or reduces through-life-support costs, rather than acting as parasitic, albeit necessary, weight.

Just as the move from fabric to metal skins in the 1930's produced a fundamental improvement in aircraft capability and a paradigm shift in operational use, so MAS technology has the potential over the next 10-20 years to produce similar enhancements in capability and changes in use. It would radically alter the way aircraft are designed, manufactured, operated and supported, however it would also allow aircraft to be designed and operated around mission requirements rather than the functional systems (particularly the military functions of receiving and transmitting data, weapons delivery and self-protection) being constrained by the vehicle [1].

The potential benefits of MAS has been reflected in the substantial R&D programs that have been conducted over the last forty years aimed at demonstrating the technology and raising it to a level of maturity where it can be introduced to operational aircraft. The three types of MAS that have been described most frequently in the literature are; structural health monitoring, shape control and CLAS. The remainder of this section provides a brief description of the MAS technologies with greater emphasis on these three.

2.1 Structural Health Monitoring

The most widely known form of MAS is smart structures for structural health monitoring (SHM). The aim of SHM is to reduce the through-life-support costs of aircraft. The first element of a SHM system are sensors installed on the airframe either by embedding during manufacture or by retrofitting to operational vehicles. The sensors would be selected to detect the degradation of interest, typically strain gauges for fatigue cracking or chemical/moisture/pH sensors for corrosion, and located where they could detect that degradation. The sensors would then be easily interrogated by the operator at the appropriate time to reveal the condition of the aircraft. If the SHM approach were accepted then maintenance could be based on the actual condition of each aircraft, so called condition based maintenance, rather than the current approach of conducting inspections/servicing at specified time intervals regardless of whether they are required or not.

The current interval based maintenance regimes are based on probabilistic statistics and are thus highly redundant and contain substantial conservatism because of the catastrophic consequences of aircraft failure. For most recognised airworthiness design requirements the probability of catastrophic structural failure in any aircraft during its life is 1 in 1000. Thus, for every 1000 flight critical components that are scrapped/removed because they have reached the end of their interval based operating lives, only 1 of these has genuinely reached the end of its life, the remaining 999 have at least some remaining safe operating life. In contrast, a condition based maintenance regime would call for maintenance actions only when damage had actually reached the pre-determined level. Even if substantial conservatism were built into this approach, say 9 out of every 10 scrapped/removed parts were still functional, this would still represent a 100 fold reduction in the current support burden for those parts.

SHM has been the subject of extensive R&D over the last twenty years and this technology is progressing toward operational service. An on-board prognostics and health monitoring (PHM) system will certainly be installed in the engine of the F-35 Joint Strike Fighter (JSF). There is some possibility that a system may also be installed in the airframe. DSTO has been a world leader in this field and is currently flying at least two SHM demonstrators on ADF aircraft, a “smart patch” on an F/A-18 trailing edge flap hinge and a corrosion sensor on AP-3C aircraft.

It is reasonable to expect that increasing numbers of aircraft manufactured in the 2010-2020 timeframe will contain SHM and PHM systems for both the engine and airframe. DSTO is well positioned to inform ADF decisions regarding the development, purchase and operation of such systems.

2.2 Shape Control

There are two technologies that may be considered under the broad heading of shape control. The first is load alleviation and is directed at reducing through-life-support costs while the other is gross shape control that focuses on capability enhancement.

Load alleviation uses a combination of active flight controls and actuators, typically piezoelectric patches bonded to external surfaces of the structure, to resist airframe deformations and therefore reduce structural loads. This has the potential for substantial benefits because reducing stresses by 20 % can double the fatigue life of an aircraft [2]. DSTO has a strong program in this area including a major role in the Buffet Load Alleviation (BLA) program coordinated by the Air Force Research Laboratory (AFRL). In one experiment piezoelectric patches were bonded to the inboard and outboard faces of an F/A-18 vertical tail. The patches were energised dynamically to reduce airframe stresses arising from the buffet generated when flying at high angles of attack. Work is continuing in this field and it is possible that systems shall be fitted to operational aircraft in the 10-15 year timeframe.

The second form of shape control is morphing structure and it is used to enhance vehicle capability. The concept is to change the gross shape of an aircraft to optimise it for each mission segment. For example long unswept wings maximise lift at low speeds and so are more suited to landing, takeoff and transit/cruise. Thin swept wings are optimal for high speed and would be used for combat and rapid ingress/egress mission segments. A simplified version of this concept has been in operational service with the swing wings of the General Dynamics F-111, Northrop Grumman F-14, Panavia Tornado and Rockwell B-1. A subtler form of morphing structure was incorporated on the very first heavier than air aircraft, the Wright Flyer. Roll control was achieved by warping the wings rather than using separate, hinged, ailerons, flaps and spoilers.

The concept of morphing structure has been the subject of extensive worldwide R&D, from fundamental material properties through to flight tests on modified aircraft, over the last 40 years. The largest reported research program was the joint USAF/National Aeronautics and Space Administration (NASA) Advanced Fighter Technology Integration (AFTI) program in the 1980s. Mission Adaptive Wing's (MAWs) were installed on F-111 aircraft and produced 7-20 % reductions in drag [3]. AFRL will be continuing this R&D using the recently designated X-53 Active Aeroelastic Wing flight research vehicle. However the MAW, or any other form of gross shape control, has not been introduced to operational aircraft.

It appears unlikely that airframes with significant morphing capabilities will be installed on inhabited aircraft in the next 10-15 years. At present the unresolved technical issues and large development costs for such a system outweigh the demonstrated performance advantages. A possible early use of morphing structure on inhabited vehicles will be the replacement of separate hinged flight control surfaces with aeroelastic surfaces. Flight control would be achieved by deforming (twisting, bending, warping) a compliant surface through actuators fastened to the sub-structure or embedded in the skin. It is more likely that Uninhabited Aerial Vehicle (UAV) technology demonstrators, and possibly even operational UAVs, with significant morphing capabilities will be produced in the 5-10 year timeframe. More ambitious morphing concepts will occur as the technology matures.

2.3 Conformal Load-Bearing Antenna Structure (CLAS)

The third major area of reported MAS research has been CLAS. The concept of CLAS is to replace existing antennas, particularly blades and wires, that protrude from the outer mould line (OML) of aircraft with airframe structure, typically skin, that (i) supports primary structural loads, (ii) conforms to the OML and (iii) can perform the transmit/receive (T/R) function of the existing antenna. CLAS will reduce drag and has the potential to reduce weight and signature, and enhance electromagnetic performance. A more detailed discussion of the benefits and limitations of CLAS is given in Section 3.

2.4 Other Multifunctional Aircraft Structure

Electrical wiring	Aircraft contain many kilometres of electrical wiring for the distribution of power and data. This wiring is costly and time consuming to install, inspect, repair, re-route and upgrade. The multifunctional approach would be to embed conducting paths, either metallic strips or conducting structural composites, into the airframe structure. This would require the development of reliable, high efficiency, embedded conductors and panel-to-panel connectors. Complex routing paths could be accommodated by multiple entry/exit points in each circuit. Redundancy could be built-in by incorporating multiple circuits in each panel and survivability enhanced by separating these multiple circuits. Support costs are likely to be lower because embedded conductors would be more isolated, and thus less likely to be inadvertently damaged, than wires in traditional exposed looms.
Thermal management	Many aircraft and spacecraft systems generate significant heat, however the ducts/radiators/pumps that are used to cool these systems are bulky and heavy. The multifunctional approach would be to either take advantage of the natural thermal conductivity of the airframe materials (e.g. use carbon fibres as heat pipes) or manufacture channels/galleys into the structure and use these to transport a thermal transfer media (coolant).
Directed energy weapons	Directed energy weapons such as lasers and microwaves are being developed for on-aircraft use. These weapons focus intense beams of electromagnetic radiation at the target to produce effects such as physical damage, disabling equipment or incapacitating people. The weapons are very high powered versions of their conventional electromagnetic counterpart. For example a microwave beam would be a high powered X-band antenna operating in the transmit mode. It is possible that these beams could be created using CLAS, however substantial technical hurdles remain given that mega-watts of power are required to disable equipment or people at even moderate range.

Energy storage	Directed energy weapons require mega-watts of power to be effective and power supplies are heavy, 2500 kg of conventional capacitors are required to store 1 MJ. A potential alternative is the structural capacitor, where energy is stored in coated wires that are woven into structural composites. At the currently achievable power storage densities, many hundreds of kilowatts could be stored by such structural capacitors if they were incorporated into the wings and fuselage of an aircraft.
Armour	Intuitively it should be relatively straightforward to incorporate ballistic protection into airframe structure and thus obtain synergistic weight reductions. However it must be noted that the areal density of aircraft skins and floors is in the order of a few kg m^{-2} while that of armours suitable for protection against military weapons is in the order of tens of kg m^{-2}. Thus only 10 % of the weight of armoured aircraft structure is the airframe. Even eliminating the structure entirely will only produce modest weight savings. The greatest weight gains from integrated armour will come when the density of the armour can be reduced substantially. The support offered by airframe structure may facilitate this, i.e. aircraft skin could act as a stiff backing for the armour.

3. Conformal Load-Bearing Antenna Structure

3.1 Construction

Many of the reported CLAS demonstrators and laboratory test specimens have taken the form of honeycomb stiffened sandwich panels. A typical design is shown in Fig. 1. This figure should be referred to when reading the discussion presented in the remainder of Section 3.1. It is likely that the details, and possibly even the configuration, of any specific CLAS component will be different from that shown in Fig. 1, however the basic components and concepts are still expected to be required and applied.

CLAS must support significant structural load, so ideally the outer skins of the panel would be manufactured from high stiffness materials such as carbon fibre reinforced polymer (CFRP) or even high strength aluminium alloys. Unfortunately these materials are opaque to electromagnetic radiation, thus a bathtub shaped recess is usually manufactured into the inner skin so that it can (i) remain continuous and thus continue to support structural loads, (ii) provide a space within which the antenna components can be located.

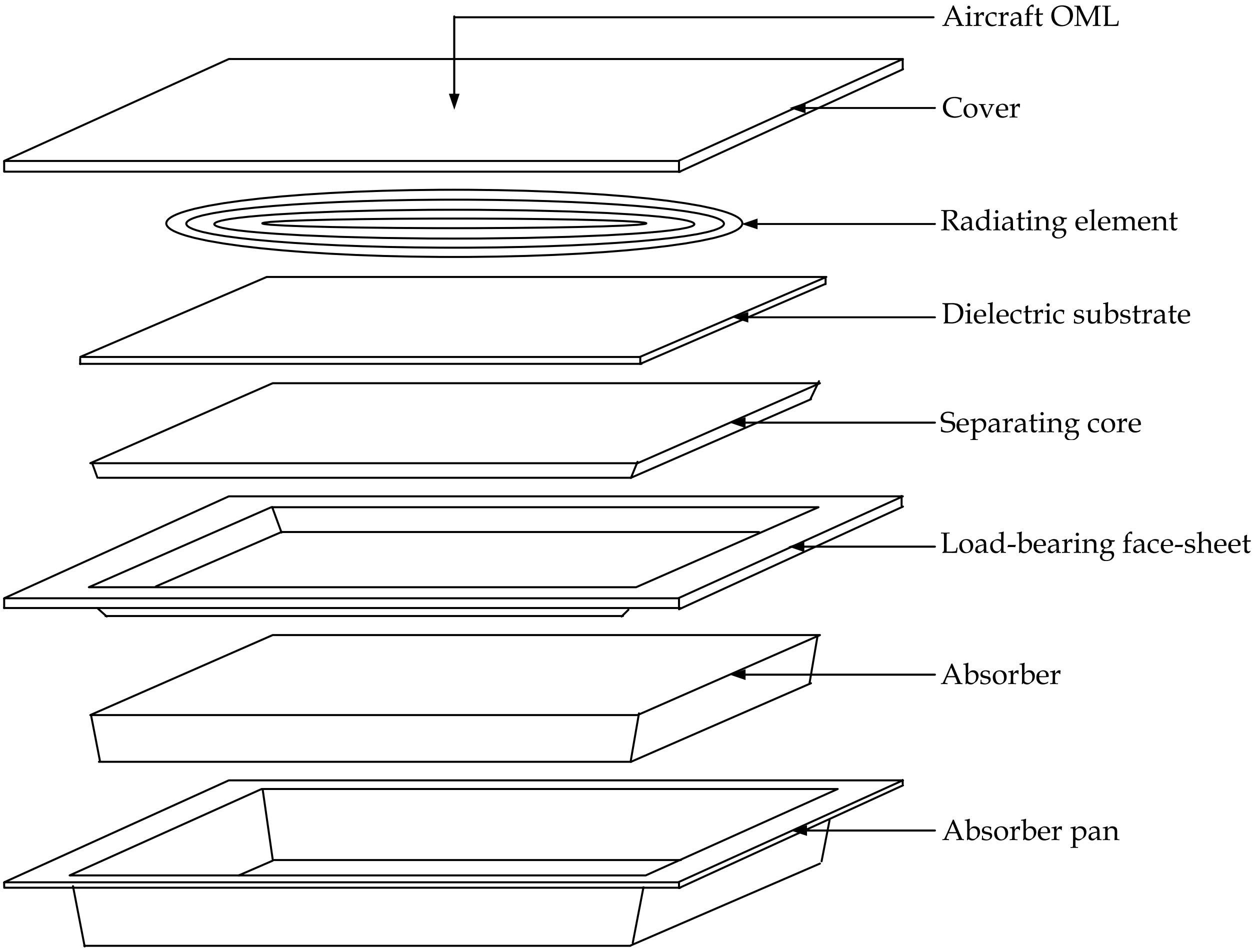


Figure: 1 Typical CLAS components, after [4]

Commencing at the OML, CLAS antennas tend to comprise the following components:

Cover	The outer face of the CLAS lies flush with the aircraft OML. This face may contain the radiating element, however it is more common to protect the element with a cover. The cover must be transparent to radiofrequency (RF) radiation and so is typically constructed from glass (GFRP) or quartz (QFRP) fibre composites. Transmission losses through these covers are minimised by controlling their thickness (in the order of a few mm) and distance from the radiator (in the order of a half wavelength). The lower stiffness of the GFRP or GFRP covers relative to the load bearing CFRP skins must be accounted for otherwise secondary bending will reduce fatigue life and allow deformation under load that may impair antenna performance.

Radiating element	Radiating elements, or radiators, tend to be electrodeposited copper films in the order of 15 μm thick. Copper is used because of its high conductivity. Unfortunately it is also very dense and its long term durability when embedded in composite structures has not been proven. It is likely that other less dense and more compatible conductors may also be acceptable radiators. The shape and dimension of radiators are critical parameters in determining the electromagnetic performance of an antenna. Shapes may be regular (circles, squares and rectangles) or irregular (spirals, slots, L's, U's, fir-tree) and dimensions approximate that of half the operating wavelength (millimetres for K-band, centimetres for X-band, tens of centimetres for Ultra High Frequency (UHF) and metres for Very High Frequency (VHF)). Most CLAS radiators are oriented in-plane with the aircraft OML, presumably to minimise antenna thickness, however some recent designs have used radiators that were oriented in the through-thickness direction. All orientations that satisfy the volume/size constraints and produce the desired radiation pattern could be considered for any specific application.
Dielectric substrate	Radiators are usually electrodeposited onto a dielectric substrate. The dielectric constant and thickness of the substrate are critical parameters because they dictate the extent of coupling between the feed and the radiator. Both can be closely controlled by modern manufacturing processes. The simplest approach to feeding is for the radiator to be connected directly to the centre line of an incoming coaxial cable. In some CLAS designs the radiator has been fed indirectly, by coupling energy that was radiated from elements (typically apertures or patches) located beneath the radiator. In these designs additional layers, consisting of the various feed elements on their dielectric substrates, were located between the dielectric substrate and load-bearing face-sheet.
Separating core	In bonded aircraft structures a honeycomb or foam core is sandwiched between load-bearing face-sheets (skins). Mechanically this construction is very efficient because the skins support the applied loads (skins are located at the extremities of the structure where they have maximum mechanical advantage) while the low density core stabilises the skins and transfers shear loads between them. Most reported CLAS has used honeycomb because it has lower density and electromagnetic losses than foam. In some CLAS designs there may be additional layer(s) of honeycomb between the radiator and cover and/or between feed elements if indirect feeding is used.

Load-bearing face-sheet	The load-bearing face-sheet, typically CFRP, is bonded to the core. The face-sheet contains the bathtub shaped recess within which the radiating components are located. If the face-sheet has sufficient conductivity then it may also act as the ground plane.
Absorber	Some antenna designs produce a significant back-lobe (EM energy directed in the backwards direction). If this occurs then it is possible that a layer of very lossy dielectric material will be bonded to the back face of CLAS to absorb this undesirable radiation. The material is typically a low density foam loaded with absorbing particles.
Absorber pan	A lightweight, non load-bearing, enclosure to contain the absorber material.

3.2 Benefits

3.2.1 Reduced drag

The most commonly quoted benefit of conformal antenna is drag reduction. To realise this benefit the antenna may be either load-bearing (CLAS) or non-load-bearing (conformal non-load-bearing antenna - CNLA). Clearly replacing externally mounted antennas with antennas that are flush to the OML will reduce drag. Most military aircraft, such as those shown in Fig. 2, are festooned with externally mounted antennas. The AP-3C has up to 100 while the F/A-18 has over 70.

Large antenna structures, such as reflecting dishes or planar arrays, are usually housed in fairings or radomes. While these shield the antennas from the airstream, thereby reducing the extent of drag, the shape of the vehicle can depart significantly from the aerodynamic optimum. Prime examples are shown in Fig. 3, the "top-hat" Multi-role Electronically Scanned Array (MESA) on the Airborne Early Warning and Control (AEW&C), the radar disc on the E-3 Airborne Warning and Control System (AWACS) or the bulging nose on the RQ-4 Global Hawk. It is clear that substantial gains in aircraft performance may be realised if the size of these housings could be reduced or they could be eliminated.

The drag coefficients of some antenna types at some flight conditions have been reported in the literature. However the reduction of this data to establish the effect of specific antenna on the performance of specific aircraft is outside the scope of this report. DSTO aerodynamicists are investigating this topic and shall report their findings in the future.

When considering the drag reduction offered by CLAS/CNLA, the level of conformity must be known and two parameters must be considered, the (i) shape of the antenna OML relative to that of the aircraft, and (ii) tolerance between the OML of the aircraft and outer face of the CLAS/CNLA.

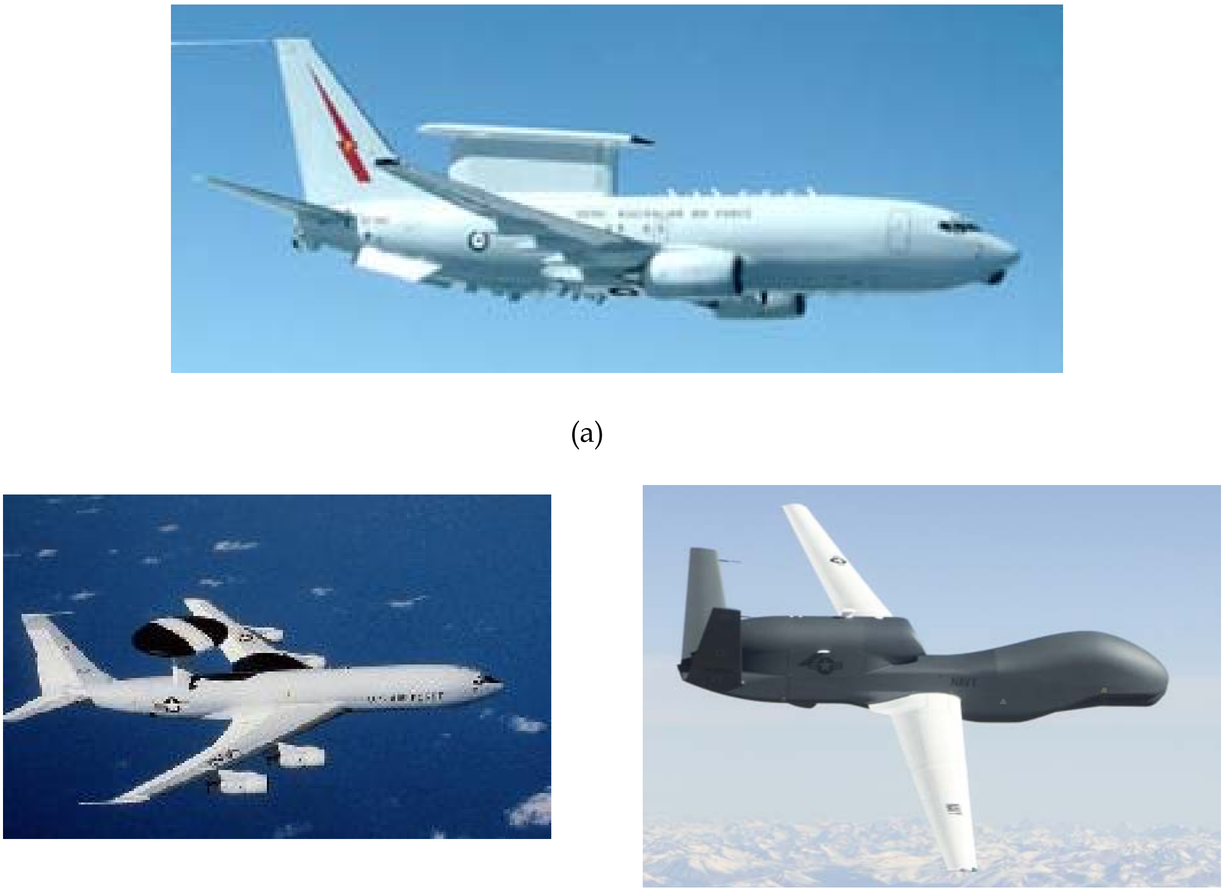
(a)

(b)

Figure 2: ADF (a) AP-3C and (b) F/A-18 aircraft showing some of the many antennas that protrude from their OML

In terms of shape, the OML of the CLAS/CNLA may be:

(i) flat	This is most likely the lowest cost to design, manufacture and maintain. However it offers the minimum performance benefit because a planar antenna can only be truly flush (tangent) to the airframe OML at one point for complex curvature or along one line for simple curvature. This may be acceptable in some cases. For example some of the antennas on the AP-3C are mounted onto a flat bottomed plinth that is fastened to the lower fuselage. This plinth provides a flat area of approximately 1.5 m x 1.5 m on the underside of the circular fuselage barrel. Clearly the enhanced functionality offered by the installation of these antennas on the flat plinth outweighed the loss in aircraft performance imposed by the relatively large obstruction.



(a)

(b)

(c)

Figure 3: Aircraft with large radar housings/fairings. (a) Boeing 737-700 AEW&C, (b) Boeing E-3 AWACS, and (c) Northrop Grumman RQ-4 Global Hawk

(ii) simple curvature	The OML of a range of aircraft surfaces are approximately cylindrical, the most obvious being the fuselage barrels of large transport aircraft. Significant drag reduction would arise from installing curved CLAS/CNLA on these surfaces, even if the curvature of a cylindrical antenna did not match exactly that of the aircraft OML. In order to reduce costs it is conceivable that manufacturers could offer standard products that covered the range of curvatures commonly found on customer aircraft.
(iii) complex curvature	Minimum drag, and thus maximum performance benefit, occurs when the OML of the CLAS/CNLA matches the three dimensional shape of the aircraft OML. These performance benefits would be accompanied by design, manufacture and maintenance costs that increase as shape complexity increases.

The second factor that must be considered when evaluating conformity is distance that the antenna can extend from the OML without adversely affecting aircraft performance. This will depend on a range of factors including airspeed, skin smoothness, aircraft shape and atmospheric conditions. Two examples showing the range of possibilities are (i) the plinth on the AP-3C that extends in the order of 30 cm from the OML at its edges yet has been judged acceptable, and (ii) that less than 0.1 mm thick scotch tape on the wall of a wind tunnel operating at Mach 2.0 induced a pattern of diagonal Mach lines in the tunnel even though the Mach 1.0 boundary layer was 7.6 mm thick and the full boundary layer was 76 mm thick [5].

3.2.2 Enhanced electromagnetic performance

Within a factor of 2 or so, antennas are approximately equal to half the wavelength of EM radiation that it will T/R. Thus a 50 cm antenna can T/R approximately 100 cm (300 MHz) signals. Higher frequencies (shorter wavelength) can be T/R by dividing the antenna into smaller elements, however lower frequencies (longer wavelengths) cannot be accessed unless the antenna length is increased. Techniques such as wrapping and spiralling can increase antenna length without greatly increasing area, however this approach does have its limits.

The general trend in communication and radar systems over the last sixty years has been toward higher frequencies, leading to dramatically increased data transfer rates and improved angular resolution. Prior to World War II most antennas were of the wire type with maximum frequencies at the upper limit of the VHF band, 300 MHz. With the invention of microwave sources in the 1940's the frequencies increased to a few GHz. Further improvements from the 1950's to the 1990's increased the typical operating frequencies to tens of GHz, with the 8-12 GHz X-band being most common. The advent of high speed processors in the 1970's allowed individual antenna elements to be combined into arrays, producing a major advance in system capabilities. Today's most powerful radar systems are arrays. More recently, interest has turned to ground and foliage penetrating radars. These operate in the VHF range (hundreds of MHz) and can identify targets in built up areas. Practical systems have been developed but they require large antennas. Improvements in these systems could be made my by using arrays but these would increase further the system size.

The maximum size of antennas on most military aircraft tends to be in the order of 1 m. For example the GlobalHawk Satcom antenna dish is 1.2 m diameter while the Active Electronically Scanned Array (AESA) tracking radars in fighter/attack aircraft (APG-63 in F-15, AN/APG-77 in F-22, APG-79 in F/A-18 E/F and EA-18G, APG-80 in F-16 Block 60 and the APG-81 in the F-35 JSF) are in the order of 0.9 m diameter. These sizes are a compromise between communication/tracking system performance and available volume.

CLAS/CNLA technology offers the potential to radically alter the shape and size of antennas and antenna arrays. It is possible that the performance of high frequency X-band AESA systems could be radically enhanced by distributing array elements across the entire aircraft, rather than the current state-of-the-art where elements are located in a single planar array in the nose. The capability to field low frequency foliage penetrating radar arrays could be realised by distributing the larger VHF elements across the entire lower surface.

Clearly the addition of new capabilities such as ground penetrating radar would produce major operational benefits. However benefits may also arise by simply changing the characteristics of existing systems. For example, as detailed in Section A2.4, a demonstrator CLAS produced a five fold increase in the range of a F/A-18 voice communications radio. This could be of major benefit to ground forces because they could communicate directly with the aircraft from a much greater range than is currently possible. Among other things, attacks could be coordinated from positions of relative safety or assistance calls made from more remote positions.

Studies have claimed that a single CLAS can replace multiple traditional antenna and that less than ten multifunctional apertures, distributed appropriately around an aircraft, could replace all existing antenna [6]. This claim of only nine multifunctional apertures needs to be clarified, some of these nine apertures would actually contain multiple separate antennas installed on the same panel. However, the principle remains that it may be possible to replace the 70-100 externally mounted antennas on current military aircraft with a far smaller number of flush mounted apertures.

Two major developments are required to achieve the goals described in the previous three paragraphs. Firstly the broadband performance of individual antenna must be improved substantially so that the fewer numbers of CLAS/CNLA can cover the full range of frequencies and radiation patterns that are currently covered by a multitude of antennas. The second major technical challenge is in the area of signal processing. At present it is very rare for a single antenna to be connected to more than one system, however true multifunctional apertures would require each antenna to cover 5-10 systems. Achieving this goal is someway off given that the scientific literature claims progress when one antenna can be used for two systems.

3.2.3 Reduced signature

Reducing the number of antenna that protrude from the OML will certainly reduce the radar cross-section (RCS) of an aircraft. Conformal antenna are a necessary, but not sufficient, condition for an aircraft to be low observable (LO) or very low observable (VLO). There are many features besides the antenna that contribute to the RCS of an aircraft. These include the shape and geometry of the OML, orientation of radar reflective structure including that buried below radar transparent structure, orientation of discontinuities in the skin (panel joints, fastener holes and external mountings) and the material properties of external surfaces. These factors mean that simply replacing protruding antenna with CLAS/CNLA is not sufficient to make a traditional aircraft into a LO or VLO aircraft.

For an aircraft to be LO or VLO the curvature of the CNLA/CLAS and the steps or gaps between the antenna and surrounding skins must be controlled within very tight tolerances. No open literature exists regarding the tolerances on this flushness however one article states that the machine used to mill the inside of the composite skins for the F-35 JSF was accurate to a tolerance of 50 μm [7]. It is doubtful that the tolerance on flushness and step tolerances will be this tight, but it would not be unreasonable for them to be substantially less than 1 mm.

Maintaining this tolerance represents a substantial challenge for an aircraft when service life may approach 40 years. In addition to the degradation in tolerances due to "normal" airframe deformations such as landing and manoeuvre, the effect of damage and repairs must also be considered. The traditional approach to repairing damaged bonded composite skins is to remove the damage, fill the cavity, then fasten or bond a doubler over the cut-out region. The effect of this type of repair on the OML is generally ignored because doublers tend to be relatively thin (a few mm) and usually do not adversely affect flying qualities. However the signature requirements for LO/VLO aircraft mean that this will certainly not be the case for such aircraft. New maintenance and repair processes will need to be developed to address the very tight flushness tolerances. These will be difficult enough to develop for structure, let alone CLAS where electromagnetic, in addition to structural, constraints will need to be satisfied.

3.2.4 Enhanced damage resistance

Protruding antenna, typically blades, are often damaged when objects pass close to the aircraft OML and contact the antenna. This may occur during (i) flight operations e.g. fixed wing aircraft flying through hailstorms or helicopters contacting foliage when operating from unprepared landing zones, (ii) ground handling e.g. collisions between taxiing aircraft or ground vehicles and aircraft, or (iii) maintenance e.g. dropped tools or inadvertent contact with the aircraft while working on other systems.

The likelihood of damaging contacts with flush antenna, relative to that for blade antenna, will be different for each of two orthogonal directions. Contact in a direction approximately parallel with the OML (tangential to skin) is far less likely with flush antenna because the external protuberance has been removed and the antenna surface will be flush with the OML. Susceptibility will thus be reduced. In contrast, contact in a direction approximately perpendicular to the OML (e.g. hailstones falling on the upper surfaces of an aircraft parked in the weather) may be more likely because the surface area of a flush mounted antenna on an aircraft OML mould be larger than that of the equivalent blade antenna.

The consequences of impact must be assessed for each contact direction. Intuitively the type of contacts that would be most damaging to blade antennas are those perpendicular to the blade, or parallel to the aircraft OML. This type of contact would induce bending moments in blades causing either the antenna break, the mounting to break free from the skin or the skin to fail. The large aspect ratio of blade antennas places them at a mechanical disadvantage because large bending moments at the base may be generated by even moderate lateral loads at the tip.

Loading parallel to the OML is expected to be far less damaging to CLAS/CNLA. In this case the majority of the load would be directed parallel to the face of the conformal antenna. The type of damage sustained by such contact would be scratches or grooves in the outer layers of the antenna, most likely a cover-sheet. Larger load would be required to penetrate into the underlying structure and components because the fraction of load perpendicular to the OML would be proportional to the sine of the contact angle. For a true tangential glancing contact this would be zero.

The consequences of perpendicular contact with conformal antenna are less clear. It is possible that perpendicular contact onto a CLAS/CNLA could be more damaging than the same contact onto a blade antenna. Load would be transmitted through the outer skin and into the underlying components. The extent of damage would depend on the construction of the antenna and would be reduced if there was a (i) protective outer cover, and (ii) energy absorbing layer such as honeycomb between the outer surface and the radiating element.

3.2.5 Enhanced structural efficiency

The traditional approach to installing aircraft antenna/sensors are to drill fastening holes, machine cut-outs into the airframe, reinforce these cut-outs, install the antenna/sensor mounting into the cut-outs, then fasten the mounting into the holes. This is structurally inefficient. Cut-outs remove load-bearing material and therefore reduce the structural integrity of the airframe. This integrity may be restored by reinforcing the cut-out and holes, however this adds weight that is sometimes beyond that of the original airframe. In addition, antenna/sensor mountings tend to be relatively massive so they can retain their dimensional tolerances while being subjected to aerodynamic loading. The loads transmitted into the airframe arising from the weight of these mountings and the aerodynamic load can necessitate further reinforcement. CNLA can overcome some of these disadvantages and CLAS can overcome many.

CNLA would greatly ease airworthiness certification, relative to CLAS, while realising some of the benefits of conformal antenna, because the structure would be able to withstand Design Ultimate Load (DUL) in the absence of the antenna. No structural "credit" would be required from the antenna. Thus the level of analysis and testing required to demonstrate that the airframe remained airworthy would be relatively low. Some CNLA may be installed by bonding or fastening to the external skin with no requirement for cut-outs, while others will require a cut-out with reinforcing to support the antenna housing.

The situation would be different when installing CLAS onto existing aircraft. It is expected that either of the following two approaches would be required. In the first, a pre-existing airframe sub-component such as a door, panel or flight control, would be redesigned to contain the antenna. The redesigned sub-component would then be used as a direct replacement for its non-antenna-containing counterpart. It is expected that in many cases the structural efficiency of a modern, redesigned, sub-component would exceed that of the original, as a result of the continual advance in design methodology and the manufacturing flexibility afforded by modern composite materials. It is quite possible that the antenna function may be incorporated into the airframe with little or no weight penalty, especially when compared to the weight that would have been added had a traditional, externally mounted, antenna been used.

The second approach for installing CLAS would be a conventional cut-out-and-mount if there were no logical component/sub-component within which to install it. The advantage of CLAS would be that the mechanical response of the CLAS would match, to a large extent, the behaviour of the structure that it replaced. Therefore the disruption to existing load paths and the requirement for additional reinforcement would be minimised. It must be noted that it will be impossible for retrofitted CLAS to match the stiffness and exceed the strength of the existing airframe for all load-cases because the construction materials and geometry of the CLAS would be different to that of the original structure. However, it is expected that the adverse effect on surrounding structure would be far lower than that experienced with externally mounted antenna or even some types of CNLA (additional reinforcement may be required to support CNLA and this may attract load).

3.3 Limitations

3.3.1 Design complexity

Clearly, designing CLAS will be far more complex than separately designing the airframe and antenna. Airframes are designed by structural engineers using the principles of mechanics and materials engineering while antennas are designed by electrical engineers using the principles of radiofrequency photonics and electronics. In designing CLAS the requirements from each of these fields will impose constraints on the other. Thus the traditional approaches to design cannot be used.

Although the analysis and design of CLAS will be more complex than stand-alone structure or antenna, experience in doing this already exists within a moderate number of R&D organisations and at least one aircraft manufacturer. As with most complex engineering systems a far lower level of expertise would be required to maintain and support CLAS that was retrofitted to existing aircraft or installed in future aircraft when compared with that required to design the system. It is expected that qualified structural and communications engineers should be able to be trained sufficiently to maintain the systems that are likely to be employed in the foreseeable future.

In the long term future, as MAS technology matures, additional capability will be added by increasing the level of integration. For example the electrical wiring and coaxial cables that distribute power and data may be replaced by conductors embedded in a CLAS. This will increase further the complexity and level of expertise required for analysis, design, manufacture, certification, operation and through-life-support.

3.3.2 Matching existing radiation patterns

Different antenna applications require different radiation patterns. For example target tracking requires tightly focused beams while direction finding requires uniform coverage over an entire hemisphere. Many antenna concepts are available and antenna design is a well developed area of electrical engineering. The very large number of journal articles that describe antenna concepts and designs suggest that conformal antenna concepts could be designed to duplicate, to a large extent, the radiation pattern for virtually all blade mounted diploes and probably most of the other commonly used aircraft antennas. However it is almost certain that the radiation pattern of these new antennas would not match precisely the pattern of the existing antenna because the CLAS would be manufactured with a different configuration and from different materials than the original. Thus any systems retrofitted with a CLAS/CNLA would need to be re-calibrated.

Polarisation of the radiation is an important parameter. It is defined as the direction of the electric field vector of the T/R signal relative to the surface of the Earth. In vertically polarised signals the electric field vector is perpendicular to the surface of the Earth, i.e. vertical. The polarisation of a dipole antenna, such as that contained in a typical blade antenna, is parallel to that dipole. Thus a dipole antenna that is mounted vertically on an aircraft, say along the upper or lower surface of the wing or fuselage, would T/R a vertically polarised signal. It would not be possible to duplicate the behaviour of this antenna by simply laying a dipole flush to the OML (and so converting the blade mounted dipole into a CNLA) because the direction of polarisation would no longer match that of the original.

One method that has been used to partially overcome this constraint was to maintain the original orientation of the dipole (perpendicular to the OML) but recess the antenna into the airframe and place a RF transparent window over the antenna. In this way the externally mounted blade antenna could be converted to a CNLA. A number of commercially available conformal antenna do just this. While these do retain antenna functionality and produce a conformal OML they tend to be inefficient because (i) power is lost as signals are transmitted/received through the window, (ii) the field of vision may be restricted because signals must enter/exit through the window, (iii) additional reinforcement may be required in the airframe structure to support the larger antenna housing, and (iv) volume within the aircraft is lost to the CNLA housing.

A more efficient approach would be to use a true CLAS configuration, albeit with an alternative antenna concept that would require recalibration. For example slot antennas are the electrical complement of wires, thus an in-plane slot may be an acceptable alternative to an externally mounted dipole. It has been claimed that microstrip antenna can be designed to produce a range of polarisations including vertical, horizontal, left hand circular and right hand circular polarisation. These could be used to match, or at least closely approximate, the polarisation characteristics and radiation pattern of many existing antenna types.

3.3.3 Airworthiness certification

The airworthiness certification of conventional antennas is typically, as is the certification of any aircraft system, a long and expensive process. Many issues must be addressed and compliance with all relevant regulations must be demonstrated. The major airworthiness issues for antennas relate to electromagnetic environmental effects – do the antennas perform the intended function and do they interfere with other systems? The actual performance of the antenna is not an airworthiness issue unless of course it interferes with other systems. The structural airworthiness requirements are relatively straightforward. The major requirements are that the airframe must be able to withstand Design Limit Load (DLL) with no permanent deformation and DUL for three seconds without failure, in the absence of the antenna, its housing or mounting structure. The antenna too must be able to withstand these conditions. Satisfying these requirements is the reason that reinforcement may be added to airframe structure onto which antennas are mounted. However given their relatively small size, only a moderate amount of analysis and possibly some testing may be required for blades and even CNLA to demonstrate compliance with the DLL and DUL requirements.

Demonstrating airworthiness for CLAS will be much more onerous. If the CLAS has been designed well then the airframe will not be able to withstand DLL or DUL in its absence and so structural credit must be given to the CLAS. The extent of analysis and testing that will be required by airworthiness regulators to certify that the structure is safe will be far in excess of that required for bolt-on antennas or CNLA. It is expected that the building-block approach would be used to demonstrate airworthiness. The response of the structure would be predicted using finite element models that have been validated by mechanical testing at the coupon, detail, element and full-scale level. Note that relative to an aircraft most CLAS would be considered as sub-components, thus a full-scale test in this context would mean a test of the CLAS component only, and not the entire aircraft.

Additional complexity will be introduced to the certification process because the structural and EM effects cannot be considered separately. Analysis and testing will be required to assess the interactions between the two. It is expected that, as a minimum, structural integrity must not compromised by failure of the CLAS. It is also likely that the CLAS will need to remain functional if it receives the type of damage that other composite airframe structures must tolerate, such as surviving DUL in the presence of Barely Visible Impact Damage and surviving DLL in the presence of Visible Impact Damage.

3.4 Introduction-To-Service For CLAS

Clearly MAS has the potential to fundamentally change the instruments of air power. Effectively integrating functional systems into airframe structure will lead to aircraft that have substantial improvements in performance and new capabilities. The recognition of this potential has been reflected in a significant investment in MAS technologies, particularly over the last twenty years.

Some MAS concepts, including CLAS, are at a sufficiently high level of maturity to be considered ready for operational service. They have been proven in the laboratory and tested on aircraft. In the absence of formal statements, it must be concluded that to-date the manufacturers consider that the costs associated with introducing CLAS, or other MAS, onto their products outweighs the expected benefits of this technology.

The first reported example of CLAS planned for introduction to operational service will be on the F-35 JSF [8]. The function or type of CLAS antenna has not been released. The manufacturer, Northrop-Grumman, indicated that the JSF antennas will exploit the experience gained by the company in previous load-bearing antenna programs. These programs, largely sponsored by the USAF, are described in Appendix A.

A moderate number of CNLA systems are operational on existing aircraft and more are planned for aircraft currently under development. However, as discussed previously, a CNLA will not impart the full benefits of true integration.

4. CLAS for the ADF

4.1 What Can Conformal Antenna Do For The ADF?

The installation of conformal antenna on ADF aircraft will impart the benefits described in Section 3.2, namely:

expanded flight envelope (increased speed, range and endurance),
enhanced antenna T/R performance and/or additional T/R capabilities,
reduced platform signature,
reduced susceptibility to damage, and
enhanced structural efficiency.

CNLA systems can offer some of these benefits, and to a lesser extent, but with lower complexity and cost than CLAS.

The relative importance of each of these benefits will vary depending on the application. Expanding the flight envelope may be a compelling argument for some ADF aircraft because the Australian land mass and its maritime borders are large and sparsely populated. Thus aircraft range and endurance tend to be more important than for other defence forces. This factor may be coupled with enhanced T/R performance because increased communications range may partially compensate for lower platform performance. For example a slower aircraft may be acceptable if it can communicate at greater range. Additional T/R capability, even if they reduce aircraft performance or increase costs, may be sufficient justification for acquisition if it has been established that this capability is required. Robust T/R systems may be very important for helicopters flying close to the ground or operating out of unprepared landing zones and less so for High Altitude Long Endurance (HALE) UAV's.

4.2 Acquisition

4.2.1 Retrofit onto existing aircraft

CNLA or CLAS may be retrofitted to operational aircraft on an ad-hoc basis although it is more likely that, for the following two reasons, such replacement would occur as part of a larger mid-life upgrade. Firstly it is almost certain that any system with different antennas would require recalibration. Secondly it would need to be demonstrated that the aircraft with the new antennas complies with airworthiness requirements. Both the recalibration and airworthiness assurance may be very expensive and time consuming processes. A sufficiently strong justification for such expense could probably only be made when the CNLA/CLAS replacement is one part of a larger package of performance/capability enhancements.

There are no specific plans to introduce CNLA or CLAS into ADF aircraft however potential candidates could include:

specified upgrades	C-130H replacement Radar Warning Receiver (RWR),
unspecified upgrades	AEW&C mid-life upgrade,

ADF wide programs	Projects Echidna ("Electronic warfare self protection for ADF aircraft", AIR 5416) or Bunyip ("Force level electronic warfare", DEF 224).

4.2.2 Fitted to future aircraft

Production of the Eurocopter Aussie Tiger is well underway with initial operational capability scheduled for 2008. This helicopter is fitted with conformal, probably non-load-bearing, VHF antenna in the tail.

Although a final decision has not been made, Australia is expected to acquire the F-35 JSF in the 2012-2015 timeframe. At least some of the antennas on the F-35 will be CLAS [8]. As a minimum the antennas on this, and any other LO/VLO aircraft or UAV that Australia may acquire, will be CNLA.

4.2.3 Suppliers

As detailed in Section A.4 there are a number of manufacturers that can supply CNLA and only Northrop Grumman claims to have a capability to produce CLAS.

Currently only a small number of organisations have experience, typically through R&D contracts with the US Departments of Defense (DoD), in the design, analysis, manufacture and test of CLAS. However there appears to be no technical reason why organisations with no such experience could not successfully develop them. This development requires close coordination between the airframe structures and antenna design teams. Difficulties are more likely to be encountered between, or within, organisations where there is insufficient interaction between the structures and antennas teams.

As a minimum, any CLAS supplier would require access to a manufacturer of composite aircraft structure. It is likely that specialist composite component manufacturers would need to partner with antenna suppliers in order to obtain the required expertise in antenna design and manufacture. It is likely that the prime aircraft manufacturers, such as Northrop Grumman, Lockheed Martin and Boeing, would have these capabilities in-house.

The production of CLAS has the potential to be a profitable business for Australian manufacturers. The market has yet to be established so there would be fewer restrictions on new entrants. The infrastructure requirements would be similar to that already in existence for the manufacture of other composite aircraft sub-components such as flight surfaces, doors and panels. These facilities would be substantially smaller than that required for the production of entire aircraft or even large aircraft components (wings, fuselage). CLAS parts are of a size that could be designed, analysed, tested, certified and manufactured within Australia then shipped to the user for installation. Although CLAS would be complex to design, it is expected that manufacture would be relatively straightforward once the appropriate tooling and processing were developed. The largest investment required would be to develop the expertise necessary for the analysis, design and process engineering.

4.3 Certification

Certification issues have been highlighted in this report because it will probably be expensive and time consuming, especially for the first few CLAS systems. It is the high cost of airworthiness certification that prevents many potentially beneficial technologies from being introduced to operational service. It is expected that airworthiness for CLAS will be demonstrated using the same approach as for any other structure or functional system – the airworthiness and electromagnetic performance requirements shall be demonstrated through a building block approach of analysis supported by test. Large numbers of simple tests will be conducted to provide data for predictive models. The models shall be applied, validated and refined using successively larger and more complex tests. The final proof-of-structure test will be performed on a full-scale CLAS (sub-)component.

If CLAS/CNLA is retrofitted to an existing aircraft then the functional system will probably need to be recalibrated. If CLAS/CNLA is being fitted to a new aircraft then, depending on the type of functional system, calibration may only need to be performed on one or two early production aircraft. The decision regarding whether to calibrate will be made by considering the type of functional system. Calibration for each individual aircraft may not be required for simple systems such as a voice communications radio but will certainly be required for more critical systems such as radar tracking arrays.

The major difference between CLAS and traditional airframe/antenna combinations is that with CLAS systems both the structural and electromagnetic T/R performance requirements will be evaluated on the same part. In contrast the load bearing capacity of the aircraft is established by examining the airframe structure while electromagnetic T/R performance is established by examining antenna behaviour. Certainly the airframe is examined to ensure that it does not interfere with the antenna and the antenna is examined to ensure that it has sufficient stiffness and strength, however by-and-large these systems are treated separately.

4.4 Operations

From the perspective of the operator the major difference between an aircraft fitted with conventional antennas and one fitted with CLAS/CNLA will be that aircraft performance will improve. It is also possible that there may be additional T/R capabilities. The CNLA/CLAS would interface with operators in the same way as the system with a conventional antenna, i.e. under normal circumstances no specific maintenance actions or intervention would be required.

The enhanced T/R performance or additional capabilities offered by CNLA/CLAS may provide the opportunity to (i) provide greater options in the way that existing operations are conducted, for example increasing the range of voice communications may allow ground support to be provided with a greater stand-off or increasing aircraft endurance will allow missions to be conducted at greater range, or (ii) perform missions that were previously not possible, for example installing low frequency foliage penetrating radar would allow aircraft to conduct Intelligence, Surveillance and Reconnaissance (ISR) missions over different types of terrain than currently possible.

4.5 Through-Life-Support

Although it is expected that CLAS/CNLA would be less likely to require repair/replacement than existing antenna systems, it is more likely that once required, any repairs would be more complicated than for airframes or antennas alone. CLAS/CNLA antennas will be an intimate part of the structure. As a minimum the ground support personnel at the squadron and depot level would require additional training to assess and repair damage to such structure.

It is possible that damage to CLAS/CNLA may be assessed with only a minimum of additional equipment. However, conducting repairs would require, as a minimum, a level of facility commensurate with that currently used to support composite aircraft structure or conduct composite bonded repairs. The dimensional tolerances for antenna become tighter as frequency increases. It is estimated to be in the order of multiple millimetres at VHF (30-300 MHz), millimetres at UHF (300 MHz - 3 GHz), hundred of microns at X-band (8 - 12 GHz) and tens of microns at Ku-band (12 - 18 GHz). It is quite possible that additional tooling would be required to maintain these tolerances during repair, particularly for higher frequencies.

As part of its through-life-support activities, it would appear necessary for the ADF to develop, or gain guaranteed access to, the capability to maintain and assure the tight tolerances necessary to retain LO/VLO and electromagnetic characteristics.

5. Conclusions

Conformal Load-Bearing Antenna Structure (CLAS) replaces aircraft antenna such as blades, wires and dishes with electromagnetic radiators that are embedded in the airframe structure. Relative to the current approach of mechanically fastening antennas to the airframe this approach reduces weight, drag and signature, and enhances electromagnetic performance, damage resistance and structural efficiency. However the design, manufacture, certification and through-life-support of CLAS will be more complex than for non-integrated airframes and antennas. The performance benefits of CLAS may be partially realised, but at lower cost and complexity, by using conformal non-load-bearing antenna (CNLA). The relative importance of each benefit and limitation must be evaluated on a case-by-case basis when assessing whether to retrofit CLAS/CNLA systems onto existing Australian Defence Force aircraft or to acquire these systems in new aircraft.

The state-of-the-art in CLAS technology was established by examining the literature, with a focus on United States Air Force research programs. CLAS demonstrators for Very High Frequency (UHF), Ultra High Frequency (UHF) and X-band communication applications have been successfully designed, analysed, manufactured and tested. Current programs include demonstrator X-band and UHF radars. CLAS will form part of the load-bearing airframe structure of the F-35 Joint Strike Fighter. It is predicted that the ongoing completion of demonstrator programs and the performance advantages likely to be realised by operational systems will lead to a gradual acceptance of this technology and an increase in the number of aircraft types containing CLAS in the ten year timeframe.

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7. References

1. Air Force Research Laboratory, "Transforming the future of warfare with unmanned air vehicles", AFRL Horizons Technical Articles Online, VA0209, September, 2002, http://www.afrlhorizons.com/Briefs/Sept02/VA0209.html
2. Ryall, T.G., Moses, R.W., Hopkins, M.A., Henderson, D., Zimcik, D.G. and Nitzsche, F., "Buffet load alleviation", NASA technical Report, NASA-99-2ACAM-TGR, 1999
3. National Aeronautics and Space Administration, "F-111 AFTI/MAW cockpit instrument left side panel", Project Description section of caption to DFRC Photo # EC86-33385-002, 29 March, 1988, http://www.dfrc.nasa.gov/Gallery/Photo/F-111AFTI/HTML/EC88-0052-4.html
4. Alt, K.H., Lockyer, A.J., Coughlin, D.P., Kudva, J.N. and Tuss, J., "Overview of the DoD's RF Multifunction Structure Aperture (MUSTRAP) program", SPIE Conference on Smart Structures and Materials, SPIE Volume 4334, Newport Beach, California, USA, 5 March 2001, pp. 137-146.
5. Baals, D. D., "Wind Tunnels of NASA", NASA SP 440, Chapter 5, http://www.hq.nasa.gov/office/pao/History/SP-440/ch5-4.htm
6. Lockyer, A.J., Alt, K.H., Kudva, J.N., Kinslow, R.W., M.D. and Goetz, A.C., "Conformal load-bearing antenna structures (CLAS): Initiative for multiple military and commercial applications", SPIE Conference on Smart Structures and Materials, SPIE Volume 3046, San Diego, California, USA, 4-6 March 1997, pp. 182-196.
7. High Performance Composites, "Lockheed Martin completes F-35 production facility", High Performance Composites Online Articles, July, 2004, http://www.compositesworld.com/hpc/issues/2004/July/499/1
8. Northrop Grumman, "Northrop Grumman's load bearing antennas offer airborne surveillance systems a better look at ground targets", Northrop Grumman Press Release, 11 March 2004, http://www.irconnect.com/noc/press/pages/news_releases.mhtml?d=53974

9. Johnson, P., "SensorCraft, From vision – to initiative – to program", AFRL presentation to Defense Planning and Analysis Society (DPAAS), 14 February, 2001, 17 pp,
http://www.dpaas.com/DPAAS%20Brief_14Feb01.pdf
10. Air Force Research Laboratory, "The SensorCraft challenge", AFRL Horizons Technical Articles Online, SN0312, June, 2004,
http://www.afrlhorizons.com/Briefs/Jun04/SN0312.html
11. Adams, C., "Breakthroughs in Military Sensors", Aviation Today, 1 May 2002.
12. News Breaks, Aviation Week and Space Technology, 24 July 2006, p. 20.
13. DARPA, "Integrated Sensor Is Structure", DARPA Microsystems Technology Office,
http://www.darpa.mil/sto/space/isis.html
14. Clark, T., "Integrated Sensor Is Structure (ISIS)", DARPS Special Projects Office, Program Briefing Presentation, 24 August 2005, 6 pp,
http://www.darpa.mil/sto/space/pdf/ISIS.pdf
15. Raytheon, "DARPA asks Raytheon to develop radar for "Integrated Sensor Is Structure" program, News Release, 8 August, 2006,
http://www.prnewswire.com/cgi-bin/micro_stories.pl?ACCT=910470&TICK=RTNB9&STORY=/www/story/08-08-2006/0004412233&EDATE=Aug+8,+2006
16. Northrop Grumman, "Northrop Grumman reaches milestone in development of embedded antennas", Northrop Grumman Press Release, 12 May 2004,
http://www.is.northropgrumman.com/media_news/2004_data/mn04_embedded_antenna.pdf
17. Northrop Grumman, "Northrop Grumman begins flight testing of new radar technology for Global Hawk", Northrop Grumman Press Release, 18 July 2006,
http://www.irconnect.com/noc/press/pages/news_releases.mhtml?d=102130
18. Northrop Grumman, "Northrop Grumman reveals first advanced Hawkeye fuselage", Northrop Grumman Press Release, 17 July 2006,
http://www.irconnect.com/noc/press/pages/news_releases.mhtml?d=102056
19. Northrop Grumman, "Northrop Grumman begins flight testing new radar antenna for B-2 stealth bomber", Northrop Grumman Press Release, 13 June 2006,
http://www.irconnect.com/noc/press/pages/news_releases.mhtml?d=100654
20. United States Department of Defense, "Multi-purpose antenna", SBIR N06-038, proposals due 13 January 2006,
http://www.acq.osd.mil/osbp/sbir/solicitations/sbir061/navy061.htm
21. United States Department of Defense, "Low cost conformal transmit/receive SATCOM antenna for military patrol aircraft", SBIR N06-117, proposals due 14 July 2006,
http://www.dodsbir.net/solicitation/sbir062/navy062.doc
22. Cheeseman, B.A., Jensen, R. and Hoppel, C., "Protecting the future force: Advanced materials and analysis enable robust composite armor", The AMPTIAC Quarterly, Vol. 8, No. 4, 21 March 2005, pp. 37-43,
http://ammtiac.alionscience.com/pdf/AMPQ8_4.pdf
23. Wetzel, E.D., "Reducing weight: Multifunctional composites integrate power, communications, and structure", The AMPTIAC Quarterly, Vol. 8, No. 4, 21 March 2005, pp. 91-95,
http://ammtiac.alionscience.com/pdf/AMPQ8_4.pdf

24. Walsh, S.M., Maher, M. and Advani, S., "Manufacturing a more affordable Army through low cost composites processing", The AMPTIAC Quarterly, Vol. 8, No. 4, 21 March 2005, pp. 44-48, http://ammtiac.alionscience.com/pdf/AMPQ8_4.pdf
25. Lockyer, A.J., Alt, K.H., Kudva, J.N. and Tuss, J., "Air vehicle integration issues and considerations for CLAS successful integration", SPIE Conference on Smart Structures and Materials, SPIE Volume 4332, Newport Beach, California, USA, 5 March 2001, pp. 48-59.
26. Lockyer, A.J., Alt, K.H., Coughlin, D.P., Durham, M.D., Kudva, J.N., Goetz, A.C. and Tuss, J., "Design and development of a conformal load-bearing smart-skin antenna: Overview of the AFRL Smart Skin Structures Technology Demonstration (S^3TD) program", SPIE Conference on Smart Structures and Materials, SPIE Volume 3674, Newport Beach, California, USA, 2 March 1999, pp. 410-424.
27. NASA, "Flight tests validate smart skin antenna", NASA Dryden News Release, 97-09, 7 March 1997, http://www.nasa.gov/centers/dryden/news/NewsReleases/1997/97-09_pf.html
28. S. Trimble, "Over the horizon", Flight International, 5 July 2005, http://www.flightglobal.com/Articles/2005/07/05/200103/Over+the+Horizon.html
29. Air Force Research Laboratory, "AFRL successfully tests SIXA antenna", AFRL Monthly Accomplishment Report – Executive Summary, Item 14, February, 2006, http://www.afrl.af.mil/accomprpt/feb06/accompfeb06.asp
30. McCarville, D.A., Herndon, G.F., Marshall IV, J.A., Vos, R.G. and Banks, D.L., "Design and fabrication methodology for a phased array antenna with integrated feed structure-conformal load-bearing concept", United States Patent Application US 2006/0097946 A1, 11 May 2006, 38 pp.
31. Air Force Research Laboratory, "Conformal array antenna technology", AFRL Horizons Technical Articles Online, SN0310, February, 2004, http://www.afrlhorizons.com/Briefs/Feb04/SN0310.html
32. Raytheon, "U.S. Air Force Research Laboratory exercises Raytheon's option to the X-band thin radar aperture contract", News Release, 25 January, 2005 http://www.prnewswire.com/cgi-bin/micro_stories.pl?ACCT=683934&TICK=RTN7&STORY=/www/story/01-25-2005/0002902142&EDATE=Jan+31,+2005
33. uavworld.com, "Stealthy UAVs make new material demands", Newsletter, January, 2004, http://www.uavworld.co.uk/newsletterjan2004.htm
34. Richardson, D., "Stealth – The combat 'ace'", Armada International, Issue 4, August/September 2003, http://www.armadainternational.com/03-4/article-full.cfm
35. Verpoorte, J., Schippers, H. and Voss, G., "Technology for conformal load-bearing antennas on aircraft structures", NLR-TP-2000-520, National Aerospace laboratory, October, 2000, 10 pp.
36. Schippers, H., van Tongeren, H., Verpoorte, J. and Voss, G., "Distortion of conformal antennas on aircraft structures", NLR-TP-2001-055, National Aerospace laboratory, 7 February, 2001, 14 pp.
37. Lockyer, A.J., Alt, K.H., Kudva, J.N., Kinslow, R.W., M.D. and Goetz, A.C., "Structural finite element modelling strategies for a conformal load bearing antenna structure

(CLAS) (Air Force Contract F33615-C-93-3200)", SPIE Conference on Smart Structures and Materials, SPIE Volume 3046, San Diego, California, USA, 4-6 March 1997, pp. 166-172.

38. Lockyer, A.J., Kudva, J.N., Alt, K.H., Goetz, A.C. and Tuss, J., "Development of a conformal load-carrying smart-skin antenna for military aircraft", SPIE Conference on Smart Structures and Materials, SPIE Volume 2448, San Diego, California, USA, 2-3 March 1995, pp. 53-62.
39. Lockyer, A.J., Kudva, J.N., Kane, D.M., Hill, B.P., Martin, C.A., Goetz, A.C. and Tuss, J., "A qualitative assessment of smart skins and avionic/structures integration", SPIE Conference on Smart Structures and Materials, SPIE Volume 2189, Orlando, Florida, USA, 14 February 1994, pp. 172-183.
40. Lockyer, A.J., Kudva, J.N., Coughlin, D.P., Alt, K.H., Martin, C.A., Durham, M.D., and Goetz, A.C., "Prototype testing and evaluation of a structurally integrated conformal antenna installation in the vertical tail of a military aircraft", SPIE Conference on Smart Structures and Materials, SPIE Volume 3046, San Diego, California, USA, 4-6 March 1997, pp. 173-181.
41. Alt, K.H., Lockyer, A.J., Martin, C.A., Kudva, J.N. and Goetz, A.C., "Application for smart skin technologies to the development of a conformal antenna installation in the vertical tail of a military aircraft", SPIE Conference on Smart Structures and Materials, SPIE Volume 2448, San Diego, California, USA, 2-3 March 1995, pp. 42-52.
42. Northrop Grumman, "Capabilities, Radio Systems, Antennas", http://www.ms.northropgrumman.com/NCD/antennas.html
43. Ball Aerospace, "Joint Strike Fighter, A leader in low observable (LO) antenna technology", Brochure, Ball Aerospace & Technologies Corp., 1600 Commerce Street, Boulder, Colorado, USA,
http://www.ballaerospace.com/pdf/jsf.pdf
44. Ball Aerospace, "Advanced antenna technologies", Brochure, Ball Aerospace & Technologies Corp., 1600 Commerce Street, Boulder, Colorado, USA,
http://www.ballaerospace.com/pdf/antennatech.pdf
45. You, C.S., Hwang, W., Park, H.C., Lee, R.M., and Park, W.S., "Microstrip antenna for SAR application with composite sandwich construction: surface-antenna-structure demonstration", Journal of Composite Materials, Vol. 37, No. 4, 2003, pp. 351-364.
46. Kim, C.K., Lee, L.M., Park, H.C., Hwang, W., and Park, W.S., "Impact damage and antenna performance of conformal load-bearing antenna structures", Smart Materials and Structures, Vol. 12, 2003, pp. 672-679.
47. Yoon, K.J., Kim, Y.B., Kim, Y.S., Lee, J.D., Park, H.C., Goo, N.S., and Lee, J.H., "Parametric study on compression deformation behaviour of conformal load-bearing smart skin antenna structure", Key Engineering Materials, Vols 261-263, 2004, pp. 663-668.
48. Kim, D.H., Hwang, W., Park, H.C. and Park, W.S., "Fatigue characteristics of composite antenna structure", Key Engineering Materials, Vols 261-263, 2004, pp. 1109-1114.
49. You, C.S., Hwang, W. and Eom, S.Y., "Design and fabrication of composite smart structures for communication, using structural resonance of radiated field", Smart Materials and Structures, Vol. 14, 2005, pp. 441-448.

50. You, C.S. and Hwang, W., "Design of load-bearing antenna structure by embedding technology of microstrip antenna in composite sandwich structure", Composite Structures, Vol. 71, 2005, pp. 378-382.
51. Kim, D.H., Hwang, W., Park, H.C. and Park, W.S., "Fatigue characteristics of a surface antenna structure designed for satellite communication", Journal of Reinforced Plastics and Composites, Vol. 24, No. 1, 2005, pp. 35-51.

Appendix A: Conformal Load Bearing Antenna Programs

A.1. Introduction

The ultimate goal of CLAS research is for operators to realise the benefits described in Section 3.2. Practical expressions of this outcome may be summarised by considering the following two paragraphs. The first is a description of the United States Air Force (USAF) SensorCraft program while the second is a magazine article reporting comments made at the 2006 Farnborough Air Show.

SensorCraft is the major USAF research program focused on developing the next generation ISR UAVs. It commenced in 1999 with plans to produce a prototype UAV around 2010 and initial production around 2020 [9]. SensorCraft, shown in Fig. A1, will be a subsonic (350 kt), high-altitude (60,000 ft) and long-range (>40 hours) UAV fitted with sensors that allow it to perform air-to-air and air-to-ground ISR missions across a wide range of the electromagnetic spectrum. Sensors will include foliage penetrating UHF radar operating at hundreds of MHz, tracking radars operating at 1-20 GHz and infrared/optical sensors. A technology that is critical for the SensorCraft to achieve its performance targets is CLAS. Integration will allow these sensor suites to become part of the wing rather than "parasitic" loads bolted onto the airframe [11].

At the 2006 Farnborough Air Show it was claimed that, "the next-generation unmanned combat aircraft are going to vary wildly from those proposed by Boeing (X-45), Lockheed Martin (Polecat) and Northrop Grumman (X-47)"…"the ability to build conformal active electronically scanned array radars and power them with small energy sources will allow unmanned combat aircraft to become the size of missiles. The reduction will make the UAV's harder to detect, thereby enabling them to get closer to critical targets to cripple them

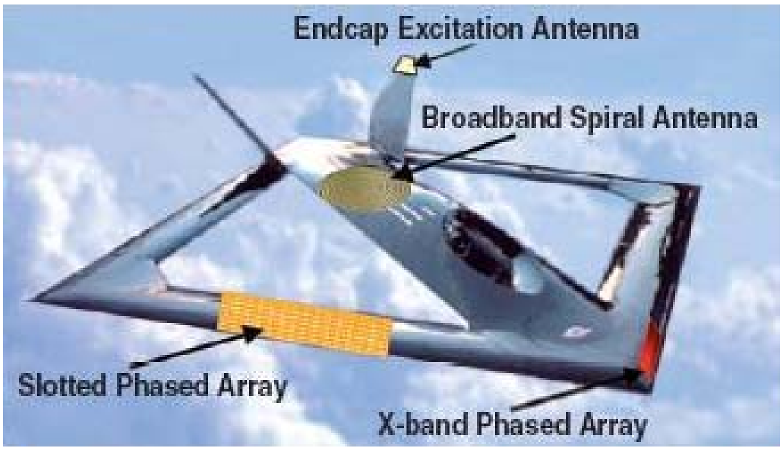


Figure A1: Artists impression of a SensorCraft UAV highlighting the structurally embedded antennas [10] with pulses of high-energy microwaves. The multifunction capability of the new, wraparound radars will ensure they can perform as sensor, precision targeting system and a directed energy weapon, so the small unmanned aircraft do not need to carry missiles or bombs." [12]

These two paragraphs describe some of the capabilities that are being developed, and may become operational, in the 2015-2020 timeframe. With the context of these long-term goals, the remainder of this Appendix provides a brief overview of some of the CLAS programs as detailed in the open-source literature.

This review is not comprehensive nor does it provide detailed technical information, however it should be sufficient for the reader to gain a broad understanding of the state-of-the-art and the key technical issues. It focuses on the programs funded by the US DoD because these have been the most widely publicised and because the author is currently on attachment to the Air Force Research Laboratory, affording him improved understanding of the context of the various USAF programs.

A.2. United States Department of Defense

The US has been publishing information regarding their CLAS programs since the early 1990's. Each of their military services, the Army (US Army), Navy (USN) and Air Force (USAF), have released information regarding their programs and long term goals. Brief outlines shall be given for the USN and US Army programs followed by a more detailed examination of the major USAF programs.

A.2.1 Defence Advanced Research Projects Agency

The majority of work conducted on CLAS has been funded by the Defence Advanced Research Projects Agency (DARPA), through their Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. Approximately one billion United States dollars (USD) per year of R&D is funded through these programs. Each SBIR/STTR project provides companies up to USD 85,000 to work on early stage R&D projects that serve DoD needs and have commercial applications. Each SBIR/STTR topic is managed by the relevant service laboratory; Air Force Research Laboratory (AFRL), Army Research Laboratory (ARL) and Office of Naval Research (ONR). The topics and calls for proposals are announced publicly every six months. It is instructive to search these proposal calls because the subject areas are consistent with the long term goals of the DoD. Also the type of work, whether it be theoretical modelling, producing a working prototype, characterising an operating system or reducing manufacturing costs, provides insights regarding the state-of-the-art in that topic.

DARPA also funds basic R&D programs to complement their SBIR and STTR projects. The major program of relevance to CLAS is currently the Integrated Sensor Is Structure (ISIS) program. The goal of ISIS is "to develop a stratospheric airship based autonomous unmanned sensor with years of persistence in surveillance and tracking of air and ground targets. It will have the capability to track the most advanced cruise missiles at 600 km and dismounted enemy combatants at 300 km." … "Extremely large lightweight phased-array radar antennas" will be "integrated into an airship platform. ISIS uses a large aperture instead of high power to meet radar performance requirements" [13]. Proposals were due in October 2005 and the program is scheduled for completion in 2011 [14]. In August 2006 it was announced that Raytheon had been contracted to develop the AESA for the 150 m x 300 m ISIS airship [15]. The extent to which the ISIS antenna will be load-bearing is unclear. It was stated the antenna would be bonded to the airframe, suggesting that it would not be load-bearing. It was also inferred that the stiffness of the antenna was so low that it could only perform when bonded to the hull. Regardless of the amount of load that the ISIS antenna will support, it is clear that the reduced weigh and mutual support associated with integrating/bonding this antenna to the airship will be a major factor in determining whether the ISIS airship will be able to achieve its stated goals.

A.2.2 USN

The USN operates a substantial range of aircraft types including fighters, ground attack, maritime patrol, surveillance and reconnaissance, tankers, rescue and transport. Many of these operate from ships, where weight and volume are at an absolute premium. In addition, shipboard aircraft must be able to withstand the rigours of landing and taking-off from moving decks, both of which impose major design constraints. The range of options available to enhance aircraft performance within these constraints is limited. For example the airframe weight of shipboard aircraft is greater than that required for flight alone. Removing some of this weight would increase speed, range and endurance but it would also degrade their ability to tolerate catapulted take-offs and arrested landings. One option for performance enhancement is the incorporation of MAS, including CLAS. It is possible that the severe design constraints placed on ship-based aircraft mean that the performance benefits offered by CLAS may be even more significant than for their land-based counterparts.

Despite the potential benefits of CLAS, very little information has been released in the public domain regarding USN funded CLAS programs. It is suspected that the sensitive nature of these programs is the reason for limited publication. Three programs have been identified and these are summarised in the following paragraphs.

In May 2004 Northrop Grumman announced that they had completed laboratory testing of a 1/5th scale model of an embedded antenna that could replace the satellite communications (Satcom) antenna in the E-2C Hawkeye [16]. It was claimed that the embedded antenna would reduce weight by 9 kg, reduce drag (thereby increasing time-on-station and single-engine rate-of-climb) and enhance overall flying qualities. This program was due for completion in December 2005, however no additional information has been found regarding progress. Although no announcements have been made that suggest this technology has been incorporated into operational aircraft, Northrop Grumman also manufacture antennas for the Global Hawk [17], E-2D Hawkeye [18] and B-2 [19]. It is possible that some of their CLAS capabilities, that will be outlined in Section A4.1, has been used in these programs.

Proposals for SBIR N06-038 "Multi-purpose antenna" [20] were due on 13 January 2006. No information regarding the funded program has been found. The aim of this program will be to "develop a multi-function antenna that can condense the current VHF/UHF line-of-sight, UHF satellite communication, L-band and global positioning system (GPS) functions into a single airborne aperture that can be used on a Navy aircraft like the E-2C". This program will attempt to address one of the key technical issues described in Section 3.2.2 – namely the ability for a single antenna to transmit and receive signals over a wide frequency range.

The most recent USN program will be conducted under SBIR N06-117 "Low cost conformal transmit/receive SATCOM antenna for military patrol aircraft" [21]. Proposals for this project were due on 14 July 2006 and at the time of writing this report no details regarding the funded project have been released. The aim of this program will be to "develop a low cost conformal satellite communication (SATCOM) transmit/receive antenna system that can operate at X, Ku and/or Ka band for military patrol aircraft" such as the P-3 or P-8A Multimission Maritime Aircraft (MMA). This work appears to be the continuation of a program that led to the new E-2C Satcom antenna described in the previous paragraph.

A.2.3 US Army

The goal of the US Army is to increase mobility, survivability and lethality, with a greater emphasis on foot soldiers and ground vehicles than aircraft. In support of the first two goals it supports R&D to minimise the weight and volume of functional systems. The modern soldier carries in the order of 50 kg of equipment and variations of even 1 kg can have significant effects on their combat performance. Such weight changes have less significant effect on ground vehicles such as a 3000 kg Humvee or 60,000 kg Abrams tank, although every kilogram of increased weight directly impinges on the speed and range of these vehicles.

The aims of US Army sponsored R&D on multifunctional structure are to minimise the weight of the heaviest systems; structure, armour and power supply. Consequently there has been less emphasis on CLAS. Significant weight loss has been demonstrated by incorporating armour into structure [22]. It is expected that further weight loss will be achieved by incorporating armour with structural batteries, structural fuel cells and structural capacitors [23].

Work on CLAS has focused more on increased durability, simplified manufacture, redundancy and increased coverage [23]. The major effort appears to be directed at solving the manufacturing issues related to incorporating antenna into glass fibre/ceramic structural armour [24].

A.2.4 USAF

The goals of USAF CLAS programs have been to (i) increase aircraft performance by simultaneously reducing weight, drag and signature and (ii) enhance T/R capability. The USAF has sponsored programs on the development of CLAS since at least the early 1990's. The most widely publicised programs have been managed by the Air Force Research Laboratory (AFRL). The two major completed programs are the Smart Skin Structures Technology Demonstrator (S^3TD) and RF Multifunction Structural Aperture (MUSTRAP) programs. Ongoing programs include the Low-Band Structural Array (LOBSTAR), Structurally Integrated X-Band Array (SIXA) and X-band Thin Radar Aperture (XTRA) programs. Technology from all of these programs will feed, either directly or indirectly, into the SensorCraft program outlined in Section A.1.

Smart Skin Structures Technology Demonstrator (S^3TD) Program

The first publicised CLAS program was S^3TD and it ran from 1993 to 1996. In the early stages of this program the key issues regarding CLAS were identified, examined and partially reported [25]. The topics were:

what would be the best location for CLAS?
how would these locations be altered by other airframe considerations?
what are the effect of electromagnetic interference and lightning?
what will be the costs of repair?

The culmination of the program was the design, manufacture and test of a demonstrator CLAS panel. The panel was 915 mm x 915 mm, of single curvature and constructed using the design shown in Fig. 1 [26]. It contained a centre-fed spiral antenna that operated from 225 to 400 MHz. It was claimed that the frequency range could be increased by adding additional spirals and using an end-feed.

This panel was tested by subjecting it to one lifetime of fatigue in combined axial and shear loading then conducting a residual strength test. Failure occurred, as-predicted, at 150 % DLL with principal strains of 4700 $\mu\varepsilon$ and running loads of 7.0 kN/cm of panel edge length in compression and 3.5 kN/cm of panel edge length in shear [4]. It is uncertain whether any test was made of the electromagnetic T/R performance of this antenna because no report has been found in the open literature.

RF Multifunction Structural Aperture (MUSTRAP)

The MUSTRAP program commenced in 1997 as a follow-on to the successful S^3TD program. It was claimed that a "multifunctional, broadband, structurally integrated, low cost antennas for communications, navigation, identification (CNI) and electronic warfare (EW) applications in the 0.03 to 2.0 GHz range" was developed [4]. Two demonstrators were produced, one was a fuselage panel that was mechanically tested while the other was an end cap for an F/A-18 that was flight tested.

The fuselage panel was 890 mm x 940 mm, single curvature and very similar to the design of the S^3TD demonstrator except for the following two aspects. These were that the:

radiating element was changed from Grade 1 electro-deposited copper foil to Grade 3 rolled annealed copper on Kapton sheet. The former was vulnerable to metal fatigue while the latter exhibited a far superior fatigue life.

design loads were a more realistic representation of those experienced by F/A-18 mid-fuselage panels. Failure occurred, after one lifetime of combined axial and shear fatigue loading, at running loads of 3.2 kN/cm of panel edge length in compression and 1.1 kN/cm of panel edge length in shear [4]. The MUSTRAP panel was of correspondingly lighter-weight construction that its S^3TD counterpart.

In the abstract for ref. [4] it was claimed that the electrical performance of this panel was "validated using anechoic chamber measurements" however no results were presented.

Perhaps the most significant output of the MUSTRAP program was its part in the development of a vertical-tail end-cap CLAS. The first of these VHF/UHF antennas was made under a previous program and was known as the Smart Skin Antenna. It was designed, manufactured, installed on the right hand (starboard) vertical fin of a NASA F/A-18 and flight tested in February 1997 [27]. Two views of the installed antenna are shown in Fig. A2. Tests were conducted at 33 and 65 MHz. At the lower frequency the signal-to-noise ratio for the end cap was 15-25 dB higher than that of the existing blade mounted antenna, sufficient to give a spectacular five fold increase in range. Part of the reason for this large increase was that the end cap was electrically connected to the conducting composite skin, in effect making the entire vertical tail an antenna.

The MUSTRAP end cap added a UHF capability to the Smart Skin Antenna by strategically placing a second feed on the existing radiator element. At least one MUSTRAP end cap was tested on the NASA F/A-18 at frequencies of 45, 120, 167, 270 and 380 MHz however no reports have been found regarding the results of this test.

Low Band Structural Array (LOBSTAR)
A joint Northrop Grumman/AFRL team successfully tested a load-bearing, 1000 mm x 1000 mm, four arm spiral antenna array in 1999 under the MUSTRAP program. Northrop Grumman funded further development under its SensorCraft Conformal Low-Band Antenna Structure (S-CLAS) program. A half-scale demonstrator of the array required for the SensorCraft was produced, at 7.6 m x 2.7 m and with 25 elements [28]. This 5x5 sub-array could not be tested electrically because of manufacturing complications.

(a) (b)

Figure A2: Photographs of the MUSTRAP end cap antenna fitted to the NASA F/A-18 Systems Research Aircraft. NASA photographs (a) EC97-43950-2, and (b) EC97-43958-1

The LOBSTAR program built on the S-CLAS concept. This USD 12 million, five year, collaboration between Northrop Grumman and AFRL commenced in 2004. The aim of LOBSTAR was to develop a low-frequency antenna array large enough to detect slow moving targets masked by heavy jungle foliage and incorporate this antenna into the primary wing structure of an aircraft [8], such as SensorCraft. This represented a major step because it was the first time that a CLAS concept had been considered in the initial design of a new aircraft, SensorCraft in this case. A major portion of the SensorCraft wings will be LOBSTAR arrays.

In the early part of the LOBSTAR program the electromagnetic performance of an S-CLAS array was measured and the lessons learned from this specimen will be incorporated into subsequent developments. The aim of the LOBSTAR program is to produce and test a full-scale fully bonded test specimen. The specimen will be representative of a SensorCraft wing, and contain a large array. It will be subjected to two lifetimes of fatigue loading under a generic ISR platform spectrum in a cold/dry environment then a residual strength test in a hot/ambient humidity environment. In addition, the RF performance of the antenna will be characterised prior to, and after, the fatigue testing. The demonstration will be considered successful if both the (i) RF performance does not degrade beyond the threshold due to the fatigue loading, and (ii) specimen supports DUL without catastrophic failure during the residual strength test. The program originally called for flight testing of a second specimen, but this plan has been withdrawn.

Structurally Integrated X-Band Array (SIXA)

The SIXA program is scheduled to run from 2003-2007 with the aim of structurally validating primary and secondary structural performance and to evaluate RF performance in an anechoic chamber. A sub-component level test was completed in February 2006 [29]. In this test part of the electronic sub-array was integrated into the skin of a 0.75 m x 3 m box type structural test specimen. As shown in Fig. A3, the box was loaded in four-point bending with the array located between the inner loading points. These inner loading points remained fixed while the actuators attached to each corner of the box moved. Loading the actuators independently subjected the array to combined in-plane axial and shear loading. This fixture was enclosed in a chamber so that fatigue loading could be conducted at non-ambient temperature. Finally, residual strength testing to failure was performed.

The design of the SIXA was different to the CLAS antennas that have been described previously. Instead of radiating elements being oriented parallel to the OML of the panel, the elements in the SIXA array were deposited onto the walls of a square section honeycomb core. In this way the radiating elements were oriented perpendicular to the OML, just as with traditional blade mounted dipole antennas. Figure A4 shows the concept for this type of structure. This figure was taken from a US patent describing how to manufacture a SIXA type of CLAS. The Boeing Company filed the Great Britain version of this patent and it is known that Boeing is one of the participants in the SIXA program [31].

An additional development demonstrated in the SIXA program was that the RF feed was transmitted to the individual elements via a layered structure bonded to the back face of the inner skin. This backing layer contained layers of conductors separated by insulators.

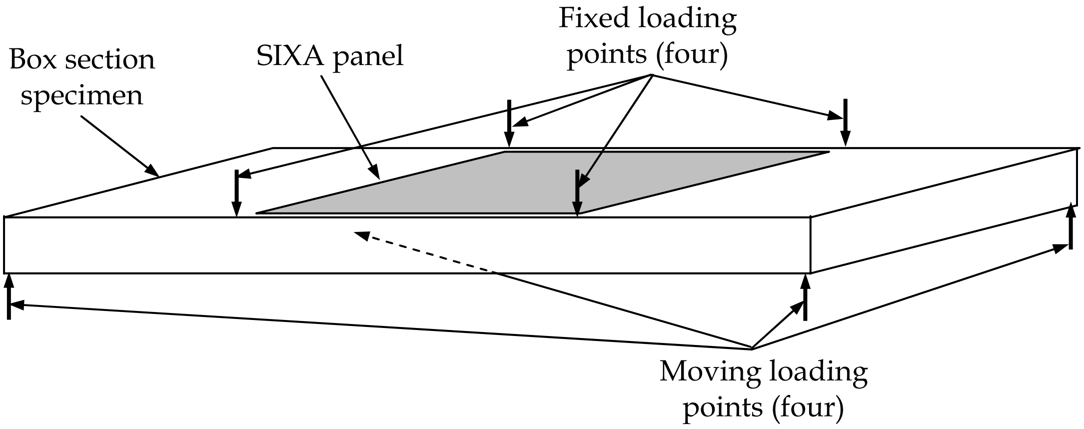


Figure A3: Diagrammatic representation of the method for subjecting the SIXA panel to combined axial and shear loading

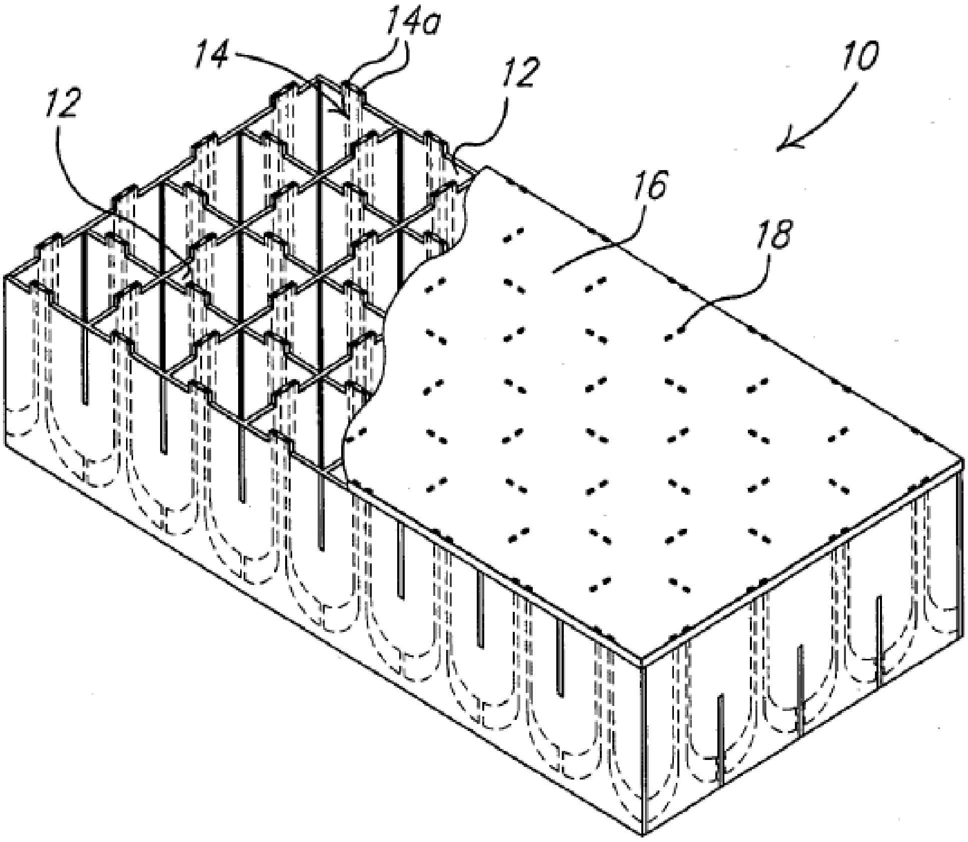


Figure A4: SIXA type concept where electromagnetic radiators (indicated by dashed lines) are deposited on the walls of honeycomb core [30]

Additional conductors oriented perpendicular to the conducting layers allowed signals to be transmitted between these layers and into the individual array elements.

X-band Thin Radar Aperture (XTRA)
In January 2005 Raytheon announced that it had been awarded a USD 4M contract to develop a very lightweight and thin radar antenna for the Joint Unmanned Combat Air System (J-UCAS) [32]. This follows on from an initial program awarded in April 2004. The XTRA was predicted to be lighter weight and lower cost than existing systems. However no additional information has been released regarding the XTRA program. The J-UCAS program was cancelled in early 2006 and it has been claimed that the USN and USAF have been directed to pursue independent UAV programs. Although no announcements have been made, it is possible that the development of XTRA will continued on one of the alternative UAV programs.

A.3. Europe

The European countries with major aerospace industries; France, Germany and the United Kingdom have released almost no information in the open literature regarding their CLAS programs. However for the following three reasons it is expected that many of these countries have strong programs. Firstly the potential benefits of CLAS technology would appear to justify substantial investment as it certainly has in the US. Secondly the occasional article or press release suggests that work is occurring [33, 34]. Finally, Holland, a relatively small European country has published at least two papers regarding work conducted in a national program. A summary of the information from the Dutch papers is given in the following paragraph.

The Netherlands Ministry of Defence funded the Conformal Load-Bearing Antennas on Aircraft Structures (CLAAS) program at least during 2000 and 2001. It contracted the Dutch National Aerospace Laboratory (NLR) to establish the effects of deformations and vibrations on the electromagnetic performance of conformal antenna arrays with an emphasis on phased arrays for synthetic aperture radar (SAR). Numerical modelling was conducted for conformal antenna mounted on the upper wing of an F-16 type aircraft [35] and a reconnaissance pod mounted on this aircraft [36]. It was concluded that the vibrations and deformations caused by aerodynamic loading (arising from gusts and manoeuvres) may have a significant influence on beamwidth and sidelobe level of an array and possibly an adverse effect on the performance of a SAR [35, 36]. The use of compensation techniques was reported as being a possible subject for future work. No reports regarding such compensation techniques have been identified.

A.4. Commercial

A.4.1 Northrop Grumman Corporation and TRW

Northrop Grumman (Integrated Systems, Hawthorne, California, USA) and TRW (Avionics Systems Division, Rancho Bernardo, San Diego, California, USA) have been the major contractors to AFRL on the S^{3}TD, MUSTRAP and LOBSTAR programs. This represents a continuous involvement of 14 years. Much of the design, development, manufacture and testing work for these programs have been conducted by these contractors.

The key elements of these programs were described in Section A2.4. In addition to the publications/news releases referred to in that Section [4, 6, 8, 25-27], the same AFRL/Northrop/TRW authors have published other conference papers on these CLAS programs [37-41] and the Northrop/TRW authors also hold a number of the patents identified in Section A.5. Collaboratively these organisations have conducted every phase of CLAS development from conceptualisation to flight test. They are possibly the world authority regarding CLAS technology, certainly they are the most widely published.

Northrop Grumman does advertise the capability to design and manufacture CLAS [42], and it has announced that it will use CLAS technology on the F-35 JSF [8]. It is possible that CLAS has been/or is scheduled to also be used on the Global Hawk, E-2D Hawkeye and B-2 programs identified in Section A.2.2, however no public announcement to this effect has been made.

A.4.2 Ball Aerospace

The Ball Aerospace company claim to have a long history of supplying low observable antenna. In refs [43, 44] it was stated that Ball Aerospace has, fully or in part, designed, developed, tested and manufactured the:

Harpoon missile altimeter introduced in 1975,
PAC-3 Missile RF Data Link,
Seasat array introduced in 1978,
Shuttle Radar Topography Mission (SRTM) completed in 2000,
Tactical Tomahawk Satellite Data Link (SDL) and Anti-Jam GPS receiver (AGR) antenna,
five element anti-jam CRPA GPS antenna for the Joint Air-To-Surface Standoff Missile (JASSM),
TACMS Block IA (1994) and Block II (1996) GPS antenna system for an Army air-to-ground missile,
UHF Satellite SATCOM Demand Assigned Multiple Access (DAMA) antenna for the B-2, and
Communications, Navigation and Identification (CNI) suite of integrated antennas for the F-35 JSF. The contract was awarded in 2002 and the final configuration will include a suite of 15 UHF SATCOM and line-of-sight L-band, S-band and C-band antennas, some of which are shown in Fig. A5.

The photographs from ref [43], as expected, showed all LO antenna as conformal, while one section of ref [44] focused on conformal antenna. Clearly Ball Aerospace has significant experience in the production of conformal antenna however it is unlikely that any of the antennas cited in refs [43] and [44] were load bearing. This conclusion was made because in the competitive marketplace of military antenna systems a capability to provide CLAS, rather than just CNLA, would almost certainly be advertised.

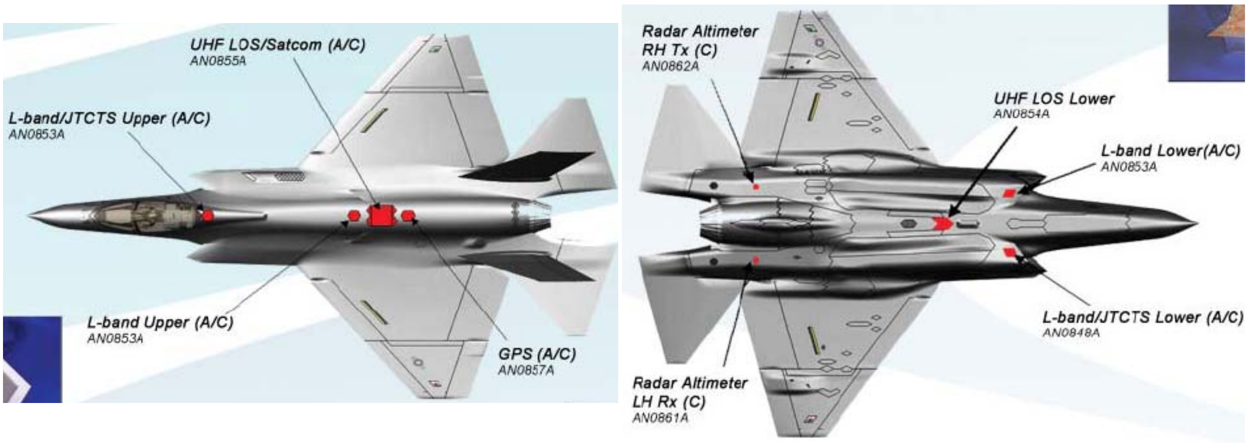


Figure: A5: Diagrams from ref. [43] showing the location of conformal antennas on the F-35 JSF that are being supplied by Ball Aerospace

A.5. Patents

A moderate number of patents regarding the design and manufacture of CLAS have been filed. Those listed in Table A.1 were identified in a short search. It is quite likely that a more thorough search would reveal more. It is instructive to note that most of the organisations holding these patents are the major aerospace manufacturers identified in Section A.2. as collaborative partners on US DoD programs. There appears to be a much larger number of CNLA patents, a brief selection of which are indicated in Table A.2. The progression of this technology may be inferred by the observation that most of these patents were filed prior to the CLAS patents shown in Table A.1.

A.6. Universities

A.6.1 Pohang University of Science and Technology

Apart from the USAF programs described in Section A2.4, the major contributors to the CLAS literature have been researchers from the Pohang University of Science Technology (Department of Mechanical Engineering, Pohang, Republic of Korea). Since 2000 they have published at least seven papers [45-51]. Their main focus has been to characterise the mechanical and electromagnetic behaviour of their CLAS designs. As shown in Fig. A.6, these designs are variations on the bonded honeycomb construction that was described in Section 3.1. The inner skin supported structural loads, outer skin was a RF transparent window and internal layers supported the skins, antenna radiator and antenna feed. The separation distance between these layers was determined with consideration to both the mechanical and electromagnetic effects. Both single element antennas and antenna arrays have been manufactured and tested.

Most of their designs used aperture coupling, as shown in Fig. A6 (b), to feed the antenna. In this arrangement the radiating patch was not directly connected to the feed-line, but rather the feed-line directed electromagnetic signals into/from an aperture, typically a slot, in a lower

Table A.1 Selected patents for CLAS type antennas

Title	Company	Patent	Date
Design and fabrication methodology for a phased array concept with integrated feed structure-conformal load-bearing concept	The Boeing Co.	US2006097946(A1) GB2419468(A)	26 Apr 06
Antenna assembly for aircraft window opening	Northrop Grumman Corp.	EP1575128(A1) US 005200526(A1) JP2005260931(A) CA2498990(A1)	14 Sep 05
Structurally-integrated, space-fed phased array antenna system for use on an aircraft	The Boeing Co.	WO03058753(A3) US6714163(B2) US2003117327(A1) AU2002365097(A1)	17 Jul 03
Conformal load bearing antenna structure	Northrop Grumman Corp.	WO0148863(A1) US6198445(B1) EP1261997(A0)	7 May 01
Structural end-cap antenna	Northrop Grumman Corp.	US6175336(B1)	16 Jan 01
A dual-feed system for a multifunction, conformal, load-bearing structure excitation antenna	TRW Inc.	EP1022802 US6198446(B1)	26 Jul 00
A conformal load-bearing antenna system that excites aircraft structure	TRW Inc.	EP0996191(A2) US6097343(A1) JP2000151246(A) EP0996191(A3)	26 Apr 00
Multifunction structurally integrated VHF/UHF aircraft antenna system	TRW Inc.	US5825332 EP0829918(A2) JP10126130(A) RU2134002(C1)	20 Oct 98
Aircraft antenna arrays	Grumman Aerospace Corp.	GB2271470(A) US5405107(A1) FR2696988(A1) DE4330736(A1)	13 Apr 94
Radar system for determining angular position utilizing a liner phased array	Grumman Aerospace Corp.	WO9006003 EP0396668(A1) US4912477(A1) CA1337569	31 May 90

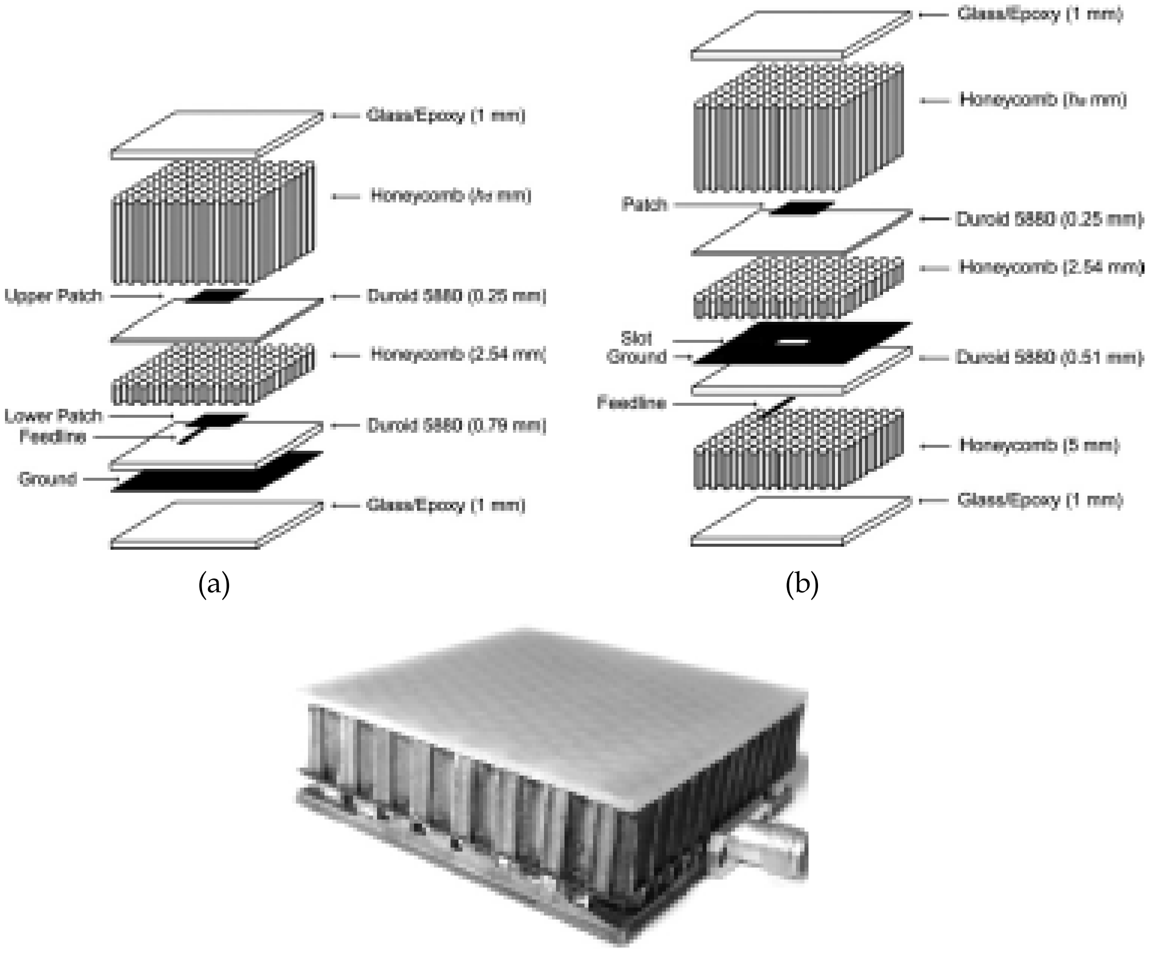
layer of the antenna assembly. The radiating patch was located closer to the OML of the antenna and the radiation from the aperture coupled with this patch to produce the desired pattern. Aperture coupling is well known by antenna designers because it increases the bandwidth of microstrip antenna by an order of magnitude (from <3 % to >20 %). The drawback is that significant radiation is emitted in the back-direction, however this may be

Table A.2 Selected patents for conformal non-load-bearing antenna for aircraft

Title	Company	Patent	Date
Lightweight patch radiator antenna	Raytheon Co.	EP0596618(A2)	14 Oct 03
Microwave antenna integrated into an artillery projectile	TDA Armements SAS (France)	EP1296409	26 Mar 03
Antenna array apparatus with conformal mounting structure	Composite Optics Inc. and Science & Appl. Technology Inc.	WO02087009(A1) EP1382085(A1) US6407711(B1)	31 Oct 02
Structure antenna for flying devices and aircrafts	EADS Deutschland Gmbh (De)	EP1204158(A2) DE10151288(A1)	5 Aug 02
A conformal phased array antenna	Roke Manor Research Ltd	EP1271694(A2)	14 Jun 02
Conformable, integrated antenna structure providing multiple radiating apertures	McDonnell Douglas Corp.	US6121936	19 Sep00
Flush mounted antenna	Raytheon Co.	EP0402005(A2)	23 Apr 90
Microstrip antenna with parasitic elements	Raytheon Co.	EP0391634(B1)	2 Apr 90
External pod with an integrated antenna system that electromagnetically excites aircraft structure, and a related method for its use	TRW Inc.	EP0997969(A2) US6094171(A1) JP2000134022(A)	22 Oct 99
Two-frequency shared antenna	Nippon Electric Co.	JP8186437	16 Jul 96
Low VSWR, flush-mounted, adaptive array antenna	Harris Corp.	US4675685	23 Jun 87
Circularly polarized hemispheric coverage flush antenna	Harris Corp.	US4431998 WO8103398(A1) EP0051671(A1) GB2089580(A)	14 Feb 84
Thin conformal antenna array for microwave power conversion	NASA	US4079268	14 Mar 78

absorbed by locating a conducting plane one half wavelength behind the slot. Aperture coupling may prove to be a useful technique to feed other CLAS antenna.

The specimens manufactured and tested by the Pohang University team have been at the design detail level, a few tens of centimetres in length and width, and a few centimetres thick. The properties that have been reported include (i) flexural strength under static and fatigue loading, (ii) radiation pattern, (iii) behaviour under axial compression, and (iv) antenna performance after impact damage. While they have not produced or tested any large CLAS specimens, their publications are valuable because they have tested important mechanical properties and provided more details regarding their work than the reports from other CLAS programs.



(a) (b)

(c)

Figure A6: CLAS concepts and test specimens from ref. [45]. (a) Direct-fed stacked patch antenna (b) aperture-coupled patch antenna, (c) photograph of a fabricated direct-fed stacked patch antenna

A.6.2 Other

In addition to the Pohang University work, a modest number of publications in the scientific literature have been identified as referring to CLAS development. These typically refer to one element of a total CLAS system and shall not be detailed here. They support the conclusion that the capability to design and manufacture CLAS exists at a research level. The next step is to bring this into the prototype environment and then onto production.

Journals such as Electronics Letters, Institute of Electrical and Electronic Engineers, Inc. (IEEE) Antennas and Propagation Magazine, IEEE Transactions of Antennas and Propagation, IEEE Transactions on Microwave theory and Technique, IEEE Antennas and Propagation Letters, Microwave Journal and Microwave Review abound with publications describing the design, manufacture and testing of antennas. These publications tend to be written by workers from a wide range of universities, typically from electrical or communications engineering departments, and companies, typically antenna manufacturers. The work may be broadly classified as antenna development and it describes the techniques that have been used to produce antennas with a particular desired performance (radiation pattern, type of polarisation, bandwidth, cross-polarisation behaviour, side lobe level, etc.) within the constraints of the particular system being considered (limited size, limited power, type of design software, limited time for design, etc.). It is reasonable to conclude that for many CLAS applications, an antenna concept will have been published that provides an acceptable concept from which a specific design may be based.

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19. ABSTRACT

Conformal Load-Bearing Antenna Structure (CLAS) replaces separate aircraft structure and antennas such as blades, wires and dishes, with electromagnetic radiators embedded in the structure. This approach reduces weight, drag and signature, and enhances electromagnetic performance, damage resistance and structural efficiency. However the design, manufacture, certification and through-life-support of CLAS are more complex than for its non-integrated counterparts. The first half of this report describes the advantages and limitations of CLAS and the factors to be considered when deciding whether to incorporate CLAS into Australian Defence Force aircraft.

The second half of this report describes the state-of-the-art in CLAS technology through a review of the open-source literature. It focuses on United States Air Force CLAS programs where demonstrators for Very High Frequency/Ultra High Frequency (VHF/UHF) and X-band communication applications have been successfully designed, analysed, manufactured and tested. Current programs include demonstrator X-band and UHF radars. CLAS will form part of the load-bearing airframe structure of the F-35 Joint Strike Fighter. It is predicted that the ongoing completion of demonstrator programs and the performance advantages likely to be realised by operational systems will lead to a gradual acceptance of this technology and an increase in the number of aircraft types containing CLAS in the ten year timeframe.