ATS-6 EUROPEAN L-BAND AERONAUTICAL EXPERIMENTS

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Summary. This paper describes the European experiments and test results obtained in L-band (1550-1650 MHz),using the NASA ATS-6 satellite, to conduct communication and navigation tests over the North Atlantic thus assisting in the definition of modulation techniques to be used with an Aeronautical Satellite System, AEROSAT.

The experiments conducted by ESA and some of its member states covered voice, data transmission and ranging measurements.

The tests were performed on board a Comet IV aircraft equipped with a slot dipole array antenna, especially designed to operate within the coverage required in the AEROSAT MOU (Memorandum of Understanding for the AEROSAT programme signed by Europe (ESA), the USA (FAA) and Canada (DoT) in August 1974. The voice tests compared DELTA-PSK with adaptive NBFM using test tapes consisting of logatoms, SCIM sequences, and PB word lists.

An investigation of multipath noise effects on the PSK data transmission system was carried out and led to the general conclusion that this problem is a serious one for coherent demodulators. The DECPSK system tested exhibited a strong tendency towards a Rayleigh channel BER situation at low antenna signal to multipath interference ratios.

The ranging results show the feasibility of achieving standard deviations of range of around 500-600 m for the PLACE tone system with its rather short integration time of 120 ms, and 100 m for the DIOSCURES pseudo random coded system operated on a CW basis.

1. Introduction. To assist in the definition of future aeronautical and maritime systems ESA sent to NASA a joint European proposal for aeronautical and maritime experiments in July 1972, to be conducted using the ATS-F satellite at its 94°W longitude station. Care was taken in the preparation of these experiment proposals to ensure compatibility with the NASA PLACE equipment; the idea being that transmissions could be used simultaneously by several experimenters. This feature became all the more attractive when a decision was made by NASA in 1973 to officially limit the L-band use of the satellite to 300 hours in its first year of operation.

On May 30th 1974, the ATS-F satellite was successfully launched into synchronous orbit and, upon being declared operational at 94°W, was renamed ATS-6. The NASA Rosman Ground station contained the ESA equipment racks which interfaced with the C-band up and down link equipments, and was used to access the satellite for all the experiments described.

The ESA experimental programme involved the use of four separate instrumented mobile elements. For the first phase, August 28th-October 1st a COMET IV aircraft, based at FAA-NAFEC, Atlantic City, N.J., was used for experiments over the Western Atlantic together with the Norwegian ship “MV SKIENFJORD” which crossed the Atlantic twice during the month of September 1974 on a normal cargo voyage from Norway to the USA and back.

For the second phase (February 21st to April 5th 1975) the COMET IV aircraft operated over the mid-Atlantic and was joined by the nuclear ship “OTTO HAHN”. The base of operations was the islands of the Azores in order to cover the low elevation angles (down to 0°) most economically.

Four signals were passed through the satellite transponder; a quadrature modulated tone ranging and low speed access channel, a narrow band frequency modulation voice channel, a 1200 or 2400 b/s bi-phase shift keying data channel, and a 25.6 kb/s Time Division Multiplex channel; also bi-phase PSK.

However, for the multipath tests an unmodulated carrier was transponded by the satellite, usually replacing one of the above channels in the set. The frequency plan was carefully chosen to be an intermodulation free set for the forward link since the satellite transmitter was of the hard limiting type.

2. Experiment Objectives. These were as follows:

- comparison of NBFM and Delta-PSK voice modems over a range of elevation angles, carrier to noise density ratios, and signal to multipath noise interference ratios.
- evaluation of a DECPSK 1200/2400 b/s data transmission system over a range of elevation angles, carrier to noise density ratios, and signal to multipath noise interference ratios.
- evaluation of the multipath fading frequency spectra and amplitude distributions for various elevation angles and signal to multipath noise ratios.

- evaluation of a side-tone ranging system operated on a burst or TDMA basis and a general comparison with a PRNS system.
- demonstration tests, performed jointly with the FAA and the USCG, to show the practical advantages of the system in future air traffic control and SAR applications.

3. Instrumentation. A detailed description of the instrumentation used in these experiments is contained in ref 1. It should be noted that the aircraft antenna received particular attention in the design and development phase. This Royal Aircraft Establishment project enabled ESA to rent the COMET IV aircraft equipped with the necessary antenna system (ref 2); the Comet was instrumented by ESA-ESTEC. The ATS-6 satellite is described in ref 3.

4. Voice Experiment

4.1 Voice Evaluation. Experiments. Two candidates for the AEROSAT system were tested; these were the digitally companded delta voice transmission system developed by TRT in France under contract to the French Civil Aviation Authorities, (ref. 4), and the analogue Narrow Band Frequency Modulation transmission system developed by the Bell Aerospace Company, U.S.A., under contract to NASA-GSFC as part of the PLACE study, (ref. 5).
The companded delta voice transmission system was transmitted at the 19.2 kb/s rate using a PSK modulation on the carrier.

The dynamic range of the modem was very large, having about 40 dB input dynamic range for the 10% error case. This is a reasonable threshold, which for 19.2 kb/s, corresponds to a C/No of 44.0 dB-Hz and 95% intelligibility.

This large companding range was important because of the large peak to RMS power density distribution in the average voice in addition to the variations of talker level, loud to soft, which are normally experienced.

The digital voice system has the advantage that it can be easily digitally multiplexed with data and pseudo random digitally encoded ranging signals, forming one serial data stream comprising a number of channels. These can be transponded through a satellite hard limiting repeater without the intermodulation product losses associated with a multicarrier transmission. Such a system has been developed by TRT and is referred to as the TDM system in this report. It has also been called the Dioscures system, (Ref. 6).

The Narrow Band Frequency modulation system which was tested is an efficient analogue voice transmission system developed by ESTEC. It is similar to the Adaptive NBFM developed by Bell Aerospace for NASA.

The voice is pre-emphasised from 300 Hz to 3000 Hz at 6 dB/octave and clipped to give a peak to rms ratio of about 12 dB for a mean level talker, then phase-modulated at 70 MHz with an index set at 1.45 rad. with a 1 kHz tone set to equivalent mean talker level. The 70 MHz modulated signal is then up-converted to C-band for transmission from Rosman.

The demodulator is fed from a 10 MHz signal, down converted in the receiver, limited by a band pass limiter, and fed to a modulation tracking P.L.L. demodulator. The recovered audio signal is then de-emphasized between 300 Hz and 3000 Hz at 6 dB/octave. Note that there is no expansion corresponding to the clipping performed in the demodulator. There are two reasons for this: the first is that the demodulator has no knowledge of the envelope of the voice signal which would be required to operate the expander, and the second is that a peak to RMS ratio of 12 dB is only exceeded for about 1% of the time for voice signals. Hence the distortion introduced by the voice clipper has only a negligible effect on the transmission quality of the system.

4.2 Results of the Voice Tests. The two types of voice modem were subjected to laboratory tests prior to each test phase to check and optimize their performance.

The flight tests consisted of 20-30 minute test runs at a constant heading, so that the conditions, such as the antenna gain and multipath fading, would not vary. The carrier-to-noise density ratio C/No was set at the beginning of each run by adjusting the level of the attenuator installed between the antenna and pre-amplifier. The Delta and the NBFM were transmitted simultaneously at equal power levels in order to ensure simularity of test conditions. In the Atlantic City and Azores campaigns the elevation angles investigated lay between 2.5 and 20 degrees. The intelligibility curves were plotted with various symbols to indicate the groups of elevation angles.

The test method consisted of transmitting a common test tape through both systems simultaneously. Demodulation was performed in the respective receiving chains on the aircraft, these being branched from a common preamplifier chain after the aircraft antenna.

The test material consisted of logatoms, a syllabic test in the French language, (Ref. 7), Phonetically Balanced (PB) word tests, (Ref. 8) and SCIM tests. The latter consists of short bursts of pseudo speech and noise, which are then analysed by spectral analysis over 9 contiguous bands covering the spectrum. The articulation index is derived from a weighted signal to noise measurement from the 9 bands. The details of the SCIM signal and the analysis are contained in Ref. 9.

The logatom tests provided data in the form of Articulation Indices (AI), Intelligibility, and Speech Quality or “how pleasant the channel was to listen to”. The results are plotted in

Figures 4.1 to 4.6 and are subdivided into different data symbols showing the results in 5 groups of elevation angle from 2.5 up to 22.5 degrees.

Of the three testing methods the logatoms provided the most versatile tool for our purposes giving Articulation Index, Intelligibility, and Speech Quality measurements,

It is fortunate that a requirement on the Articulation Index (AI) for the AEROSAT system is imposed in the M.O.U. This value has been set at 0.6 and has been indicated on the relevant graphs. Taking first the complete group of measurements and considering the imposed AI in figures 4.1 & 4.2, the 19.2 db/s delta modulation system requires a C/No of 43-44 dB-Hz, and the NBFM requires a C/No of 46-48 dB-Hz to reach this value.

Taking secondly the group of measurements related to intelligibility, the values obtained at the CNR corresponding to an AI of 0.6 were both 95% for 44 dB-Hz with delta and 47 dB-Hz for NBFM. In both cases this is within a few percent of the standard curve correlating AI with intelligibility shown in Ref. 9. The intelligibility curves are both reasonably flat above the threshold region in both systems indicating that system background noise does not affect intelligibility too greatly, even though both systems exhibit different types or sounds of noise to the listener.

The speech quality measurement which is really a subjective test on “how pleasant a system is to listen to” gave results of 85% and 83% respectively at C/No values of 44 dB-Hz for Delta and 47 dB-Hz for NBFM, see Figures 4.5 and 4.6.

Here again, there was a good correlation between the results of the two systems based on the AI and the intelligibility measurements. With regard to the measurement of speech quality it is important to note that the effect of the background noise is predominant on the listener and excessive noise can be extremely tiring when listened to for long periods.

To summarise the logatom analysis, the Delta system has about 3 dB advantage over the NBFM in all three aspects of the measurements.

The second type of test was the SCIM test, the results being analysed for ESA by NASA-GSFC. For both the delta and the NBFM the SCIM AI values showed a linear relation with increasing CNR above system threshold. Again the criteria of an AI of 0.6 was taken as a reference value for comparison, requiring a C/No of 44-46 dB-Hz for the Delta system and 46-48 dB for the NBFM system.

Examination of figures 4.7 and 4.8 shows that the spread of data points is far larger on the NBFM system, particularly at the low elevation angles. This indicates that the NBFM phase lock loop detector probably translates phase errors due to multipath into detected speech errors, the loop being a modulation tracking type. The Delta-PSK system, whilst having a coherent detector, has a relatively high tolerance of errors. For example when the C/No value representing 10% BER has been reached the multipath errors are not translated into detected speech errors as the system remains above "speech threshold", i.e. AI ~0.6 C/No ÷ 44 dB-Hz.

Another point of interest is that the correlation between SCIM AI and logatom AI is very good, being within 1 dB. This shows that SCIM is useful in assessing digital voice modulation techniques such as the delta system; this point was previously rather controversial. This is very important, since the SCIM signal could eventually be analysed on board the aircraft in real time, if the aircraft is equipped with a data reduction system based on a powerful minicomputer.

The third method of voice system assessment was the use of test tapes containing phonetically balanced word lists PB. These were transmitted through the system and recorded on board the aircraft. They were then sent to the US Transportation Systems Centre, which arranged for the analysis to be performed by a specialist contractor.

The idea behind the above analysis was to establish a direct comparison between US and European candidate modems in order to eventually select one or two favoured types for assessment in the Aerosat evaluation period under the auspices of the Co-ordinated Programme. The PB test list of words is sometimes called the American National Standards List. The output of the PB test is a measure of Articulation Index and these results are plotted on Figures 4.9 and 4.10.

Here again, the tendency is to show the superiority of the Delta system over the NBFM, the spread of data points on the latter being quite large at low and medium elevation angles. The distinct threshold effect on the Delta system is very apparent at a CNR of around 43 dB-Hz.

In general, our conclusions are that the digitally companded Delta modulation system phase shift keyed on the RF carrier is a more effective method of speech transmission than NBFM, where the speech is compressed prior to modulation. This is particularly true under conditions of sea multipath fading. The dispersion of the word intelligibility on the Delta system is far less, thus ensuring a reasonable degree of service at C/No's of 44 dB-Hz and above.

5. Data Transmission. The experiment consisted of transmitting a pseudorandom coded data stream at speeds of 1200 b/s for the Atlantic City phase and 2400 b/s for the Azores phase. This differentially encoded data stream was phase shift keyed on the carrier, using a double balanced mixer at an intermediate frequency of 70 MHz and then heterodyned to the C-band uplink frequency in the Rosman Ground Station up-converter. After translation to L-band in the ATS-6 transponder, it was then transmitted over the service area, where it was received, demodulated and decoded for bit error rate analysis in the aircraft.

The type of demodulator used in the ESRO experimental aircraft was a coherent type, consisting of a Costas Loop which fed an Integrate and Dump bit detector followed by a Pseudo-random code synchronizer and Bit Error Counter and Display unit. During the experiment the Bit Error Rate and Carrier to Noise Density Ratio were available for observation on a Chart Recorder and recorded together with error per second counts, aircraft attitude parameters, and time and position on a punch tape recorder.

One of the main objectives of this experiment was to see if the multipath interference from all causes was likely to cause a limitation of the achievable probability of error over that set by system limitations, such as thermal noise.

The sea multipath effects are twofold, the first being intersymbol interference due to the coherent reflection off the sea surface of the PSK modulated RF carrier. The second is the non-coherent of diffuse sea reflection of the signal causing a Rayleigh distributed interference, which effectively sets the S/N in the channel. If large enough, this dominates the thermal noise and limits the probability of error in the channel (Ref. 10). Reflections off the aircraft structure are specular in nature but really fall into the composite antenna-airframe characteristic which was previously discussed. The time delay of the coherent component for the satellite at zenith is a maximum of 67 µs and represents a loss of 16% of the 2400 b/s period; however, the multipath rejection of the aircraft is greater than 30 dB for this case and can therefore be neglected. The diffuse or noise-like interference has the effect of increasing the noise in the channel by the ratio of the aircraft antenna pattern multipath discrimination to the diffuse reflection coefficient of the sea. Since the product of these quantities is fixed for any particular aircraft heading, satellite elevation angle and sea state, this type of multipath interference is irreducible.

The Diffuse or Rayleigh multipath noise affects the coherent demodulator in two distinct ways. Firstly an increase in S/N in the loop filter bandwidth, causing imperfect carrier synchronization; and secondly the increase in the S/N in the data bandwidth, which reduces the efficiency of the bit and message synchronizers. In the case of this aeronautical experiment the differential doppler shift is less than 35 Hz, which is less than the phase lock loop bandwidth of 100 Hz at nominal signal input level. The fading bandwidth of the diffuse multipath is a function of wave slope and has been found to have a bandwidth greater than a hundred hertz which more than covers the loop filter bandwidth $2B_L$, see Ref 1.

5.1 Results of the Tests. The technique used for the tests was to fly the aircraft on a constant heading for periods of 20-30 minutes at various elevation angles in the range 3° to 20°, while recording the number of errors per second. The heading of the aircraft, together with the latitude and longitude information, was recorded on the punch paper tape system together with time. This was to permit reference to the antenna measurements (Ref. 1) from which the ratio of signal to multipath rejection ratio S/I could be deduced. For the purpose of this report, 1200 b/s data has been extrapolated to 2400 b/s by the addition of 3 dB to the measured C/No, thereby enabling direct comparison of the data collected, in the two campaigns.

The test data has been plotted in groups of elevation angle with an indication of increasing or decreasing S/I. The results are shown in Figs. 5.1 to 5.4. C/No is derived from the product of E/N (per bit) x 10 $\log_{10}$ (Bit Rate). Each data point is the average of 20 minutes of measurement for the lowest BER ~ 1 x 10^{-5}

The test-data shows that the deviation of the measured data from the laboratory measurements increases with a decrease in elevation angle and with a decrease in S/I. The two indications are a result of the multipath noise in the channel. Ref. 10 shows the probability of error in the Rayleigh channel to be

$$\mathrm{BER} = \frac{1}{2}\left[1 - \left(\frac{Er/N_o}{1+Er/N_o}\right)^{\frac{1}{2}}\right]$$

where BER = bit error rate

Er/N_o = the ratio of multipath signal to noise ratio in the channel

Thus the BER decreases linearly with E/N_o in the Rayleigh channel, whereas in the channel where only thermal or Gauossian noise is present the BER rate for a differentially encoded PSK signal with coherent detection is

$$\mathrm{BER} = \tfrac{1}{2} \exp - E/N_o$$

Here the BER decreases exponentially with increasing E/N_o or signal to noise ratio.

The situation existing in this experiment lies between these two bounds. This is called a Ricean channel, comprising a constant signal vector representing the direct path added to a Rayleigh distributed vector representing the multipath noise plus a Gaussian distributed vector representing the thermal noise.

Both the Rayleigh and the Gaussian BER curves are plotted on each figure of measured BER for reference. In the case of the Gaussian BER curve 1 dB is added for margin, to correspond to actual laboratory measurements on the Data Modem flown. Correspondingly, the Rayleigh BER curves have been modified accordingly, since it is assumed that the detection efficiency of the integrate and dump bit detector operates as efficiently as on Gaussian noise.

The consequences of the results are the following: With the slot dipole array antenna flown on the Comet, which represents a class of reasonable low cost, feasible antennas for the L-band Aerosat service at the present time, the multipath noise rejection is not sufficient to permit the achievement of coherent data detections on a PSK signal at the 1200 or 2400 b/s rate down to 10° elevation angle with the C/No limit of 48 dB-Hz. A consequence of this for Aerosat is the mandatory use of encoding of the data transmission, assuming the carrier to noise density limitation of 48 dB-Hz for the channel, if a message error rate of 1×10^{-5} is finally required.

6. Ranging Tests. Use has been made of the NASA PLACE ranging system in order to perform ranging measurements with the mobiles, Ref. 5.

The tone frequencies were 8575, 8550, 8400 and 7350 Hz. These are in fact of relatively high frequency and all are used for fine ranging. The difference frequencies are used for ambiguity resolution, viz, 25, 175, 1225 Hz.

In addition, a 600 b/s data channel is transmitted in phase quadrature on the same carrier. This is used to sequentially interrogate different mobiles, each mobile having a unique address code. In each mobile the range tones are received continuously along with the 600 b/s data.

The process for the ground station to interrogate a mobile is the following: The computer assigns a mobile by adding a mobile address in the data format to an address giving the exact place where the reply from this mobile has to be made.

At its first reply, the mobile replies by means of a pure CW carrier during one slot interval in order to give time to the computer aided phase locked loop to lock at the ground station. When lock is acquired at the ground station, the computer memorises the frequency received by the mobile and when this mobile is expected to reply once more, the computer sets the VCXO frequency of the phase locked loop to the original frequency.

The second reply comprises a 27 ms CW burst followed by a 133 ms of range tones and data status information, the last 40 ms being free of transmission in order to provide a guard time to prevent simultaneous reception at the ground station of two signals.

The 27 ms CW carrier burst is necessary for the phase locked loop to acquire rapidly and to be locked when the ranging measurement starts. Each mobile was interrogated at intervals of 10 replies per format, i.e. every 6.4 s.

Due to the fact that a measurement was made every 6.4 s. and that both the mobile and the spacecraft are moving, it has been assumed that the resulting displacement in a relatively low period of time was a straight line and therefore a linear regression method was used to establish the standard deviation of the range measurement.

6.1 Tone Ranging Results. The results of the aircraft tests are presented in Table 6.1 and show the two way range Rosman → aircraft → Rosman.

TABLE 6.1 AIRCRAFT RANGING RESULTS - PLACE TONES

Day	Elevation Angle	Data Points analysed	Correlation Coefficient	Measured C/N_o	Range Standard Deviation (metres)
81	11.2°	32	-.999	45	467
	9.4°	31	-.998	44	590
	11.6°	32	-.999	44	545
	12.6°	29	-.999	44	344
67	7.0°	23	-.997	47	609
	7.5°	20	-.998	47	418
	8.0°	11	-.992	47	654
	9.1°	19	-.998	47	419
	9.6°	25	-.997	47	664
	9.6°	28	-.998	48	705
	8.5°	39	-.999	48	850

The carrier to noise density C/No shown is, however, only that measured in the aircraft, the return link being operated at a relatively high C/No. Each data point in the table consists of a burst of 343 cycles of transponded tone, each burst taking place at 6.4 s. intervals, so that 32 data points cover an elapsed time of 3.31 minutes. The data validation criteria taken was that the correlation co-efficient for the linear regression should be better than 99% to avoid “system jumps” corrupting the data: as a result of this strict criterion a lot of the ranging data had to be rejected. The correlation of increasing ranging standard deviation with decreasing elevation angle was not absolutely established, although the trend was identified, leading us to believe that the same type of multipath noise corruption which affects the performance of the data channel is responsible. The C/No seems to play very much a secondary part, since the expected precision at 44 dB-Hz is about 100 m due to Gaussian noise alone. The PRNS system, (Ref. 13), gave results of about 100 m standard deviation under similar conditions.

7. Aeronautical and SAR Demonstrations. In order to demonstrate the capability of the AEROSAT system to potential users, airlines and aeronautical authorities, a series of tests using the satellite to relay operational voice and data messages was performed (Ref 11). The operational centre for the aeronautical demonstration was the NAFEC facility of the FAA, whilst the operational centre for the search and rescue (SAR) was the USCG HQ at Washington D.C., both centres being patched on telephone lines to the NASA Rosman Ground Station.

In the aeronautical demonstrations, voice and data messages were passed to the ESRO Comet and the FAA KC-135 aircraft.

For the SAR demonstration, performed about 100 miles North of the Azores, the DFVLR buoy (ref 12) was placed in the water and transmitted its AMVER-coded signal at 64 b/s FSK via the satellite to the Rosman ground station. Rosman alerted the USCG HQ at Washington D.C. which then coordinated via satellite links the Comet aircraft and the USCG ship Gallatin in the search for the buoy. The aircraft obtained a fix on the buoy after a 2-hour search, then vectored the Gallatin onto this fix, which was then refined by the direction-finder on the Gallatin. The buoy was picked out of the water about one hour after the aircraft fix. The wind force at the time was BFT 6. This was the first time that a SAR operation had been started and conducted using satellite communications.

8. Conclusions. The voice tests compared DELTA-PSK with adaptive NBFM from test material consisting of logatoms, SCIM sequences, and PB word lists. The winning candidate was clearly DELTA-PSK; partly because of transmission efficiency but mostly because of the capability to be unaffected by multipath noise at the lower elevation angles, since it can provide AEROSAT MOU voice link quality at 10^{-1} BER.

An investigation of multipath noise and its effects on the PSK data transmission system was performed leading to the general conclusion that this problem is a serious one for coherent demodulators of the phase-lock type. The DECPSK system tested exhibited a strong tendency towards a Rayleigh channel BER situation at low antenna signal to interference ratios.

The MOU requirement for BER of 1×10^{-5} required C/No’s in excess of 48 dB-Hz for the 10 degree elevation angle contour measurements. The solution to this problem is clearly encoding of the data message, allowing perhaps a reduction in the data error rate to 10^{-4} or even to 10^{-3}, which can then provide adequate data link performance over an AEROSAT 48 dB-Hz channel.

A fading analysis ref 1 shows that a 5 dB margin is adequate for the AEROSAT service; when the aircraft are equipped with the slot dipole class of antenna system. However, the margin could be reduced for future generations of the system when phased arrays on the aircraft might reduce the multipath fading to negligible proportions.

The ranging results show the feasibility of achieving standard deviations of range of around 500-600 m for the PLACE tone system with its rather short integration time of 120 ms. A standard deviation of 100 m has been measured on the pseudo-random coded system operated on a CW basis (Ref 12). This latter, however, could be operated on a TDMA basis with a consequential increase in error due to a shorter measurement time from each aircraft.

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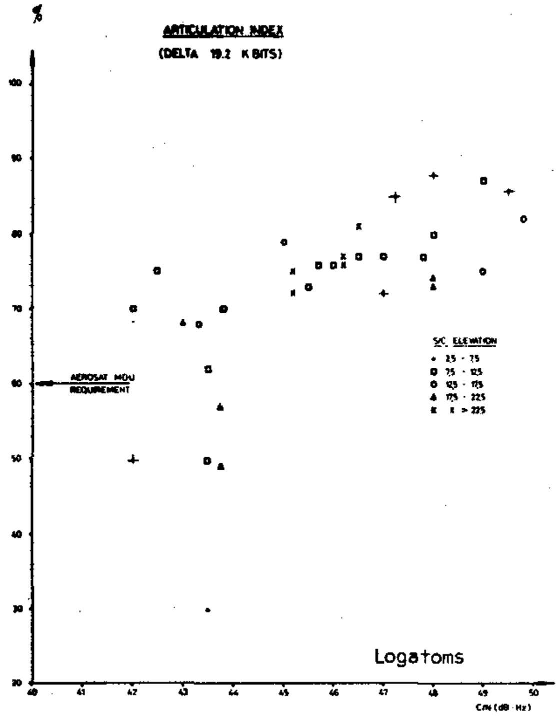


Fig. 4.1

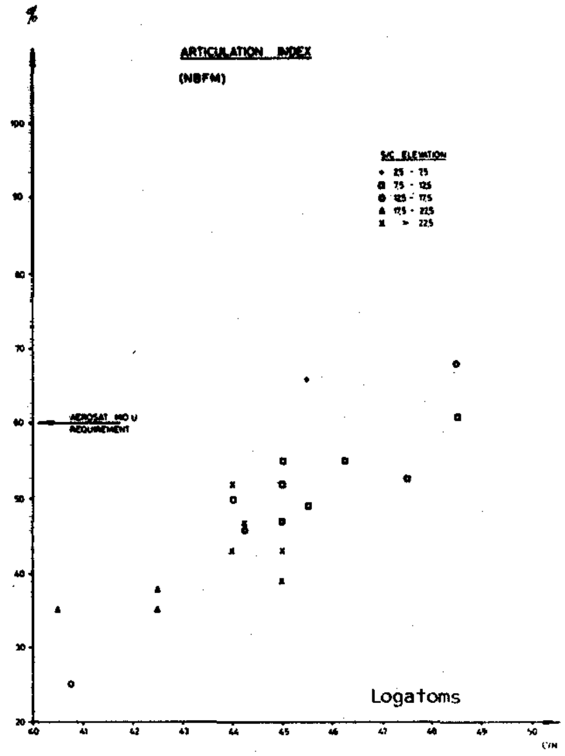
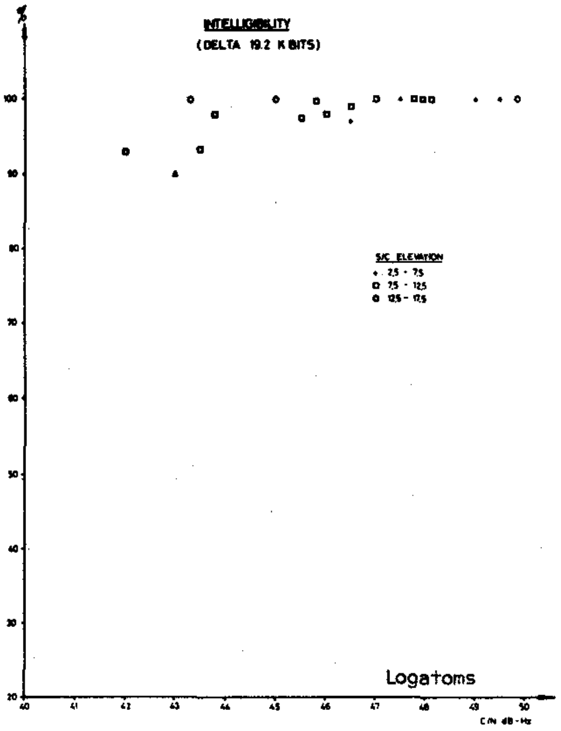


Fig. 4.2



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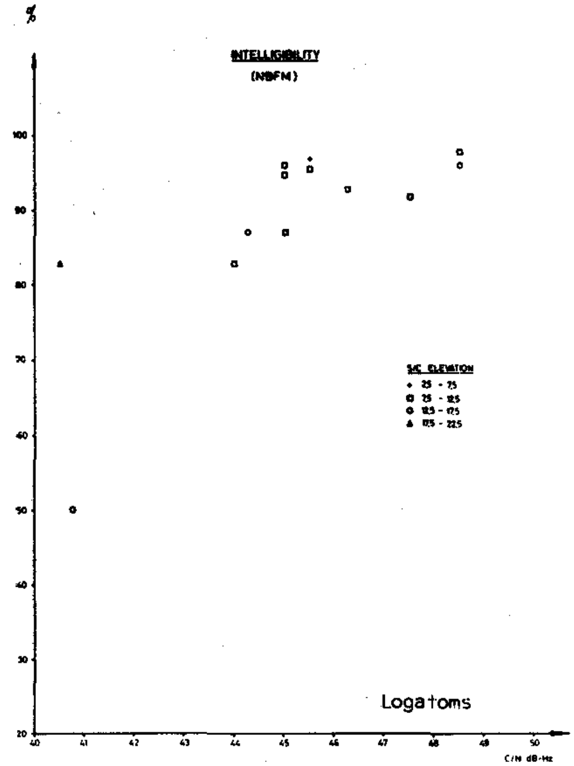

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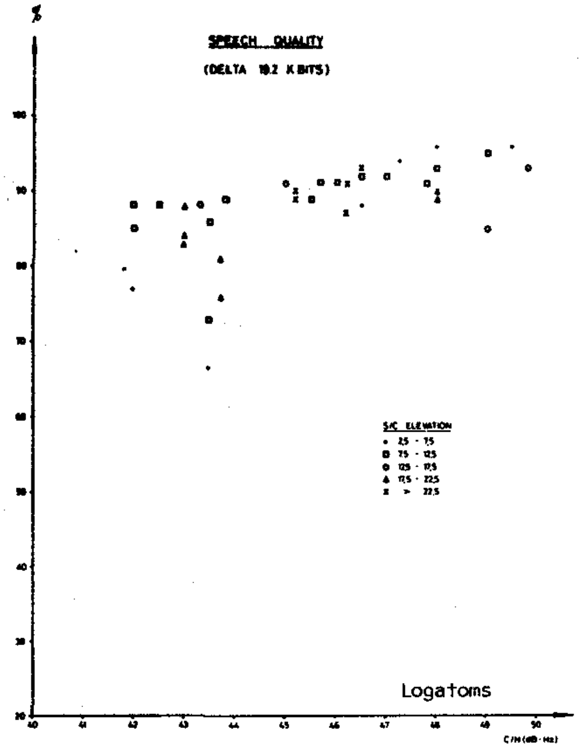

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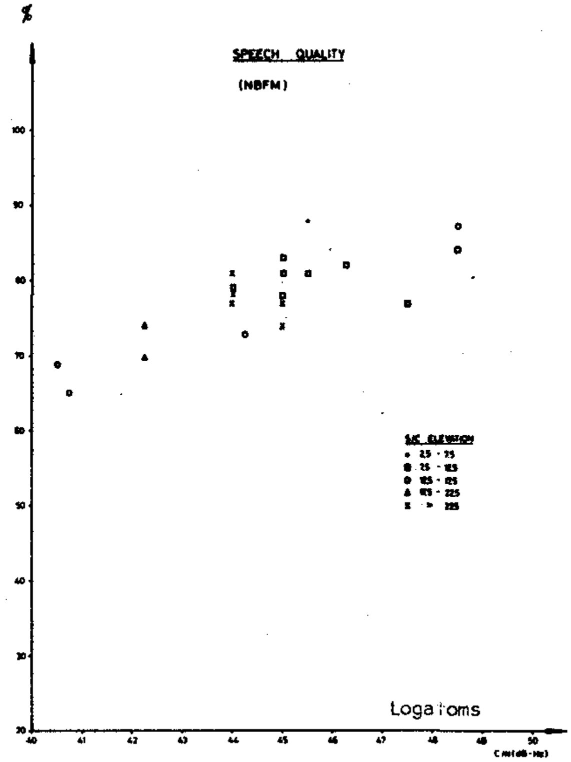


Fig. 4.6

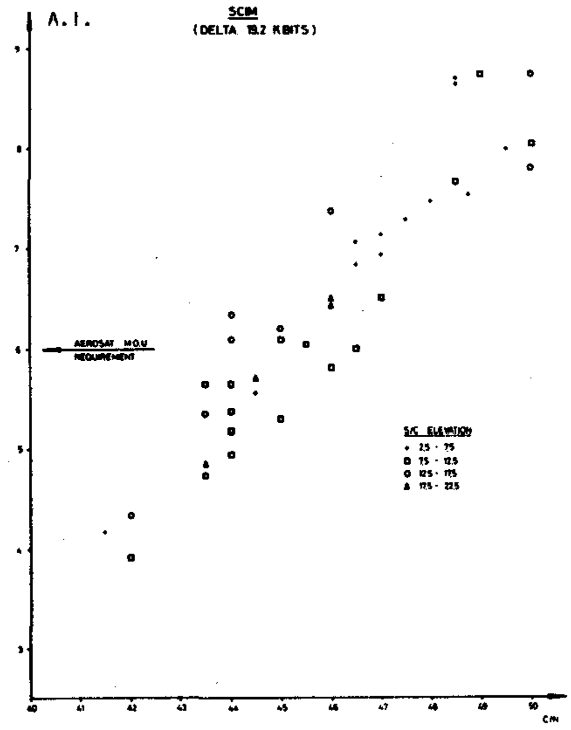
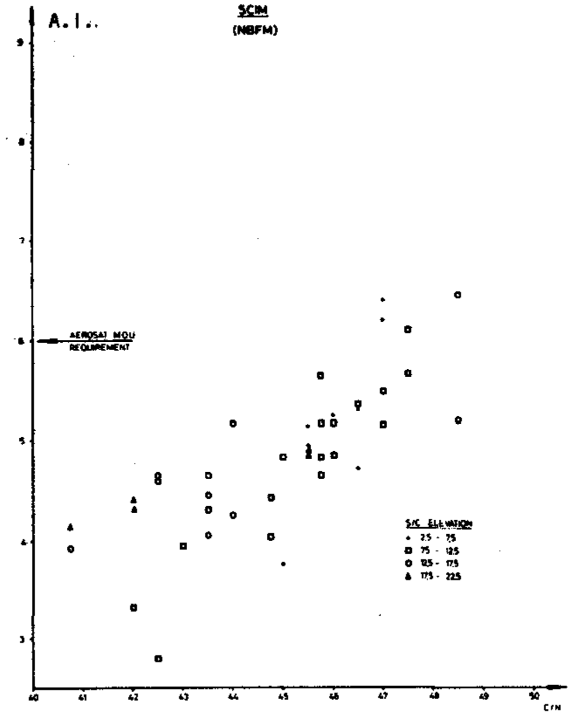


Fig. 4.7



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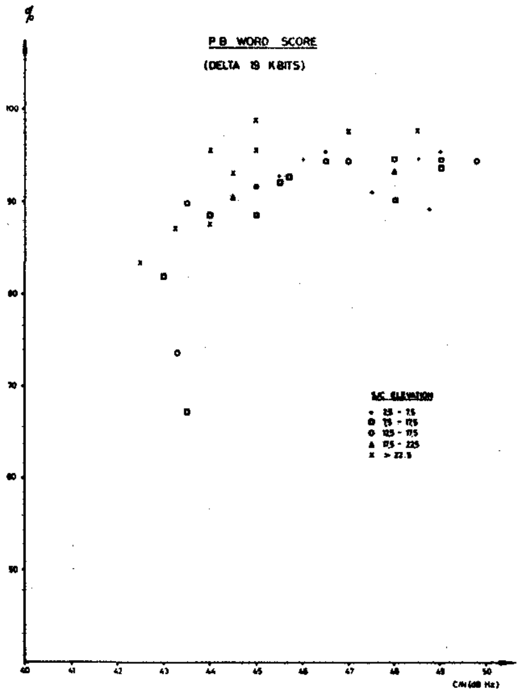

Fig. 4.9

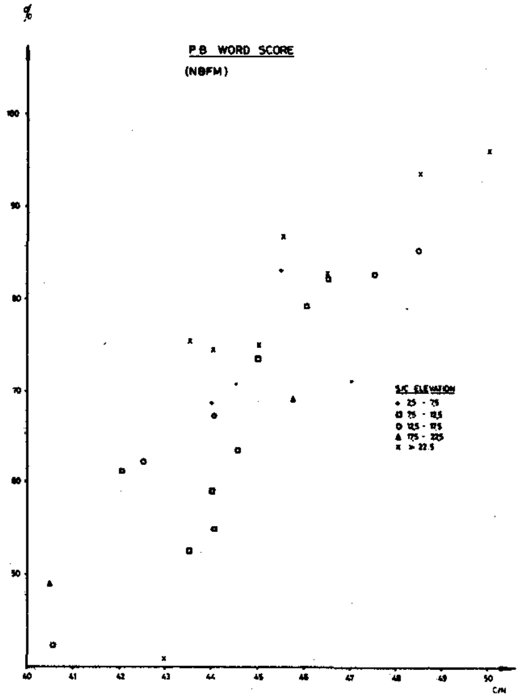

Fig. 4.10

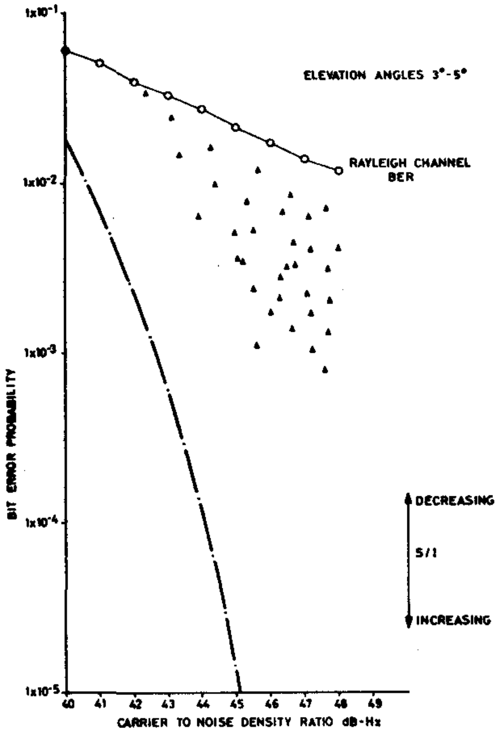

Fig. 5.1

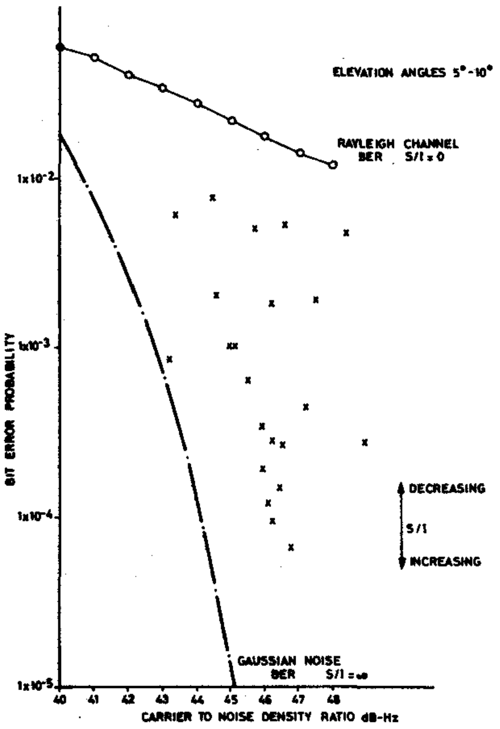

Fig. 5.2

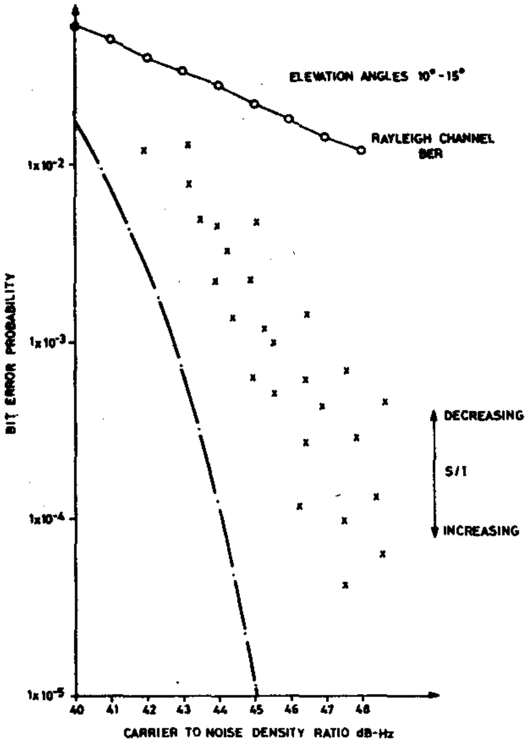
ELEVATION ANGLES 10°-15°
RAYLEIGH CHANNEL BER
BIT ERROR PROBABILITY
1x10^-2
1x10^-3
1x10^-4
1x10^-5
DECREASING
S/I
INCREASING
40
41
42
43
44
45
46
47
48
CARRIER TO NOISE DENSITY RATIO dB-Hz

Fig. 5.3

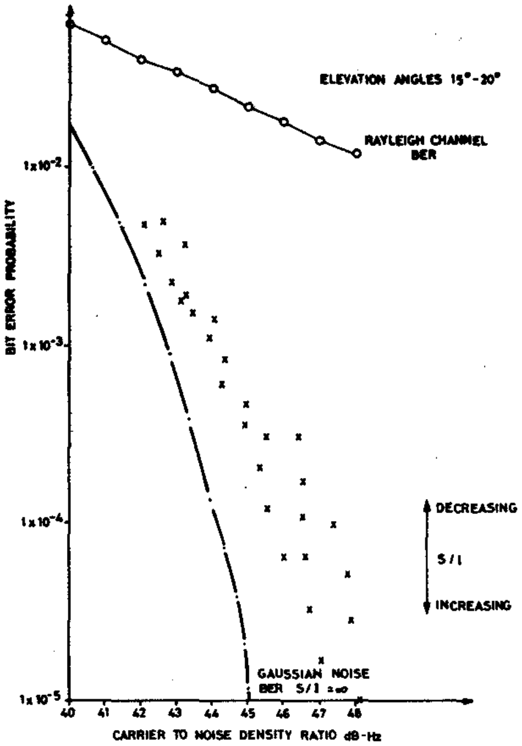
ELEVATION ANGLES 15°-20°
RAYLEIGH CHANNEL BER
BIT ERROR PROBABILITY
1x10^-2
1x10^-3
1x10^-4
1x10^-5
DECREASING
S/I
INCREASING
GAUSSIAN NOISE BER S/I =∞
40
41
42
43
44
45
46
47
48
CARRIER TO NOISE DENSITY RATIO dB-Hz

Fig. 5.4