The Post Office Electrical Engineers' Journal

VOL 64 PART 3/OCTOBER 1971

Concorde over Goonhilly

P. S. J. DUFFY, C.ENG., M.I.E.E. and J. D. HATTON†

U.D.C. 536.011.5: 534.83: 621.396.677

The alarm generated by the proposed supersonic flights by Concorde, together with conflicting opinions about the likelihood of structural damage being caused, led to a study of the effects of sonic booms on satellite-communication earth-station aerials, followed by experiments to determine the validity of theoretical findings. Measurements of simulated and actual sonic booms were made. The results show that the aerial structures were well able to withstand the shock loads and that satellite-communication services were unaffected.

INTRODUCTION

Following the announcement of plans for Concorde to fly near to the satellite-communication earth-station at Goonhilly Downs, Cornwall, at supersonic speeds, an investigation was carried out into the probable effects of the pressure waves on the large steerable aerials to determine if any interruption or degradation of service was likely to be caused. In particular, the possibility was considered that pressure waves might be focused by the paraboloidal reflectors and cause excessive structural deflections, vibrations or damage. Theoretical studies were made by the British Post Office (B.P.O.) in conjunction with experts from the Royal Aircraft Establishment (R.A.E.), Farnborough, Husband & Co., the designers of the two Goonhilly aerials and the Marconi Co. Ltd., builders of the No. 2 aerial. These showed that there was little likelihood of trouble occurring. Nevertheless, it was decided that the theoretical studies ought to be confirmed by practical tests. At the suggestion of the R.A.E. it was agreed to simulate sonic booms by firing explosives near to an aerial. Test shock-wave pressures could then be created ranging from low values up to the maximum likely to be experienced from a sonic boom. The tests could be stopped at any stage if it was found that damage was being caused. Moreover, such tests would enable the probable effects of actual supersonic flights to be predicted. Subsequently, measurements were made of actual sonic booms from Concorde.

SHOCK WAVE GENERATION AND PROPAGATION

An aircraft flying at a subsonic speed generates pressure waves from its nose and stern. These pressure waves propagate outwards from the aircraft at the velocity of sound in a manner analogous to the spreading of ripples in water.

At supersonic speeds the aircraft travels faster than the pressure waves, which then accumulate at the nose and stern, forming strong waves of compression that travel with the aircraft and radiate from it. The pressure waves take the form of a solid cone with the aircraft at its apex. Thus, as the aircraft moves, it produces a circular corridor within which the pressure waves exert their influence. The maximum effects are experienced directly beneath the flight path, and these diminish with increase of distance away from the flight path. At long distances from the aircraft, the nose and stern pressure waves produce a waveform which has a nominal *N*-shape. It is this pressure wave which is heard as a sonic boom. The difference between the actual pressure and ambient atmospheric pressure at any instant is called the overpressure. The actual shape of the pressure wave is determined by the shape, size, weight, speed and altitude of the aircraft together with the prevailing weather conditions in the lower atmosphere.

The four basic waveforms generally encountered are shown in Fig. 1. The *nominal N-wave* is the theoretical waveform, and the *pseudo-nominal* is similar to it except that there is a slight rounding of the waveform at the maximum and minimum levels. The *rounded* waveform has more pronounced rounding at the maximum and minimum levels and the maximum overpressure is less than that of the *nominal N-wave*. The *spiky* waveform has a fast initial transient rise to a maximum overpressure of 2–3 times that of the *nominal N-wave* followed by a fast fall to the normal value, then a slower rate of fall followed by a sharp fall to well below the normal minimum. On each waveform the main slopes can be projected to give the approximate value of the maximum overpressure on the equivalent *nominal N-wave*.

The magnitude of the energy in the shock wave, Fig. 2, is only significant at frequencies up to about 100 Hz. Maximum energy occurs at around 3 Hz. Between these frequencies the energy content of the shock wave decreases at a rate of 6 dB per octave. Structures having low resonant frequencies would not respond differently to the various waveforms, whereas structures having high resonant frequencies may respond to the transient peak overpressure of a *spiky* shock wave.

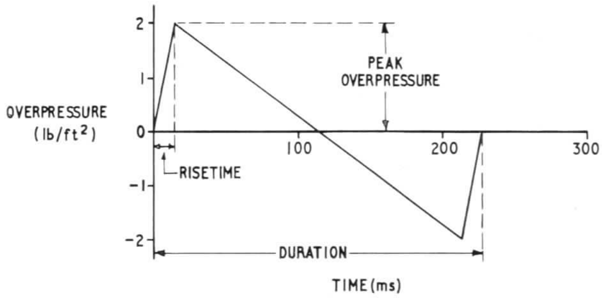
The sonic booms generated by Concorde flights were expected to have maximum overpressures of $1\cdot5$–$2\cdot5$ lb/ft^2, rise times of about 10 ms and durations of 200–250 ms. On the advice of the R.A.E. the theoretical studies were based on maximum overpressures of 3 lb/ft^2.

EFFECT OF SHOCK WAVES ON STRUCTURES

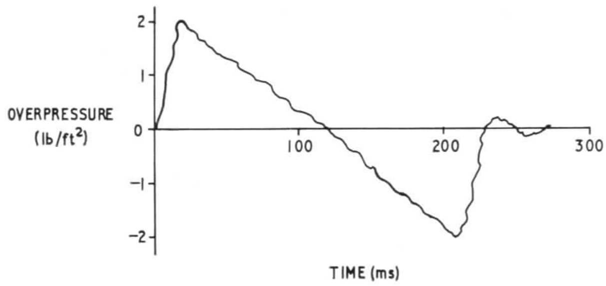
Structures have components with natural frequencies of vibration within the frequency range of the sonic boom, but if a structure is in good condition it is unlikely to suffer damage. In a few instances minor damage such as breaking or cracking of windows and cracking of plaster has occurred. It is believed to have resulted from the sonic-boom excitation of structural components having abnormal stress concentrations owing to faulty design, construction or maintenance. More rarely, the damage has been serious but has often been shown to be caused by other sources of excitation acting in conjunction with the sonic boom. Exceptionally, the sonic boom has been shown to be the sole cause of damage to poor-quality structures.

It is possible to calculate the probable effects of a sonic boom on a structure if its size, mass, stiffness and damping are known. If the structure is complex, the calculations will also be complex and difficult. Excitation of the foundations

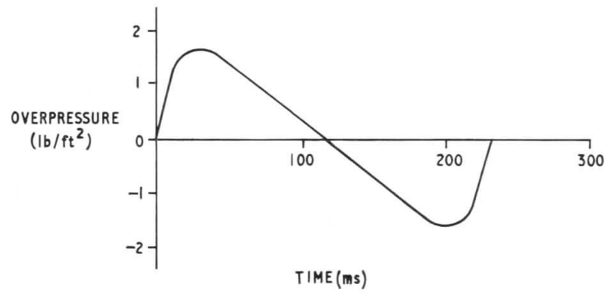
† Telecommunications Development Department, Telecommunications Headquarters.



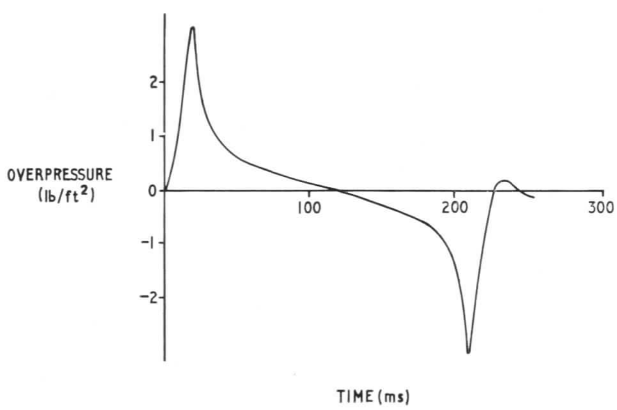
(a) *Nominal N-wave*



(b) *Pseudo-nominal waveform*



(c) *Rounded waveform*



(d) *Spiky waveform*

FIG. 1—Basic overpressure waveforms

of a structure can be caused by the sonic boom through the production of seismic waves. A sonic boom produces a dynamic load that can produce structural deflection up to 2·5 times that which a static load of the same amount would produce. To cater for variations of the shock-wave waveform and the response of the various resonant-frequency components of the structure, the R.A.E. advised that for calculations the nominal maximum overpressure should be multiplied by a dynamic gain factor of 2·5. This would be equivalent to a maximum shock-wave overpressure of 7·5 lb/ft^2.

It was concluded that the short-duration loadings likely to be imposed on the aerial structures would be relatively insignificant, and that apart from a quartz waveguide window and a quartz vane polarizer in an aerial feed, the aerial and associated equipment were unlikely to be harmed by sonic

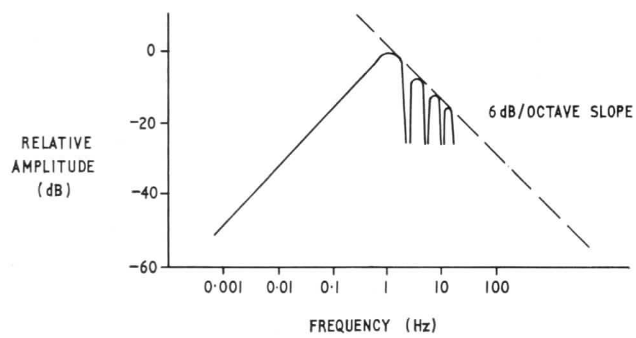


FIG. 2—Frequency distribution of energy for a typical Concorde sonic boom

booms. Subsequent tests carried out on the waveguide window and vane polarizer indicated that these items also were unlikely to be damaged. These conclusions were based on theory, supported to a limited extent by practical work carried out by the R.A.E. on different types of structures. The B.P.O. and their consultants accepted the suggestion of the R.A.E. that simulated sonic booms should be generated by the strictly-controlled firing of explosive charges at Goonhilly prior to the actual sonic booms. A program of tests was then drawn up.

Focusing of Sound Waves

By analogy with the transmission of electromagnetic waves where, if the wavelength of the signal is small compared to the reflector diameter, the gain is given by:

$$G = \left[\frac{\pi D f}{v}\right]^2,$$

where G is the gain,

D is the reflector diameter in feet,

f is the frequency in hertz, and

v is the velocity of propagation of the wave in feet/second.

Thus, for a given reflector, the pressure gain increases with frequency at a rate of 6 dB per octave. For a sonic-boom duration of 0·25 s, and a velocity of sound of 1,100 ft/s, the fundamental frequency is given by:

$$f = \frac{1}{0 \cdot 25}\ \text{Hz},$$

and the corresponding wavelength $= \frac{v}{f}$,

$= 1{,}100 \times 0 \cdot 25,$

$= 275$ ft.

This wavelength is large compared to the reflector diameter, and it is therefore unlikely that the pressure gain through focusing will be as large as that calculated. Also, the increase of pressure gain at 6 dB per octave will be offset by the reduction of energy at the same rate, and there will not be any apparent focusing effect.

Reflection of the incident pressure wave affects the overpressure. With a focal length of 30 ft it takes 0·055 s for the pressure wave to travel from the focus to the reflector and back to the focus. This is about one-fifth of the duration of the pressure wave and, consequently, the reflected pressure wave merges with the still incoming pressure wave and affects the pressure at the focus. In this time interval the incoming wave pressure is still greater than the ambient pressure and the reflected wave can add to it, thus raising the overpressure. The arrival of the reflected wave at the focus is too late to coincide with the peak overpressure, but it will arrive during the fall of overpressure period and produce another peak the value of which depends on the incident wave-shape.

Equivalent Wind Loading

Large steerable aerials are designed to withstand wind loadings which take into account the effects of wind gusts having frequency components at or near the frequencies of structural resonance. Hence, it is convenient to consider the shock wave in terms of the equivalent wind loadings. If the reflector is considered as a flat plate normal to the shock wave, then for each 1 lb/ft^2 of pressure loading, an 85 ft diameter reflector will experience a total shock load of 2·53 tons, while that for a 90 ft diameter reflector will be 2·84 tons.

The 90 ft diameter No. 2 aerial is designed to withstand wind gusts of 130 miles/h which give short-duration loads of about 120 tons. At Goonhilly, it is expected that wind gusts greater than 108 miles/h will only occur once in 50 years, and that gusts of 80 miles/h or more will occur for 0·01 per cent of each year, i.e. for 52 minutes. In fact, during the 10 years of its existence, the Goonhilly earth station has only once experienced wind gusts of about 80 miles/h. Hence, taking a wind of 80 miles/h as the upper practical limit, adding to its loading the sonic boom overpressure gives the effect of an 80 miles/h wind gusting to 87·2 miles/h, to produce a wind-load increase of 3 lb/ft^2, and to 96·8 miles/h, to give a 7·5 lb/ft^2 increase. These wind-gust velocities are within the wind-loading design values of the structure for survival without damage. Moreover, a wind gust normally has a duration of about 3 s and, because the shock-wave duration is only about a twelfth of this, its effect will therefore be less.

SIMULATION OF SONIC BOOMS

There are two basic charge arrangements which can be used to simulate sonic booms. The first is called a *crackerjack* and consists of two spaced charges suspended from a horizontal wire. These charges are fired in sequence with a predetermined time delay between firings. A pressure wave of the form shown in Fig. 3 is produced, which although not

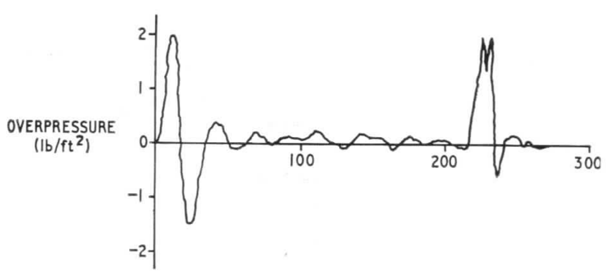


FIG. 3—Overpressure waveform generated by a *crackerjack* charge

an *N-wave*, simulates the major shock components. There is little or no energy at 3 Hz, most of it being at frequencies higher than 30 Hz, with a peak at 60 Hz. The second arrangement is called a *line charge*. This consists of bundles of charges arranged to form a 100–300 ft line which explodes progressively along its length such that an *N-wave* is produced within a solid cone centred on the longitudinal axis of the line. A shock wave of much larger amplitude is produced in the broadside direction and great care has to be taken in siting the charge. The energy in the shock wave is mostly at frequencies below 30 Hz, with a peak at about 5 Hz.

The R.A.E. have carried out many tests on a wide variety of structures and structural components using simulated shock waves. By the use of well-tried routine procedures they are able to ensure that tests are safely carried out. The initial simulated pressure waves are designed to have low overpressure values, e.g. 1 lb/ft^2, and these are increased in stages until the structures show signs of stress or the maximum test overpressures are reached. For a particular charge arrangement the amount of charge is kept constant and is situated progressively nearer the structure under test to produce higher pressures.

INSTRUMENTATION

It was decided that measurements should be made on the No. 1 aerial of the incident and focused pressure waves, structural vibrations at selected points on the aerial structure and associated equipment, and levels of signals passing through the aerial system.

Measurement of Pressure Waves

A special capacitor-type microphone was connected to a tuned circuit, the resonant frequency of which was influenced by the microphone capacitance. The tuned circuit, which had a nominal resonant frequency of 10 MHz, was connected to a 10 MHz crystal-controlled oscillator so that small changes in microphone capacitance, caused by sound pressure on the diaphragm, frequency modulated the oscillator output. The resultant signal was fed to a frequency-modulation detector and then to a preamplifier. The oscillator, frequency-modulation detector and preamplifier were contained in the microphone head which was connected by long cables to a unit which contained the power supplies, and an amplifier with an output peak-indicating meter. The output was also fed to an oscilloscope fitted with a camera.

A microphone was attached near the foot of the tripod leg and another near the focus to enable the incident and focused pressure waves to be measured. A third microphone was placed about 60 ft nearer the explosions or planned flight path to provide a signal to trigger the oscilloscope time-base. A few minutes before the explosive charge was fired, or sonic boom expected, the camera shutter was manually opened. After receipt of the sonic boom the oscilloscope graticule illumination was turned on for a few seconds and the camera shutter then closed. Each microphone system was set up and calibrated by the use of a *pistonphone* which is a precise sound source of 124 $\pm$ 0·2 dB (0·662 lb/in^2) relative to 0·0002 μ bar.

Measurement of Mechanical Vibrations

Vibrations of the reflector rim and azimuth damper fin were measured with strain-gauge transducers and accelerometers.

The strain-gauge transducers consisted of cantilevers, with an effective length of 6 in, clamped to the reflector backing structure at strong points near the elevation bearings. Each cantilever had a strain-gauge bridge mounted on it. The free ends of the cantilevers were connected by tensioned steel wire to the reflector rim. Movement of the rim relative to the elevation bearing produced small changes in the bending of the cantilevers and thus changed the resistances of the strain gauges. The resultant variations in the output of the bridge were calibrated to show the extent of the cantilever deflections. The outputs of the strain-gauge transducers were fed to ultra-violet galvanometer recorders. Two of these systems were installed to enable the rim vibrations at the top and left-hand side of the reflector to be measured.

Three piezo-electric accelerometers were used. They were fixed to the bottom and right-hand side of the reflector backing structure, and to the azimuth damper fin. Their outputs were fed to double integrators which gave outputs proportional to the structure displacements. The integrator outputs were fed to a multibeam oscilloscope fitted with a camera.

During some of the explosive tests, vibration measurements were also made with a seismometer mounted on the aerial turntable.

Goonhilly No. 1 aerial is front fed, and vernier tracking of the satellite is provided by small azimuth and elevation tilting of the feed mechanism. Potentiometers fitted to the azimuth and elevation gimbals and wired to displays on the control console in the main building indicate the respective displacements. Pen recorders were wired in parallel with these displays to record whether the explosion or sonic-boom tests caused movement of the feed mechanism.

In service, tracking of the satellite is facilitated by spinning the feed aperture, which is slightly offset from the main axis of the feed. This results in modulation of the received satellite beacon signal which is fed to the tracking receiver. This receiver gives outputs proportional to the azimuth and elevation offsets of the aerial axis from the direction of the satellite. Samples of these signals were fed via d.c. matching amplifiers to a tape recorder. Comparison of the beam offset and tracking error enabled movement of the feed due to satellite movement to be distinguished from movement caused by sonic-boom waves.

Measurement of Signal Levels

The composite received signal in the band 3,700–4,200 MHz is fed by waveguide from the aerial feed to a low-noise amplifier and then to a travelling-wave-tube amplifier. Individual carriers are then separated in a dividing network, converted to an intermediate frequency (i.f.) of 70 MHz, amplified and demodulated to baseband. During the tests, the 3,825 MHz carrier level was monitored by measurement of the automatic gain control voltage of the appropriate i.f. amplifier, together with the level of the satellite beacon at 3,934 MHz. An in-station pilot is injected into the aerial system by means of a horn feed fitted at the reflector vertex. The pilot thus follows the whole of the station receive path but is completely independent of the satellite. By comparison of the received signals and the pilot it was possible to determine if any variations of the received signals were due to changes in the aerial system or in the satellite and propagation path.

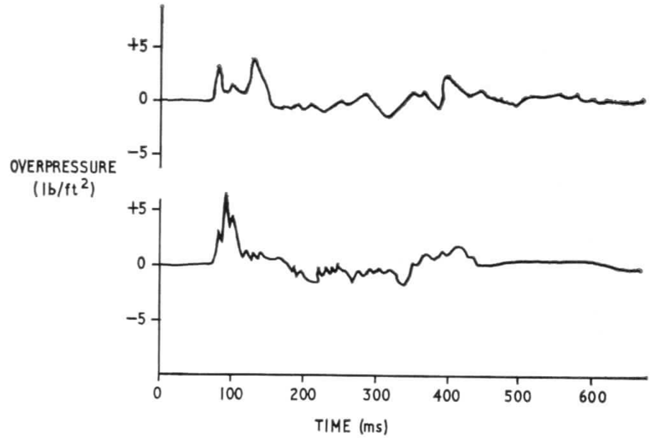
Measurements of out-of-band noise levels were obtained by filtering a 4 kHz slot of the baseband derived from the 607 kHz telephony carrier, and feeding this to noise-measuring equipment. This was connected to a teleprinter which gave a print-out of the number of noise bursts in each minute which exceeded −40 dBm0, and the total duration of these noise bursts.

SIMULATED SONIC-BOOM TESTS

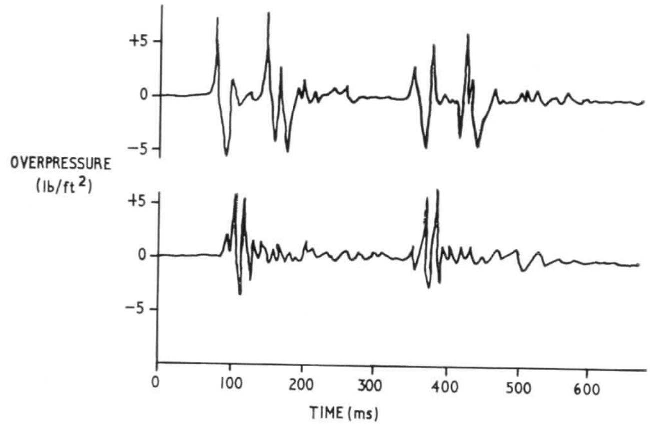
Tests using *line* and *crackerjack* charges were carried out on the No. 1 aerial. Both types of charge were detonated in turn at distances of 600, 400 and 245 ft in front of the aerial to produce calculated pressures of 1, 2 and 6 lb/ft^2, respectively, at the aerial. Measurements were provisionally analysed after each explosion to determine if it was safe to proceed to the next higher pressure. Some tests were duplicated to demonstrate the repeatability of results.

Examples of the overpressure waveforms produced by the simulated sonic booms are shown in Fig. 4. The upper traces represent the overpressures at the aerial focus and the lower traces those at the foot of the tripod leg. On the upper traces the first peak on the left-hand side is the incident wave and the second is the reflected wave plus the incident wave. The average ratio of the second peak to the first is 1·02. Thus, after allowing for the low-level incident wave, there is no evidence of focusing of the pressure wave by the reflector. The pressure microphone near the foot of the tripod leg was 5 ft from the reflector surface. Consequently the recorded pressure wave has incident and reflected components.

Examination of the recordings of accelerometer and strain-gauge outputs show that all the vibration levels are very small. The maximum reflector displacement was 0·007 in in a direction normal to the reflector surface. Such displacements will not produce any significant variation in aerial gain. The frequencies of vibration are between 10 and 70 Hz with the main response at 25 Hz. These are well above the natural frequencies of vibration of the structure and are not likely to cause structural resonance.



(*a*) *Line charge*



(*b*) *Crackerjack charge*

FIG. 4—Overpressure waveforms produced by simulated sonic booms

The recordings of received carrier levels and feed displacement show no disturbances of the telecommunication or aerial tracking systems during the tests.

The results of the simulated sonic boom tests were analysed, and although it was realized that further information could be gained, and that the pressure waveforms produced were not fully representative of sonic booms, the tests indicated that an actual sonic boom was unlikely to affect the Goonhilly aerials and telecommunication services.

Some measurements were also made whilst explosive charges were detonated in a nearby quarry, but no firm conclusions could be reached about the equivalence of quarry blasts and sonic booms.

MEASUREMENTS DURING CONCORDE SUPERSONIC FLIGHTS

For measurements during Concorde supersonic flights the accelerometers and strain-gauge transducers were removed because it was believed that there would be no significant structural vibrations caused by the sonic booms.

The flights were expected to take a North–South path a few miles to the East of Goonhilly, the direction which the No. 1 aerial faced. However, due to changes in the flight plans, the first five supersonic flights passed 5–13 miles to the West of Goonhilly with Concorde flying at heights between 44,000 and 47,000 ft, and at speeds between Mach 1·42 and Mach 1·7. This resulted in the sonic-boom pressure-wave being incident on the rear of the reflector.

Recordings made of four of the sonic-boom overpressure waveforms have maximum overpressures of 0·7, 0·6, 0·9 and 0·9 lb/ft². A sample waveform is shown in Fig. 5. The upper trace represents the overpressure at the aerial focus and the lower trace that at the foot of the tripod leg. The ratios of reflected wave plus incident wave to the first incident peak at the focus are 0·63, 1·6, 0·65 and 1·1, with an average of 1·0, and the time interval between the first two peaks is about 60 ms. It is interesting to note that the recording taken near the foot of the tripod leg shows two peaks spaced by about 40 ms, whereas the period for a sound wave to travel from the pressure microphone to the reflector and back again is about 10 ms. This indicates that the second peak may have been caused by a pressure wave reflected from the ground.

The results obtained do not provide conclusive evidence of focusing, and though the beamwidth of the aerial at acoustic frequencies is so large that the aerial would not have to point directly toward the flight path to show any focusing effects, more definite conclusions could have been drawn if the aerial had pointed directly toward the flight path.

No effects were recorded on the monitored signal levels.

CONCLUSIONS

The tests have confirmed the results of the theoretical studies, and have not produced any evidence that pressure waves from supersonic Concorde flights are focused by the large paraboloidal aerial reflectors, or that they cause harmful structural resonances and deflections. None of the valuable international telecommunication services were affected, and it seems likely that they will be unaffected by flights directly over Goonhilly.

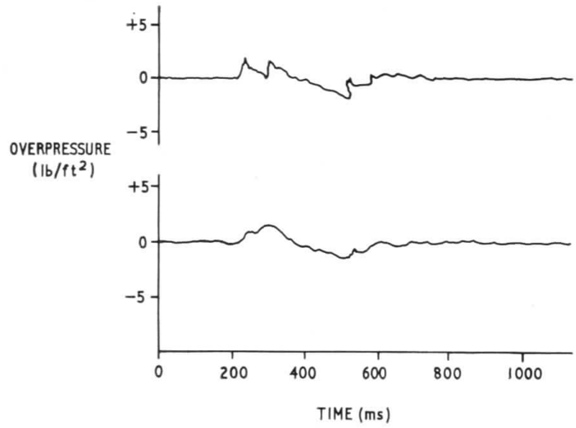


FIG. 5—Overpressure waveforms produced by Concorde

ACKNOWLEDGEMENTS

The advice, assistance and loan of equipment by The Royal Aircraft Establishment, the participation of Husband and Co., consultants to the Post Office and Marconi Communication Systems Ltd and the assistance given by colleagues in the Post Office is gratefully acknowledged.

References

1 TAYLOR, F. J. D. Equipment and Testing facilities at the Experimental Satellite Ground Station, Goonhilly Downs, Cornwall. *P.O.E.E.J.*, Vol. 55, p. 105, July 1962.