PAPER Nr.: 86

ELECTRICAL CONNECTIONS AND ANTENNA PERFORMANCE OF A LARGE COMPOSITE FUSELAGE MODULE IN THE HIGH FREQUENCY RANGE

BY

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AUGUST 28 – 31, 1984 – THE HAGUE, THE NETHERLANDS

ABSTRACT

MAJOR AIRFRAME CONSTRUCTION in carbon fibre composite (c.f.c.) materials presents many problems from an electrical view point i.e. direct and low frequency current returns, antenna performance, shielding effeciency and lightning strike tolerance. These characteristics are not so troublesome on airframes of metal skin and stringer construction but the trend towards c.f.c. introduces a resistive fibre within an insulating resin. This in turn, gives rise to a number of fabrication problems, many of which are governed by the electrical requirements of panel joints and general electrical connections.

A representative cabin module, 2m long x 2.8m wide x 2.1m high manufactured entirely of c.f.c. was produced and designated the Advanced Technology Fuselage (A.T.F.) and within the constraints of the programme the following was investigated.

1. Antenna performance in the H.F. Range of 2-30 MHz. including the necessary ground plane continuity across various panel joints. This is an area where very little information is available due to problems predicted by the use of carbon composite.

2. Electrical homogeneity of d.c. current flow by thermal imaging and potential plotting techniques.

In order to examine the above areas a certain amount of preliminary work of an exploratory nature was required and was conducted in parallel with the construction of the A.T.F.

1. A range of methods was assessed, aimed at producing an electrically conductive joint to connect the outer skins of the honeycomb fuselage panels. Low r.f. impdenace joints are necessary for any fuselage to perform as an antenna ground plane. At the other end of the scale, lightning currents of up to 200,000 Amp. The selected jointing technique was assessed by potential and thermal mapping, details of which are given.

2. A further significant problem was the production of a low impedance conneciton between the carbon fibres of the fuselage panel and the H.F. monopole antenna base. Using the general principles evolved during the above joint investigations a method is presented here which makes a metal to fibre contact of 200 mΩ/sq.cm. (31 mΩ/sq.in). This value is comparable to that presently being achieved on production light-alloy aircraft. Patent protection is being considered.

High frequency tests were conducted and compared with a light-alloy structure of identical dimensions for a reference. The results of this trial are presented.

## 1. INTRODUCTION

THE MECHANICAL PROPERTIES and production advantages of carbon fibre composite (c.f.c.) have resulted in Westland actively persuing its use for primary structures at judicious locations on certain aircraft. To obtain information that would provide constructional and performance data for electrical designers a thorough review of published material was undertaken. A certain amount of work of an inestigatory nature has been undertaken by various authorities on the performance of antennas mountd on carbon fibre materials in the frequency ranges above 100 MHz, but only a small amount of work below this frequency (Ref 1).

A c.f.c. structure designated the Advanced Technology Fuselage (A.T.F.) suitable for undertaking these tests was constructured. Comparative measurements were undertaken with an H.F. antenna fitted to an equivalent metal structure and subsequently onto the A.T.F. The aim was to compare impedance results of the two sets of measurements to aid in determining how H.F. performance was affected by a carbon composite ground plane.

Prior to commencing this trial it was necessary to develop a continuous, low impedance joint between each fuselage panel to form the ground plane, in addition to a low impedance connection between the monopole plinth base and the fuselage.

## 2. THE CARBON STRUCTURE (A.T.F.)

This structure, proportioned to represent the centre section of a large aircraft, consisted of three carbon lift frames forming two bays clad with 4 ply c.f.c. skin/nomex paper honeycomb panels adhesively bonded to the carbon frames with anti-peel fasteners set in anodised aluminium 'bucket' washers located at 250mm intervals along all edges. The 4 ply skins were of 0.5mm (0.020 inch) thick carbon with an additional woven glass surfacing layer. This open-ended structure was 2.1m high, 2.8m wide and 2m long although for the H.F. radio trial reported here, the upper surface was extended a further 2m to accommodate the full length of the antenna load wire (see section 9.1 for figure).

## 3. OBJECTIVES

Before the H.F. performance of this structure could be examined, two distinct problem areas had to be overcome:-

3.1. Develop a Panel Jointing Method: A continuous, low impedance electrical connection was required at each panel joint. Ideally this method would contact all of the fibres.

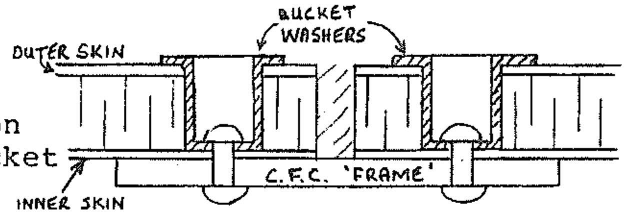
3.2. Antenna Mounting: A connection of less than 2 milli-ohm resistance is required between the antenna base and the fuselage skin. This can be achieved on metal skinned structure but the fibrous nature of composite presented difficulties for commercial conductive gaskets.

These investigation areas will now be discussed.

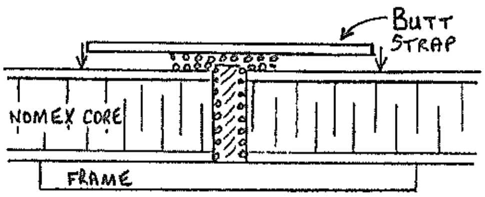
## 4. FUSELAGE PANEL JOINTING - METHODS EXAMINED

This phase of work concentrated on connecting onto all the fibre ends visible in the gap between the panel edges, the advantage of this being that the glass surfacing layer (scrim) could remain and so reduce production costs.

4.1. Represented the basic AFF construction to determine any conduction via the fasteners. Bucket washers set in epoxy adhesive.

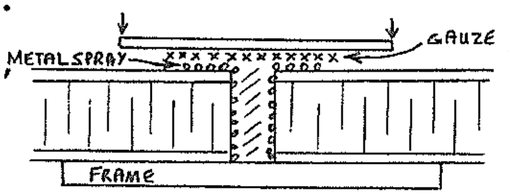



4.2. Aluminium flame spray end of panels prior to caulking the gap (non-conductor). Aluminium sprayed to bridge the joint

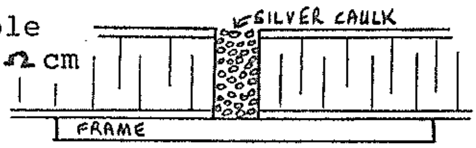



4.3. Identical to method 4.2. accept that a c.f.c. butt strap was co-cured* across the metal bridge to assist conduction.

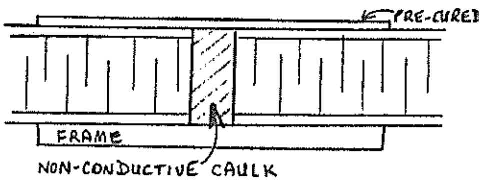
4.4. Aluminium sprayed end faces, bridged with very fine phosphor bronze gauze. Co-cured carbon butt strap.




4.5. Gap caulked with semi-flexible silver loaded caulk of 0.018Ω cm resistivity.

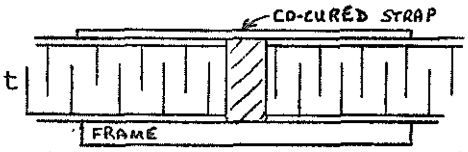



4.6. Glass scrim omitted. To determine if curing pressures could force the butt strap and skin fibres into contact.



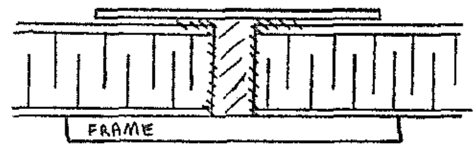

* Co-cured: Application of uncured prepreg materials with no adhesive layer present. Bond strength derived from resin present in prepreg.

4.7. Identical to 4.6 but the butt strap was co-cured. Skins not abraded.



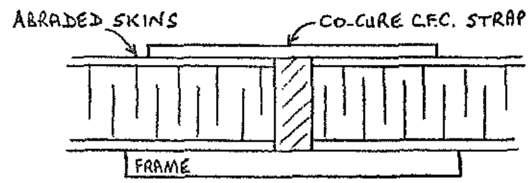

4.8. Panel edges electroless copper plated and gap bridged with very fine stainless gauze.


4.9. Panel edge electroless copper plated and butt strap co-cured. Plating slightly inferior to Method 4.8.




All the above methods aim to contact the skin edge. It was clearly unsuccessful so skin 'face' contact was investigated.

4.10. Skin abraded to expose carbon fibres and all carbon pre-preg butt strap was co-cured at a pressure of 2.75 bar (40 lb/sq. inch).




## 5. RESULTS AND DISCUSSION OF PANEL JOINTS

| Method | Resistance ($\Omega$/m of joint) | Conductivity (siemens/m) |
|---|---|---|
| 1 | Open circuit | 0 |
| 2 | 0.55 | 1.8 |
| 3 | 2.44 | 0.41 |
| 4 | 0.56 | 1.77 |
| 5 | 6.18 | 0.16 |
| 6 | Open circuit | 0 |
| 7 | 1.83 | 0.54 |
| 8 | 0.04 | 21 |
| 9 | 0.17 | 5.63 |
| 10 | $<$0.01 | $>$100 |

The above table illustrates how effective the glass scrim and cured surface resins were at preventing electrical continuity. The adhesive layer was equally effective. These non-conductors restricted any electrical contact to a narrow 0.5 mm wide strip, being the machined skin edge. Despite the variety of shorting straps and skin connection materials the joint remained excessively resistive except for method 4.10 which gave an excellent result and showed clearly that contact must be made on the skin face - this assumes that all the composite plies that comprise the skin are well consolidated with good interlaminar contact. Due to programme restrictions there was insufficient time to develop this to include the inner skin of the sandwich construction so the H.F. trial was effectively conducted on the outer skin only.

## 6. MOUNTING THE ANTENNA MONOPOLE

The objective of this phase was to produce a low impedance connection between the monopole base and the carbon skin, an area of 290mm x 83mm (11.4" x 3.3"). A resistance of 1 milli-ohm was aimed for but experience with metal aircraft has shown that the system under test here, Collins 718U-5, will operate satisfactorily with 2.5mΩ.

An interfacing conductive gasket is used on metal aircraft, either of woven aluminium mesh contained in an elastomer, or silicone rubber containing metal filaments aligned to be perpendicular to the gasket faces. Samples of these were evaluated on c.f.c. and were found ineffective. Interfacings of expanded aluminium mesh, copper electroplating and metal sprays did not produce a sufficiently low resistance contact with the c.f.c. whereas co-curing of a metal shim onto a precured test panel, using one ply of carbon prepreg, did produce a very encouraging low resistance connection.

### 6.1. MOUNTING METHODS EXAMINED

Due to the success of the co-cured specimen, further work was initiated to exploit this technique which included:

1. Determination of c.f.c. - shim contact resistance.
2. Reduction of contact resistance.
3. Enhanced conductivity composite.
4. Antenna mounting specimen.

All test panel work was on 102mm x 102mm (4" x 4") square specimens.

#### 6.1.1. Determination of Contact Resistance

A panel was constructed by curing 1 ply of c.f.c. between two smooth nickel-plated brass shims. Of the 11.9 mΩ resistance measured, 0.186mΩ was bulk c.f.c. resistance so the shim to carbon contact resistance was 5.86mΩ per shim (shim resistance negligible).

#### 6.1.2. Reduction of Contact Resistance

Contact resistance was found to be reduced by impressing 0.05mm (0.002 inch) high dimples, or bumps, into the shim at a nominal 2.5mm (0.1") spacing. A panel, identical to that in 6.1.1. except for the use of dimpled shim, produced a resistance of 6.7 mΩ showing that the contact resistance was virtually halved to 3.26 mΩ.

6.1.3. Enhanced Conductivity Composite

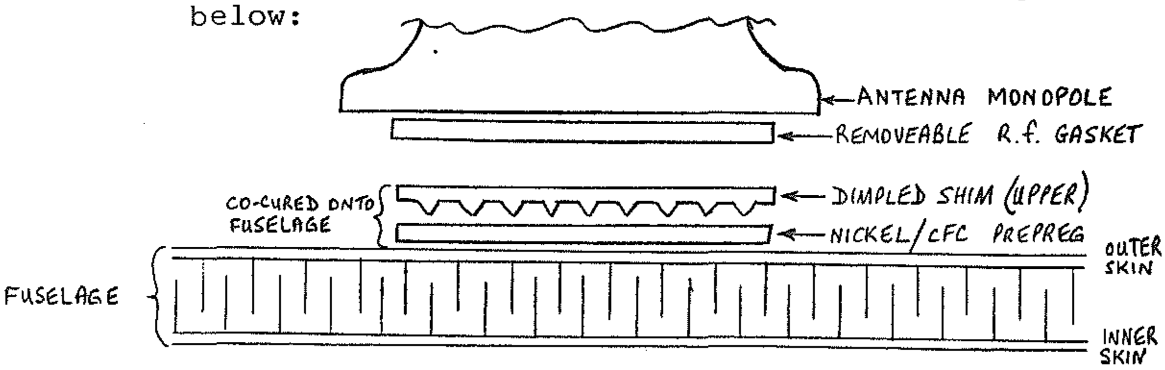
To futher reduce the resistance the c.f.c. prepreg was replaced by a nickel plated carbon fibre prepreg. Using this fibre and the dimpled shim, panel tests produced a shim to shim resistance of 0.7 mΩ.

Comparison of these three methods showed the dramatic benefits that can be achieved through the use of dimpled shim and nickel plated fibre:

| | |
|---|---|
| Plain flat shim and carbon fibre | 11.9 mΩ |
| Dimpled shim and carbon fibre | 6.7 mΩ |
| Dimpled shim and nickel/carbon fibre | 0.7 mΩ |

6.1.4. Antenna Mounting Specimen

To evaluate the latter, panels were made with a lay-up equivalent to that proposed for the actual antenna mounting and shown in figure below:




PROPOSED ANTENNA MOUNTING SEQUENCE.

Due to the well known difficulty in making contact with cured c.f.c., the fuselage skin was represented by one ply of c.f.c. co-cured onto a dimpled (lower) shim: contact and carbon 'through thickness' resistance were known i.e. 3.26 and 0.186 mΩ.

The cured c.f.c. was abraded and one ply of nickel plated fibre pre-preg and dimpled shim was co-cured onto it. From the value of 5.4 mΩ recorded between the shims, the resistance of the 'pseudo skin' must be subtracted i.e. 5.4. - (3.26 + 0.186) = 1.95 mΩ which is the connection resistance of the upper shim to the composite skin.

## 7. MOUNTING MONOPOLE TO CARBON STRUCTURE

The very low resistance of 1.95 mΩ measured on the square test panels can be extrapolated to the dimensions of the monopole base to give a resistance of only 0.73 mΩ (Ref 2). In effect, what has been achieved here is the conversion from antenna mounting onto composite into mounting onto metal which can now proceed with well established knowledge and techniques. A proprietary r.f. gasket can now be clamped beneath the monopole to given an OVERALL connection resistance or bond of 1.73 mΩ which is comparable with bonds achieved on metal aircraft.

One final unknown did in fact remain however, this being the possibility of heat degrading the composite in the monopole area due to heavy r.f. currents concentrated in a small area of resistive fibre. To examine this the shim area was extended to 406mm x 710mm (16" x 28") to reduce the power intensity with the intention of incrementally reducing this area till a minimum acceptable dimension was found. Unfortunately, due to other programme requirements this work was not done.

## 8. CURRENT FLOW IN STRUCUTURE

Direct current was injected into the side wall of the ATF in such a way that it was required to flow through the central joint. Voltage mapping of the basic structure showed highly concentrated areas of conduction around certain fasteners but with the application of the co-cured butt strap the distribution was more even. This result was substantiated by scanning the structure with thermal imaging equipment with both d.c. and h.f. currents flowing.

## 9. RADIO TRIALS

### 9.1. THE H.F. SYSTEM

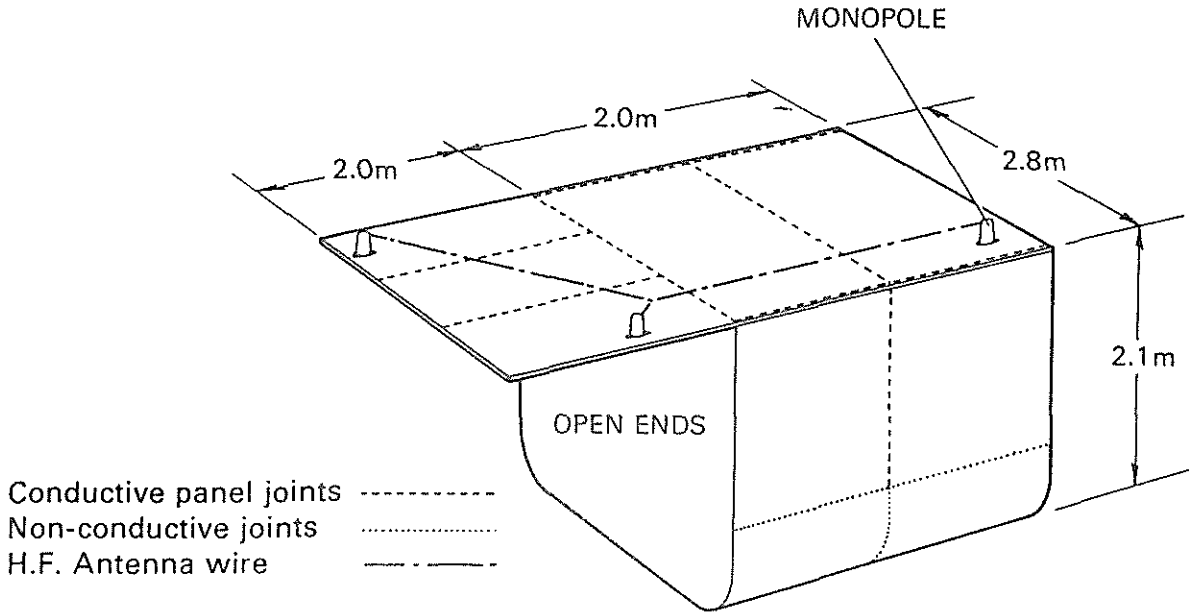
The H.F. system used for antenna tests was a Collins 718U-5 consisting of:

| UNIT | TYPE NUMBER |
|---|---|
| Blade Antenna | 437R-2 |
| Load Wire Single Core | Chelton Pt No. 5048 |

This system operated in the frequency range 2 Mhz - 30 Mhz.

So as to keep the antenna installation simple the antenna top loading wire was made 14 feet long, thus not requiring an end load unit.

Because the extension panels to the ATF were a standard length, it was not possible to provide a straight 14 feet run and so the wire was angled across both metal and composite structures.

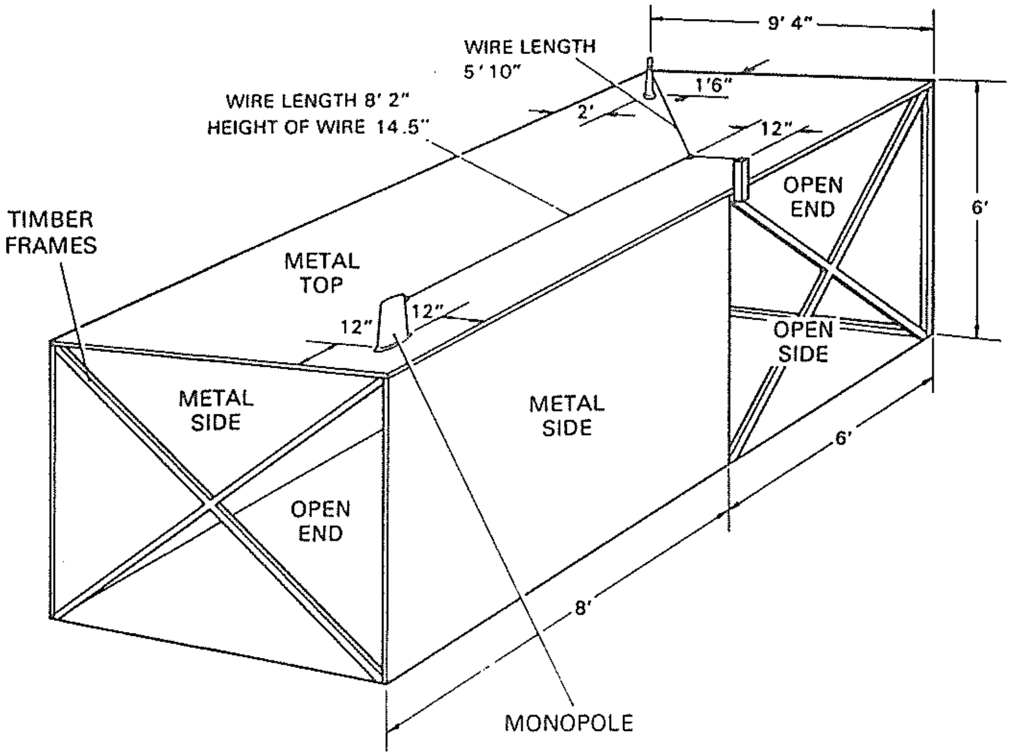



## 9.2. METAL STRUCTURE

The metal structure was a timber framed aluminium clad open ended box with an effective ground plane size of 9 ft 4 ins x 14 feet. The bonding of the 18 gauge 6 ft x 3 ft untreated aluminium panels was carried out by overlapping them at the timber frame supports and fixing them firmly to the supports with screws.

The blade antenna was mounted vertically near one corner with the aid of a stiffening plate and the top loading wire was run 14.5 inches above the ground plane to a stand off mast mounted on the opposite corner to give a total length, when angled, of 14 feet.

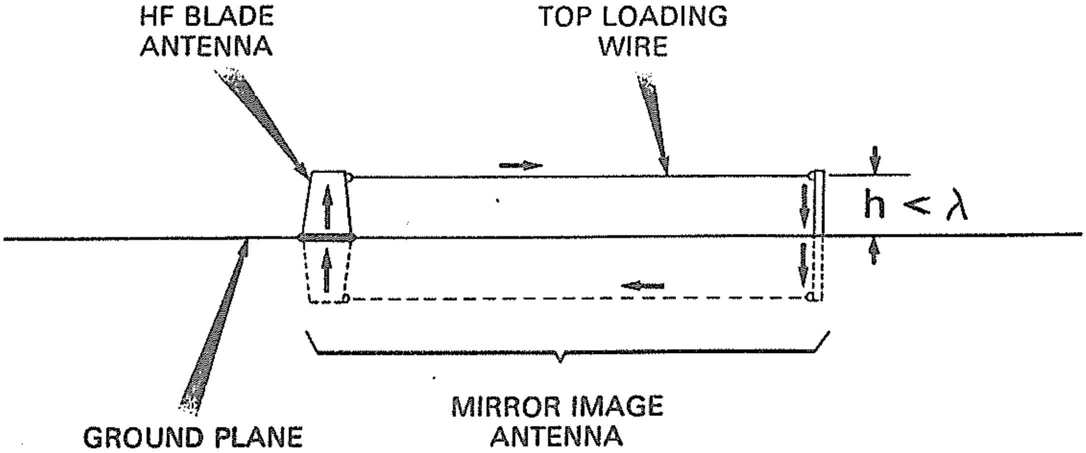
The bonding standard was checked using d.c. measurement techniques: the antenna bonding connection to the ground plane was of the order of 1 m ohm.




## 9.3. H.F. MEASUREMENTS

### 9.3.1. METHOD

The figure below shows the simplified current distribution of a H.F. antenna system mounted on a perfectly conducting ground plane. Assuming a perfectly conducting ground plane the reflection characteristics may be represented by a mirror image set up in the ground plane with current distribution simplified as shown.



Thus the impedance of this system would be that of an open circuit resonant transmission line of 29 ins spacing, using single core 0.051 inch diameter cable.

The impedance of an open circuit transmission line when measured at the sending end can be represented mathematically by hyperbolic trigonometrical functions and under practical conditions where losses are small, i.e. R.F. wire resistance etc, these can be simplified considerably. However, in this particular case it is the losses of the ground plane material we wish to determine and consequently they cannot be ignored. Because the mathematical analysis including losses would be complex it is not proposed to deal with the subject mathematically, but basically to compare results of both sets of tests and arrive at a general conclusion.

The H.F. antenna was mounted onto the metal ground plane and the A.T.F. in turn and measurements of the antenna impedance were made using the following equipment:

Vector Impedance Meter, Hewlett Packard Type 4815A
Probe Model 04814-60010

Measurements were made with the metal ground plane inside the Avionics Hangar at W.H.L. Yeovil and also with the metal ground plane sited in the open outside the W.H.L. Avionics Centre and these results were identical.

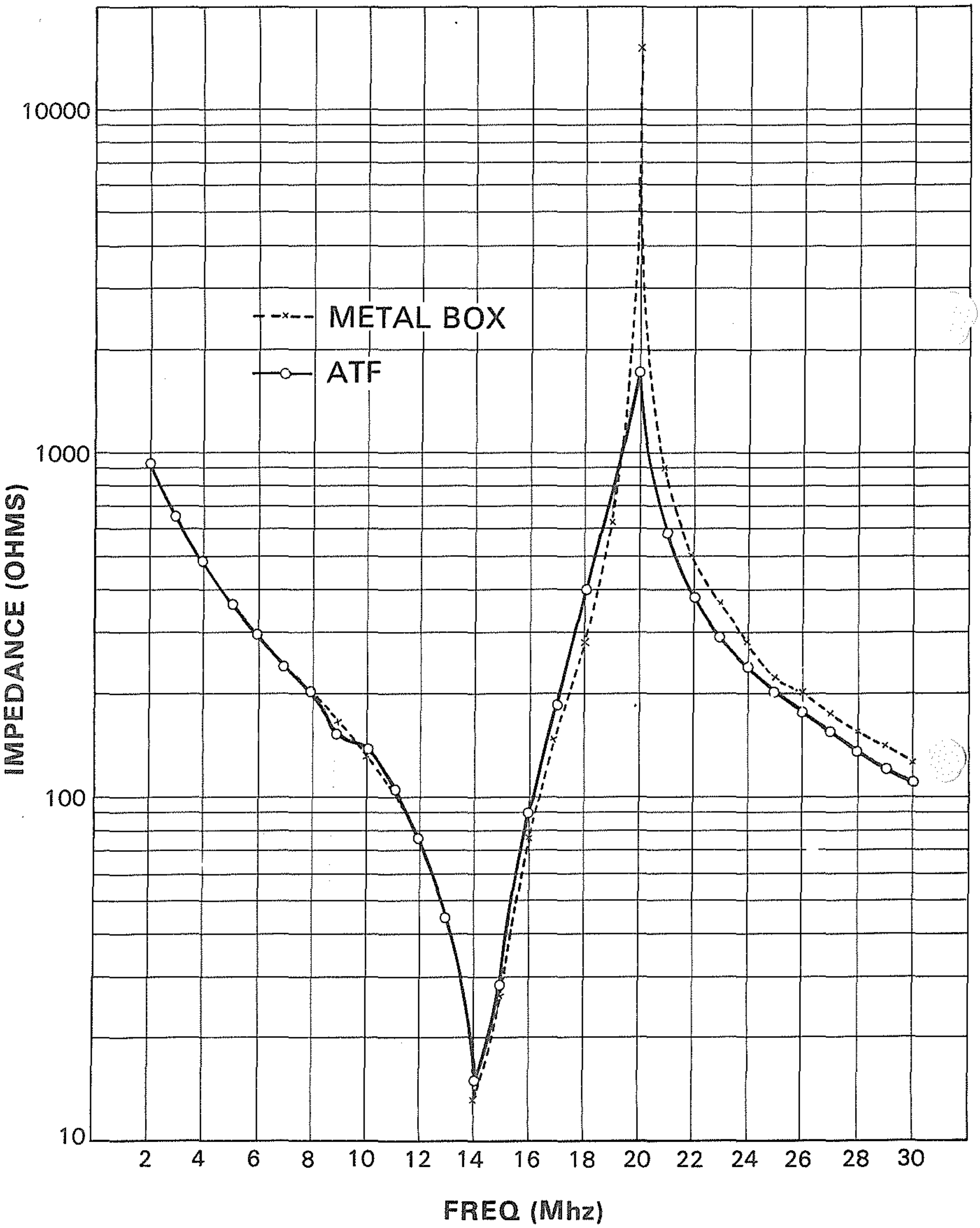
When making measurements using the carbon fibre structure in the open, problems were encountered with inclement weather and special precautions were taken to prevent the material becoming wet, and changing the impedance characteristics. Because of frequent interruptions due to this, the measurements were made in the Avionics Hangar at W.H.L.

## 9.3.2. RESULTS

### A. INITIAL CONSIDERATIONS

The impedance characteristic of an open circuit lossless transmission line against frequency takes the form of a hyperbolic cotangent with impedance peaking to infinity at the frequencies that make the impedance a maximum and the phase shift is at all points 90°, corresponding to a lossless reactive line.

## GRAPH NO. 1



METAL BOX
ATF
IMPEDANCE (OHMS)
10000
1000
100
10
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
FREQ (Mhz)

The introduction of losses into the line system has the effect of reducing the impedance peaks from infinity under lossless conditions, and in all practical cases the impedance will be finite, but the extent to which the impedance is reduced is determined by the system loss.

Losses in the line system also affect the phase angle of the impedance, introducing angles which lies between 0° and 90°, dependent upon the scale of the losses.

B. PRESENTATION

Graph No.1 shows the impedance characteristics plotted from measurements taken on the metal and carbon fibre ground planes. The results have been plotted on a log/lin basis to encompass the scope of the impedance variation.

Graph No.2 shows the impedance phase angle characteristics plotted from measurements taen on the metal and carbon fibre ground phanes.

C. DISCUSSION

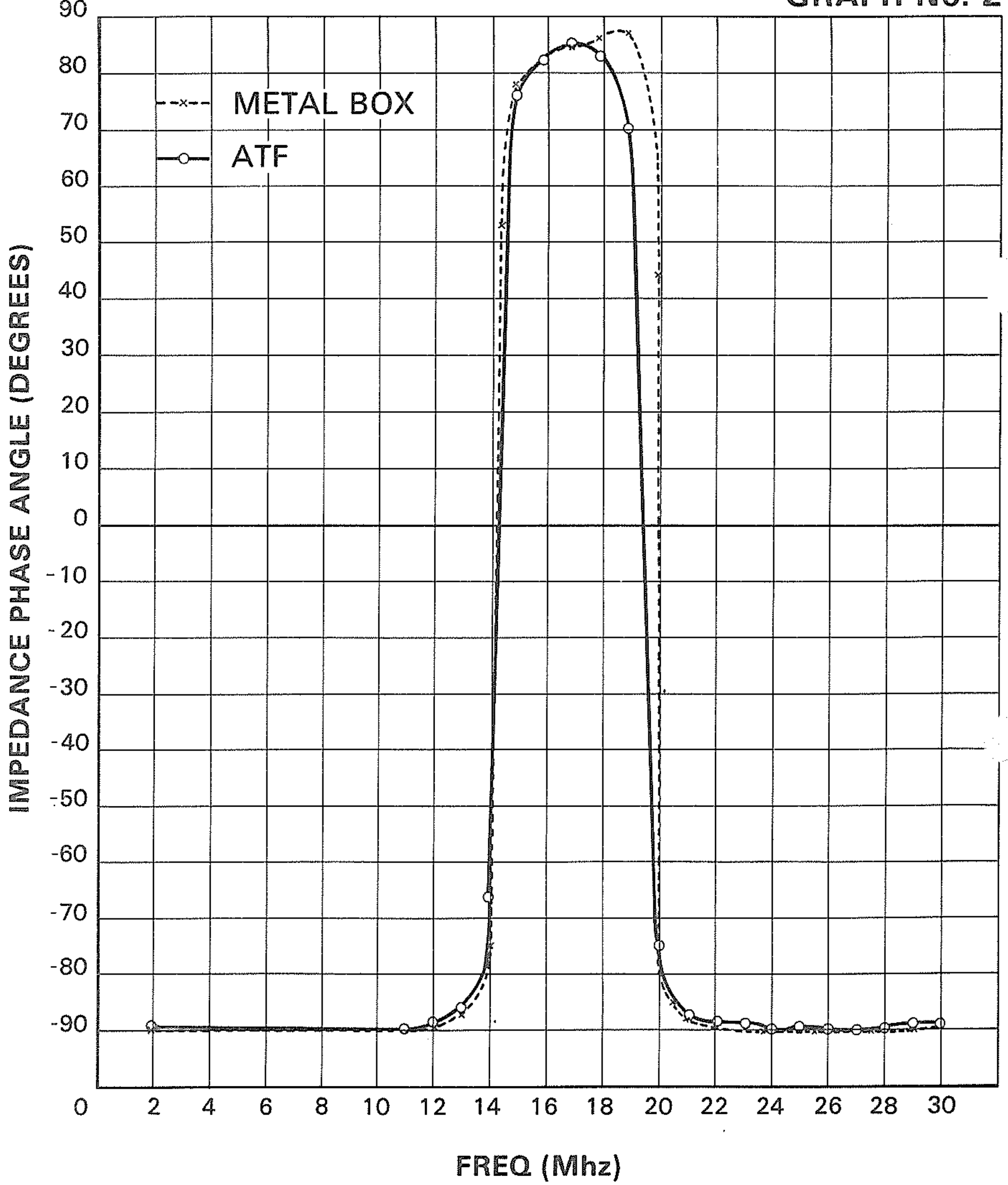
Graph No.1 shows the impedance characteristics using the metal and carbon fibre ground planes resonate at 14 Mhz and at 20 Mhz and that carbon fibre resonates at a lower peak impedance than the metal structure.

The effect of the increase in loss resistance is greater at the frequencies where the impedance peaks thus at 20 Mhz the effect is equivalent to a loss of 19 db.

Graph No.2 shows the phase characteristics of the impedance using the metal and carbon fibre ground planes.

These characteristics confirm that the effect of the additional losses due to the ATF ground plane is most marked in the 20 Mhz region by the reduced slope of the characteristic, with the phase shift less than 90° between 17 Mhz and 23 Mhz.

## GRAPH No. 2



METAL BOX
ATF
IMPEDANCE PHASE ANGLE (DEGREES)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
FREQ (Mhz)

## 9.4. CONCLUSIONS

### CONSTRUCTIONAL CONCLUSIONS

1. Co-curing a composite butt strap across an interpanel joint will produce an acceptable H.F. connection.

2. Connection onto a skin edge by any of the described methods will be unsatisfactory.

3. This particular carbon structure required an external butt strap for strength reasons. Achievement of electrical continuity by co-curing these straps therefore produced negligible weight increase, but a slightly increased labour cost was involved in abrasion of the panel edges to expose the carbon fibres. If there were no electrical requirement placed on the butt strap they could be bonded to the panels with an ambient cure adhesive, however, if continuity is required co-curing at 140°C (dependant on resin system) could prove more difficult for field repairs.

4. A low resistance connection for an antenna can be achieved through the use of a dimpled metal shim co-cured to the ground plane using a conductive fibre.

5. The use of nickel plated carbon fibre composite dramatically reduced the contact resistance to both metal and carbon surfaces.

6. Curing of these monopole shims can also be accomplished during moulding of the panel.

### ANTENNA TRIAL CONCLUSIONS

7. As a result of these measurements it is clear that a H.F. antenna mountd on a carbon fibre ground plane as defined exhibits greater losses than the same antenna mounted on a similar sized metal ground plane at frequencies between 2 Mhz and 30 Mhz when measured using low current techniques.

8. The effect of these factors on a practical H.F. system would be such that matching the antenna to a P.A. output stage would be more easily accomplished, but that the antenna system efficiency would fall resulting in less radiated output power at certain frequencies dependant upon the antenna wire length.

ACKNOWLEDGEMENT

The authors are grateful to the Advanced Technology department of Westland for the opportunity to publish the results.

REFERENCE

Ref 1 Efficiency Measurements of an H.F. Notch Aerial in a C.F.R.P. Tail Fin, by J. Owen and M. Sidford. The Electrical Properties of Carbon Fibre Composites' conference at Culham Laboratory, Oxford, U.K. in December 1981.

Ref 2 This method for mounting antennas onto composite is the subject of a pending Patent Application.