REPORT 1173

TECHNICAL AND OPERATIONAL CONSIDERATIONS FOR AERONAUTICAL MOBILE-SATELLITE COMMUNICATIONS

(Question 82/8)

(1990)

1. Introduction

The purpose of this Report is to discuss factors relating to the aeronautical satellite communications being considered for the 1.5/1.6 GHz band.

1.2 At the present time, only terrestrial radio communication networks are available in HF and VHF bands for Air Traffic Service (ATS), Aeronautical Operational Control (AOC), Aeronautical Administrative Communications (AAC) and for passenger communications. However, with terrestrial communication networks, aircraft are not always able to reliably communicate with land-based points, especially when they are far from land. Satellite services offer the capability to improve channel capacity, quality and reliability for aircraft communications in many areas of the world.

1.3 In the early and mid 1970s, extensive aeronautical experimental and demonstration tests in the 1.5-1.6 GHz band were carried out to validate the feasibility of aeronautical mobile-satellite communications and to demonstrate operational capability. There has been a renewed effort to carry out further experiments and operational tests in pursuing operational capability in the near-term.

1.4 ARINC/SITA, and others are planning to introduce aeronautical satellite communication services on a commercial basis in 1990, through the INMARSAT Space segment.

2. The present situation and future plans

2.1 The international civil aviation community is actively pursuing the implementation of an aeronautical mobile satellite service (AMSS) to provide air traffic service, operational control, administrative and passenger communications. ICAO estimates that by the end of 1990, 53 air carrier aircraft world-wide will be equipped with AMSS avionics and by the end of 1994, more than 350 aircraft, including general and business aviation aircraft, will be using this equipment. Some aeronautical authorities are in the process of implementing essential air-traffic service improvements based on satellite communications, in particular, in oceanic areas. Initial phases will be in service by the end of 1990.

2.2 In support of this aviation community initiative, the International Civil Aviation Organization (ICAO), in discharging its responsibility to adopt Standards and Recommended Practices (SARPs) for international civil aviation, is developing SARPs for AMS(R)s. The satellite system architecture developed by the ICAO Future Air Navigation Systems Committee, the aviation system definition manual of IMARSAT and the AMSS equipment characteristic adopted by the Airline Electronic Engineering Committee (AEEC) are the bases for the SARPs under development. The RTCA special committee 165 is in the process of developing avionics characteristics which are consistant with ICAO SARPs.

2.3 the SARPs will assure that aircraft operating world-wide can receive aeronautical mobile satellite service meeting aviation requirements through any conforming aeronautical earth station.

2.4 Japan is performing pre-operational communication experiments via an INMARSAT satellite to demonstrate and evaluate public telephone and facsimile services using a passenger aircraft (Boeing 747). Transoceanic flight routes between Japan and North America are being used. [Makita, F. et al., 1988] Preoperational, aeronautical satellite communication experiments are also being performed in Canada via an INMARSAT satellite. The United Kingdom has conducted development trials in 1988 (see ref. Schoenenberger) to prepare for the introduction of telephone service for aircraft passengers utilizing INMARSAT satellites. Trials, intended to lead to the introduction of a commercial service, were continuing in 1989.

2.5 Several experiments of low speed data communications have already been carried out by European Space Agency (ESA), Canada, the Federal Republic of Germany and other countries [Rogard and Pinelle, 1987] [Neal et al., 1987][Wachira et al., 1987]. Aeronautical experiments on propagation and low speed transmissions using an INMARSAT satellite in the ESA PRODAT programme have provided useful results.

2.6 In Japan a project known as the Experimental Mobile-Satellite System using the ETS-V (ETS-V/EMSS) is currently underway for establishing, inter alia, basic technologies for AMSS communications. [Hase et al., 1986]. The ETS-V was launched in August 1987 for the purpose of establishing basic technologies of three axis stabilized geostationary-satellite and satellite communications for aircraft, ships and land vehicles. Experiments on aeronautical satellite communications in the EMSS are being carried out using a commercial jet plane on transoceanic flight routes and a private plane on domestic flight routes and these experiments include low, medium and high speed data transmissions, voice and positioning [Ohmori et al., 1986] [Niimi et al., 1987].

2.7 Consideration must be given to frequency sharing with other primary services operating in the AMSS bands. Annex I presents a preliminary analysis of sharing with the terrestrial fixed service.

2.8 A planned aeronautical mobile satellite service (AIRCOM) is described in Annex II, and the INMARSAT aviation system is described in Annex III.

2.9 It should be noted, however, that though the ICAO, AMSS system architecture and the AEEC standards indicate reception and transmission capabilities of the AMSS communications in the 1544-1545 MHz and 1645.5-1646.5 MHz distress bands, respectively, precautions should be taken to preclude any and all inadvertent signal emissions in these bands which might interfere with the reception of the satellite emergency position indicating radio beacons (EPIRB) signals or other satellite distress and safety communications being transmitted over these bands.

3. Technical Aspects

3.1 System characteristics

The system architecture is fully described in the FANS/4 report [ICAO 1988]. The ICAO SARPs being developed are based on AEEC and INMARSAT submissions and will be published in the appropriate ICAO documents and subsequently in Annex 10 to the Convention on International Civil Aviation on completion of the ICAO consultative procedure. All systems providing a service to international civil aviation will have to meet the applicable ICAO SARPs. For further studies, refer to the pertinent documents of ICAO for the system characteristics of the aeronautical mobile satellite service.

3.2 Avionics Interfaces

3.2.1 General

The aircraft earth station will be required to deal with three types of inputs:

1) control information (e.g. log-on, flight number);

2) user data (e.g. ATS, AOC, AAC and passenger communications);

3) voice (cabin and cockpit).

3.2.2 Data processing

Data will come from a number of sources in the aircraft, such as the inertial navigation system, crew-operated control panels, etc. Because of the wide variety of sources and the unlikelihood of developing an entirely standardized system, it is possible that these data inputs will be pre-processed in a customized Data Management Unit prior to application to the satellite communication system. Data from the ground will normally be printed or suitably displayed for use by the crew. ICAO is using an International Standards Organization (ISO) Open System Interconnection (OSI) concept for data communication exchange [ICAO, 1988].

3.2.3 Voice traffic

Voice traffic on the aircraft will be derived from two sources, cockpit and passenger cabin. It is possible that these could be processed differently; for example, different coding rates could be used for cockpit and cabin voice although for some applications they will be the same. Several in-cabin installations could be the source of the cabin traffic; it will be necessary to select the active source from those available, possibly through an aircraft PBX.

3.3 Multipath fading

3.3.1 Multipath fading effects, especially sea reflected multipath, in aeronautical satellite communications is an important channel parameter that has been the subject of investigation since the early 1970s. The factors that need to be taken into consideration include the following:

1) differential delay time of propagation between a direct signal and signals reflected by sea and/or land surfaces; (see Report 1169)

2) frequency selective fading caused by aircraft flying at high speed and at high altitude;

3) evaluation of fading effects taking account of antenna location on the fuselage.

3.3.2 Recent experiments in multipath effects have been carried out by the Federal Republic of Germany using an INMARSAT satellite, and are summarized in ——— Report 1169.

3.3.3 At the present time, Japan and many other countries are carrying out aeronautical satellite propagation experiments. The results and discussions will greatly contribute to the early introduction of aeronautical satellite communications.

3.4 Doppler effects

Doppler effect is an important factor for synchronization of demodulator in aeronautical satellite communication. In Japan, aeronautical satellite experiments via ETS-V and INMARSAT satellites have been carried out using a commercial jet plane on transoceanic flight routes. [Hase, Y. et al., 1989, Makita, F. et al., 1988] The results indicates that the Doppler frequency shift is 1.2 kHz at its maximum and its change is 1 to 4 Hz per minute during cruising of airplane, but when the airplane changes its direction rapidly, the change of frequency shift reaches 15 Hz per second.

3.5 Modulation/Voice coding

Digital techniques can efficiently utilize the limited signal powers and bandwidth. The ICAO FANS Committee has adopted two modulation techniques [ICAO, 1988]. For radio frequency channel data rates up to and including 2400 bits per second, Aviation Binary Phase Shift Keying (A-BPSK) would be used. For rates above 2400 bits per second, Aviation Quadrature Phase Shift Keying (A-QPSK) would be used. A-BPSK is based on optimized pulse shaping/filtering applied to a form of BPSK where every second symbol is transmitted in the quadrature channel. A-QPSK is based on optimized pulse shaping/filtering applied to a form of unfiltered offset QPSK. Based on subjective tests a vocoder operating at 9.6 kbits per second has been choosen by the international airline AEEC forum. For error correcting, convolutional coding/Viterbi decoding with R-1/2, and 3/4, with K-7 has been selected by ICAO FANS [ICAO 1988]. These specifications are incorporated in the technical performance requirements for the INMARSAT system [INMARSAT 1988].

3.6 Commonalty and compatibility between terrestrial and satellite networks

Presently aeronautical mobile communications are provided by terrestrial networks implemented below 1 GHz. To simplify future avionics carriage requirements, ICAO is considering the potential of using common avionics components for both satellite and terrestrial mobile safety communications. From the initial ICAO studies it appears difficult to integrate terrestrial and satellite systems within the same frequency band and within common equipment.

3.7 Access techniques

Frequency division multiple access (FDMA) and time division multiple access (TDMA) have been selected by the ICAO FANS Committee [ICAO, 1988]. When relatively few channels on an aircraft are required, FDMA single channel per carrier (SCPC) could provide a simple, efficient and inexpensive implementation. In an aeronautical mobile-satellite system, important factors are the size and weight of on-board communication equipment and the power dissipation of the transmitter, and therefore the selection of a multiple access technique needs to be taken into account. In general, the use of FDMA SCPC technique for multiple APC channels may require a Class A linear amplifier when multiple carriers are used.

3.8 System Architecture

3.8.1 The ICAO aeronautical mobile-satellite system architecture has a minimum level 1 capability that is based on the use of a nominal 0 dBi gain aircraft antenna, and will be used for the provision of basic ATC and AOC low speed data services. The architecture includes provisions for evolutionary growth in functional capabilities and system capacity that allows for higher speed data and digital voice service as required. All aircraft operating in the global system are required to have, as a minimum, the level 1 capability. The level 1 capability uses TDM RF links in the ground to air direction, and a combination of random-access and organized TDMA links in the air to ground direction, both directions carrying packet-mode data services. Enhanced capabilities include circuit-mode voice services, for which a nominal aircraft antenna gain of 12 dBi is required.

3.9 Surveillance

In civil aviation, safe flight is the most important factor, and for this purpose surveillance is an essential function. Two types of surveillance are considered for satisfying operational needs. One is Automatic Dependent Surveillance (ADS), by which an aircraft transmits its position, derived from on-board navigation system data, to an aeronautical earth station. ADS implementation is expected to be the surveillance basis for ATC over large oceanic areas and may allow an increase of air traffic density over remote and oceanic areas when it is available. The other is Cooperative Independent Surveillance (CIS), which is analogous to Secondary Surveillance Radar (SSR), and is largely independent of aircraft signal processing.

3.10 Aircraft antenna types

3.10.1 Two types of antennas are defined:

a) Low gain. These have a gain sufficient to achieve a receiving subsystem gain-to-noise temperature (G/T) of not less than -26 dB/K over the coverage volume except that within the region +/-20 degrees of the zenith, where a G/T as low as -28 dB/K is permitted.

b) High gain. These have a gain sufficient to achieve a receiving subsystem gain-to-noise temperature (G/T) of not less than -13 dB/K over not less than 85 per cent of the coverage volume.

3.10.2 Aircraft earth stations intending to operate at rates above 1,200 bits/s may need to employ a high gain antenna system, depending on technical characteristics of the satellite system. A number of antenna types are being developed by different companies worldwide to conform to these requirements.

3.10.3 Coverage volume

Antenna systems should be installed to meet specified operational performance requirements for transmitting and receiving over a coverage volume relative to the aircraft horizontal line of flight. The minimum coverage volume should provide for a -26 dB/K G/T over an azimuth of 360 degrees and from 10 to 90 degrees in elevation from a horizontal plane except in the volume +/-20 degrees from the zenith where G/T as low as -28 dB/K is permitted.

3.10.4 For aircraft antennas not only electrical requirements but also physical requirements such as vibration, thermal and mechanical strength must be satisfied. Furthermore, it is desirable that aircraft antennas be suitable for installation on many types of aircraft.

3.10.5 Aeronautical satellite communication experiments using low gain types of antennas have already been performed by the United States, Canada and the Federal Republic of Germany. In Japan, experiments using high, and low gain types of antennas are being carried out for demonstrating ATC, AOC, AAC and passenger communications through satellite links. Japan's aeronautical satellite communication experiments using ETS-V and INMARSAT satellites are being carried out using commercial jet liners on transoceanic flight routes. The results will provide a significant contribution to the early introduction of commercial aeronautical satellite communications.

(See also Report 1047)

4. Operational Aspects

4.1 Types of Communications and Priority

4.1.1 Safety and regularity Communications

4.1.1.1 The special rules relating to types of communications in the Aeronautical Mobile (R) and Aeronautical Mobile Satellite (R) Service are contained in Nos 3630 (Mob87) and 3633 (Mob 87) of the Radio Regulations. The former reserves the frequencies allocated to these services to "communications related to safety and regularity of flight". The latter prohibits, the transmission of public correspondence in any band allocated exclusively to the aeronautical mobile or aeronautical mobile satellite services. However, the WARC-Mob'87 adopted RR 729A in which public correspondence with aircraft earth stations is permitted in the bands 1545-1555 MHz and 1646.5-1656.5 MHz.

4.1.1.2 Safety and regularity of flight are operational concepts and receive attention and definition in the documents of the ICAO, in particular the Convention of International Civil Aviation, and Annexes 6 and 10 to that Convention. Specifically Article 37 of the Convention requires the adoption of internationally agreed standards and recommended practices concerned with the safety, regularity and efficiency of air navigation. The operational circumstances to which the definition of safety and regularity may be applied are also listed in Annex 10 Vol II. The provisions quoted in Annex 10 are internationally agreed Standards for which compliance is normally obligatory and may only be waived by a declaration of non-compliance by the state concerned.

4.1.1.3 Safety and Regularity Communications may be further separated into the following two operational classifications:

a) Air Traffic Service Communications (ATS)

Under ICAO rules, as specified in Annex 6 to its Convention, and as further laid down in national regulations, an air traffic service requires the aircraft and the ground stations to exchange messages concerning distress, urgency, flight safety and regularity, and meteorological conditions. These communications are mandatory in any airspace promulgated by national authorities as being regulated for air traffic purposes and are for the specific purpose of ensuring the safe separation of aircraft in flight and for their safe landing and take-off at aerodromes.

b) Aeronautical Operational Control (AOC)

The exercise of operational control by aircraft operating agencies is a recognized and necessary practice and is covered by the internationally agreed Standard contained in Annex 6 to the aforementioned Convention. The definition for operational control in that document makes provision for the exercise of control over the "initiation, continuation, diversion or termination of a flight in the interest of the safety of the aircraft and the regularity of the flight. Such control is normally exercised by the aircraft operating agency having responsibility for the flight". It has long been recognized that operational control communications fall within the category of safety and regularity as covered by RR 3630 (see also 27/194A in Appendix 27 Aer 2 to the Radio Regulations).

4.1.2 Aeronautical Public Correspondence (APC)

4.1.2.1 Public correspondence receives mention at RR 110 to the Radio Regulations (repeated from 2004 of the ITU Convention). The non exclusive definition in these documents identifies access by the public as a prime characteristic which relates to this category of correspondence. In the context of the aeronautical mobile service and the recently agreed provisions for access by public correspondence it may be assumed that this classification will include all of those communications not meeting the definition of safety and regularity of flight (Ref. ICAO-Annex 10 Vol. II para 5.1.8.4 and 5.1.8.6) These communications may be telephone voice, telephone data, or other data for onward transmission over public fixed networks and be for purposes associated with the needs of passengers, or crew, or for airline purposes other than strict operational control.

4.1.2.2 Within the broad definition of APC the following types of communications have been mentioned and have received attention in discussions relating to the authorization of public correspondence in the Aeronautical Mobile Service:

a) Aircraft Passenger Communications

This category would comprise all those communications services used by passengers for communications with the ground whilst the aircraft is in flight. Telephonic communications, transmitted by analogue or digital methods, would form the major element in this category; however, the personal requirements of crew and other company personnel aboard may also be considered appropriate to this class. Similarly the communications of smaller executive aircraft passengers and/or crew for purposes other than air navigation would be covered by this classification.

b) Aeronautical Administrative Communications (AAC)

Aircraft operating agencies have a communications requirement related to the business aspects of the flight and the air transport service. These communications do not fall within the operational control category and may relate to a variety of purposes such as flight and ground transportation bookings, deployment of crew and aircraft, organization of supplies and services for ongoing and for return flights or any other logistic purpose which maintains or enhances the efficiency of the overall flight operation. A basic requirement would be that the purpose is one associated with the airline, aircraft, crew or passenger and a particular flight or flights.

4.2 Communication requirements for aeronautical safety services

4.2.1 These may be described as follows:

a) because of the world-wide nature of civil aviation where the same aircraft can appear in widely different parts of the world within hours, international standards (both technical and operational) are required for aeronautical safety and regularity of flight communications.

b) communication system parameters and practices must assure a very high level of performance, integrity, reliability and availability. International air traffic movements are conducted predominently on the basis of instrument flying and are subject to ground control. Accordingly, communications are required day by day, minute by minute to assure that aircraft are safely separated while achieving regular and economic operation. Virtually immediate access is required while ensuring that messages are not subject to misunderstandings, since only seconds may be available to avoid an accident.

c) the high standards imposed in b) above make it essential that these services be protected from harmful interference in accordance with Radio Regulation 953 (RR 953).

d) the long life-cycle characteristic of aircraft and aeronautical communication system ownership make it essential that adequate spectrum be available to implement near term services and to accommodate future world-wide plans for evolutionary growth while maintaining as a minimum, the current high level of safety.

4.2.2 The aeronautical mobile-satellite service has a number of distinctive features, which are brought about by the following requirements:

a) the time taken to establish a connection must be extremely short, not more than 2 to 5 seconds; this is related to the need to ensure flight safety;

b) the need to transmit large volumes of high priority information (ATS, AOC);

c) the low EIRP of aircraft satellite communications stations; and

d) substantial limitations with respect to the weight and over-all dimensions of aircraft satellite communications stations, etc.

4.2.3 Priority

4.2.3.1 It may be noted that provision has been made in footnote 729A (MOB 87) of the Radio Regulations for priority to be given at all times to communications required for the operation of the aircraft (priorities 1 to 6 of Article 51 of RR's). Where all of the types of messages described above are transmitted over a common system a technical means has to be provided to ensure that aeronautical messages with priorities 1 to 6 are not delayed by lower priority messages.

4.2.3.2 ATS and AOC carry the higher priority communications related to safety and regularity of flight. AAC and passenger communications are lower priority non safety communications and can be preempted when system capacity is exceeded or during emergencies. AAC and passenger communication may be prohibited during certain flight conditions and therefore may not always be available for use.

4.2.4 Performance considerations

Quality of channels depends on the types of communications and bit error ratio of about 10^{-5} is deemed to be needed for data communications and around 10^{-3} for voice. Forward error correction (FEC) and interleaving techniques can be used to reduce the effect of bit errors. In communication channels that require high integrity, additional block coding can be applied. Automatic Repeat Request (ARQ) techniques can be used to improve the probability of message transmission.

4.3 Service coverage

4.3.1 The area over which services will be available from the satellite for aeronautical communications depends on a number of factors including:

1) the effective gain of the aircraft antenna in the direction of the satellite as the aircraft is manoeuvring;

2) the signal level received by the satellite from an aircraft with which it is communicating, which depends on the satellite and aircraft antenna gains and on the path loss in the direction to the satellite;

3) the e.i.r.p. of the signal emitted by the satellite;

4) the signal level received by the aircraft from the satellite with which it is communicating.

4.3.2 One fundamental limitation on service area is that of the geometry relating to the geostationary satellite orbit. This results in lack of coverage in polar regions. It would be possible to use satellites in other orbits to provide coverage for the areas not served by geostationary satellites. Such systems are currently under study.

4.4 System and network interconnections

Methods of connection with private and public systems and networks, will need to be developed taking into account advice from appropriate bodies.

5. Conclusion

Discussions on aeronautical satellite communications have to take account of the priority needs for safe operation of aircraft. Avionics that satisfy the severe requirements of aircraft environments are essential. Further considerations will be needed on the possibility of compatibility and commonalty with other satellite communication systems such as maritime and land mobile communication systems, to maximize benefits from such system aspects as sharing space segments, etc. These aspects are further studied in Report 1180 on sharing aspects within the various mobile satellite services.

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ANNEX I

FREQUENCY SHARING CONSIDERATIONS BETWEEN THE AERONAUTICAL MOBILE-SATELLITE SERVICE AND TERRESTRIAL FIXED SERVICE IN THE 1.5 - 1.6 GHz BANDS

1. Introduction

In the Radio Regulations Table of Frequency Allocations (Article 8), as amended by WARC-MOB-87, the 1 545 - 1 555 MHz (space-to-Earth), and 1 646.5 - 656.5 MHz (Earth-to-space) bands are allocated on a primary basis to the aeronautical mobile-satellite (R) service. In the frequency bands 1 555 - 1 559 MHz and 1 565.5 - 1 660.5 MHz bands allocated to the land mobile-satellite service, operation of aircraft earth stations is permitted (RR 730A). The WARC-MOB-87 allowed public correspondence from aircraft in parts of these bands (RR 729B). The frequency bands 1 550 - 1 559 MHz and 1 646.5 - 1 660 MHz are also allocated to the fixed service on a primary basis within those administrations shown in RR 730. It should be noted that most of these AMSS allocations are shared with the fixed service operating on a secondary basis (RR 727).

The potential modes of interference between the terrestrial fixed service and aeronautical mobile-satellite service (AMSS) in the 1.5 - 1.6 GHz bands are listed in Table I with references to the relevant sections of this annex.

TABLE I

Relevant Modes of Interference

Interfering Station	Wanted Station	Frequency Band (MHz)	Annex I Section No.
Fixed	Satellite	1 646.5 - 1 660	2
Satellite	Fixed	1 550 -1 559	3
Earth station	Fixed	1 646.5 - 1 660	4
Fixed	Earth station	1 550 - 1 559	5

Insofar as some key characteristics of AMSS systems are not yet defined or known, including an AMSS noise budget, it is not possible to fully address the above interactions. As noted in the main text, this situation is expected to change in the near future. On the other hand, the fixed service is well established. Report 379 gives characteristics of representative fixed service systems and various Recommendations of Study Group 9 define and apply the fixed service interference budget with respect to the fixed-satellite service. It is assumed that this budget of the fixed service for interference from the fixed-satellite service may also include the AMSS.

2. Interference to AMSS Space Station Receivers form Fixed Service Transmissions

RR Article 27 stipulates the antenna pointing, antenna input power and e.i.r.p. limits for fixed stations in order to protect previously anticipated space station receivers. These limits were based on Recommendation 406 and derived from considerations of fixed -satellite systems operating at frequencies much higher than 1.6 GHz. The applicability of these limits to the AMSS is discussed below; however, a definitive analysis cannot be conducted until noise and interference budgets are established for the AMSS. (For an example analysis for the maritime mobile-satellite service, see Report 917).

RR Article 27 discourages the use of e.i.r.p. in excess of 35 dBW and antenna pointing within 2° of the geostationary orbit. When this is not practicable, the limit is 47 dBW for antennas pointing within 0.5° of the geostationary pointing and is relaxed to 55 dBW as the off-axis angle is increased to 1.5°. Such pointing restrictions are apparently designed for typical radio-relay systems operating at higher frequencies, where half-power beamwidths are on the order of 1° or less. However, at 1 660 MHz, a 1° beamwidth requires an antenna diameter of at least 12.8 meters. A more likely situation may be that radio-relay antennas in use at 1.6 GHz range in size from 1 m to 3 m and in beamwidth from 12.8° to 2.6°. Hence, the present RR pointing restrictions ranging from 0ff-axis angles of 0.5° to 2° do not appear to be meaningful.

The above e.i.r.p. and pointing limits were derived from an analysis of radio-relay main beam illuminations of the satellite, assuming few such intersections and that one-half of the interference under this mode would occur from these "direct" interference entries. The other half of the interference power budgeted for this mode was assumed to occur from "indirect" entries, where the interfering signals are radiated from the far side-lobes of the fixed station into the main beam of the satellite. (Side-lobe-to-side-lobe coupling was considered to be negligible.) The Article 27 antenna input power limit of 13 dBW is based on an analysis of the "indirect" entries, which can be assumed to relate to e.i.r.p.s towards the satellite of 8 dBW to 13 dBW. (Report 614 suggests a fixed station antenna gain value of -5 dBi for this situation, although the reference antenna pattern therein has a minimum gain value of 0 dBI.)

Some planned AMSS systems are envisioned to utilize aircraft earth station e.i.r.p.s of about 3 dBW to 26 dBW, depending on the type of service [AMSC, 1988] [Smith, 1987]. It would appear that the present Article 27 limits may not adequately protect such an AMSS system, since the e.i.r.p.s and perhaps the power densities of the interfering and desired signals are comparable. Nevertheless, the actual sharing situation may in fact be acceptable on the following basis:

- Actual fixed station antenna pointing, input power levels and e.i.r.p.s may be sufficiently constrained to preclude harmful interference. (A preliminary review of the relevant frequency assignments for the fixed service, which have been registered with the IFRB, indicates that the antenna input power levels range from 3 dBW to 10 dBW and that e.i.r.p.s. are typically about 38 dBW to 40 dBW. While these are well below the limits specified in RR Article 27, they are nevertheless of concern to the AMSS. It is realized that administrations may not notify all fixed service assignments, such as those for stations located well within their territorial borders, and that the above cited characteristics may not be representative of all systems in operation.)

\- While many AMSS satellite may be utilized, it may be practical for fixed stations to observe the appropriate pointing restrictions with respect to particular satellite positions, as opposed to the geostationary orbit in general.

\- In cases where a residual carrier of a fixed station exceeds an appropriate e.i.r.p. or power density limit, but the balance of the emission does not, it may be possible in the early years of AMSS operations to temporarily relax the limit in the case of an AMSS operations to temporarily relax the limit in the case of an AMSS using FDMA. (AMSS systems using wideband TDMA may not be able to offer such accommodations.) This may he practical provided that the AMSS system frequency plan is not unduly constrained and that intermodulation and transponder power waste levels are at acceptably low levels.

3. Interference to fixed service receivers from AMSS space station transmission

Article 28 limits interference form satellites to terrestrial stations by means of spectral Power Flux-Density (PFD) limits. However, there are no PFD limits in the existing provisions of Article 28 regarding the frequency band shown in RR 730.

As an example of the magnitude of the highest PFDs currently expected in the AMSS, the following figure is used:

$$-165 \text{ dBW/m}^2\cdot\text{Hz}$$

These are based on the following equation for required PFD:

$$\text{PFD (dBW/m}^2\cdot\text{HZ)} = E_b/N_o + T - 228.6 + 10 \text{ LOG } (R/B) - A_o + M \quad (1)$$

where:

E_b/N_o - ratio (in dB) of the energy per bit to the noise power per Hz, as required for a specified bit error ratio;

T - receiver system noise temperature (in dBK);

R - data rate (in bits per second) assuming BPSK modulation;

B - bandwidth (in Hz) of the emission from the AMSS satellite (assumed to be the bandwidth of the main lobe of the emission, which is twice the data rate for BPSK);

A_o - effective aperture area dB(m2) of the aircraft earth station antenna;

M - margin (dB) for multipath, polarization losses and other degradations.

Several of the parameter values needed for equation (1) have been specified by [ICAO, 1986], including a bit error ratio no greater than 10^{-5}; minimum aircraft receiver G/T of -26 dB(K^{-1}) and antenna gain of 0 dBi; and minimum data rate of 600 bits per second. These yield an E_b/N_o of 9.5 dB assuming BPSK; T of 26 dBK (400 K); R of 600 bits per second and B of 1 200 Hz; and Ao of -25.4 dB(m2). The PFD of -165 $dBW/m^2 \cdot Hz$ is consequently needed to provide a margin M of about 6 dB and is among the values being considered for various operational AMSS systems [Smith, 1987].

While the above example of AMSS PFD is significantly higher than the limits derived for the fixed-satellite service, the following factors may ameliorate the sharing situation

- Some AMSS systems may use spot or subregional beams from the satellite antenna, thus providing discrimination towards fixed stations outside the coverage area.

- The number of AMSS satellite is anticipated to be far less than the number of fixed satellites assumed in the PFD analyses upon which RR Article 28 is based. In any given area, it is unlikely that more than one of the above high-PFD channels will generate interference in the same 4 kHz reference bandwidth. This is virtually assured because the assumed 0 dBi aircraft earth station antenna would not permit frequency reuse in the same area on a co-channel, co-polar basis. The AMSS channels having lower PFD might generate two interference entries in the same 4 kHz reference bandwidth in the same area, but would perhaps pose a lower level of interference than one high-PFD channel.

- The fixed systems operating in the 12.5 GHz band may generally be encompassed in circuits having significantly fewer links than assumed in the fixed service hypothetical reference circuit. Fewer receivers in the fixed service system may be exposed to the AMSS PFD. Hence, the overall degradation to fixed circuits from a given PFD in this frequency range may be less than that at higher frequencies where the hypothetical reference circuit is more representative of actual networks.

4. Interference to Fixed Service Receivers from Aircraft Earth Stations Transmissions

Aircraft earth station transmissions may cause interference to fixed service receivers, as discussed in Report 773. However, in that study measurements showed the interference to be momentary (and perhaps acceptable on a statistical basis) because of the small fixed station antenna beamwidths that were considered therein (i.e., near 8 GHz). In the 1.6 GHz band, significantly broader fixed station beamwidths must be assumed. Factors that will minimize the possibility, duration and severity of harmful interference at 1.6 GHz include:

- The solution to the problem of fixed stations interfering with AMSS satellites, if by virtue of frequency planning, in that it would minimize the potentials for aircraft earth stations to interfere with fixed stations. Arrangements of frequency plans that would alleviate the one mode of interference will, to a certain extent, may also mitigate the other mode of interference if channel interleaving is used.

- The separation distances at which harmful interference occurs may not be large, since the fixed service e.i.r.p.s may be significantly higher than those of the interfering aircraft earth stations (see section 2). Hence, this potential problem may be a matter for national coordination and resolution, although this should not be prejudged to be the case.

- For the near future, geometrical configurations in which harmful interference may be expected might correspond with aircraft operations where relatively limited use of AMSS is foreseen in some areas, for example, the case of fixed-wing aircraft operations at low altitude and low speed. On the other hand, certain aircraft such as rotorcraft may characteristically operate in configurations in which harmful interference may occur.

5. Interference to Aircraft Earth Stations form Fixed Service Transmissions

The likelihood of interference from fixed service transmitters to the reception of AMSS signals aboard aircraft is significant because of the lower e.i.r.p.s from the AMSS satellites and the consequentially low received signal levels, as compared with the e.i.,r.p.s and potential interfering signal levels from fixed stations. In addition, high-flying aircraft provide the opportunity for the reception of interference form distant terrestrial transmitters. Depending on the relative coupling geometries of the radio-relay transmitting antenna and the aircraft satellite receive antenna, and antenna discrimination of 0 dB might be experienced. The line-of-sight distance over which a signal might be received from the terrestrial radio-relay is up to about 400 km. Hence, the received undesired signal may be more than 30 dB larger than the satellite signal, under line-of-sight conditions, depending on the satellite and fixed station spectral e.i.r.p. densities.

In areas of heavily-traveled air routes, potential interference may be alleviated by fixed service site selection, reduced transmitter powers with shorter paths, terrain shielding, frequency planning and geographical separation. Further study is required to verify the practicality of these measures.

6. Summary

A preliminary assessment of the frequency sharing between the AMSS and the fixed service has been conducted. It was found that there are significant possibilities for harmful interference between these services. However, further study is required in the following areas:

- noise and interference budgets for the AMSS;
- typical fixed service power spectral densities;
- derivation of fixed station antenna pointing, limits input power and e.i.r.p. limits needed to protect AMSS satellites;
- derivation of AMSS satellite PFD limits needed to protect fixed stations;
- Interference between aircraft earth stations and fixed stations, including the application of the coordination and protection area principles of Report 773.

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ANNEX II

Planned World-wide AIRCOM Service

1. Introduction

This Annex describes a planned global Aeronautical Mobile Satellite Service (AIRCOM) which will be offered to commercial airlines and their passengers.

Planning and provisioning of AIRCOM service involves OTC Australia, Teleglobe Canada, France Telecom and SITA (Societe Internationale des Telecommunications Aeronautique).

Network characteristics on this service will be fully compatible with the INMARSAT aeronautical mobile satellite specifications and the Airline Electronic Engineering Committee (AEEC) 741 specification.

2. Satellite AIRCOM Service

Comprehensive air-ground data communications together with high quality air-ground voice capabilities will be provided by Satellite AIRCOM to cater for the following applications:

- Aeronautical Operational Communications (AOC),
- Aeronautical Administrative Communications (AAC), and
- Aeronautical Passenger Communications (APC).

This system will also provide for communications related to Air Traffic Services (ATS), including Automatic Dependent Surveillance, and data/voice communications between the aircraft crew or systems and ATS personnel or terminals.

Among the benefits offered to airlines and aircraft operators by this service are:

- a coordinated network of earth stations for access to the available space segment in the 3 ocean regions: Atlantic, Indian, and Pacific Ocean Regions.
- full compatibility with VHF Air Communication services both in the aircraft and on the ground.
- uniform interfaces with public networks to ensure the consistent and efficient switching of data and voice calls.
- comprehensive centralized service administration including billing of passengers on behalf of the air carriers.
- assistance to airlines for the planning and introduction of the service, including coordination and support of trial programmes.

Regarding data communications, the following typical AOC/AAC applications may be considered:

- Aircraft weather reports sent automatically to meteorological stations worldwide, for the benefit of other aircraft flying within the same area.
- Easy and automated access to ground facilities for cockpit crew, eg. flight planning, surface weather and 'Notice to Airmen" (NOTAM) services, such as the ones available at the airline main base.
- Near real-time analysis of the data synthesized by modern Digital Flight Data Acquisition Units (DFDAU) or Aircraft Condition Monitoring Systems (ACMS).
- Aeronautical Administrative Communications to open a new range of in-flight services such as reservations, arrival procedures and assistance, etc.

From a technical standpoint, data communications via Satellite AIRCOM will be available to aircraft fitted with either:

- a low gain aircraft antenna (0 dBi), offering low rate data services from 600 bit/s with the possibility of up to 1200 bit/s using future generation satellites;
- a high gain antenna (12 dBi), through which the system can support a variety of data streams up to 10.5 kbit/s and a high quality voice communications encoded at 9.6 kbit/s.

Regarding voice communications, the following will be offered:

- Air crew voice communications to the PSTN, airlines' private networks and ATC centers, etc.

- Aeronautical Passenger Communications (APC) by means of direct dialing from the aircraft. Calls to any destination in the world through the international PSTN networks using payments by credit cards without the assistance of cabin crew.

Distress traffic and safety ATS and AOC communications will be given absolute priority by the avionics and Ground Earth stations (GES) equipment.

3.0 Satellite AIRCOM Network Characteristics

The planned system configuration will initially consist of five ground earth stations (GES) covering the three ocean regions. The ground earth stations will operate at 3/6 GHz and 1.5/1.6 GHz with the satellite and will provide the interface with the terrestrial network for public and private, voice and data communications.

The aircraft earth stations (AES) will communicate with the space segment at 1.5/1.6 GHz and will interface through aircraft equipment for the passenger and crew communications.

The following Tables 1, 2, and 3 summarize the major aeronautical system characteristics, typical ground earth station characteristics, and typical aircraft earth station characteristics respectively.

4.0 Summary

The Satellite AIRCOM service is planned for operation in the mid 1990 time frame and will be one of the first to provide a world wide aeronautical mobile satellite service in compliance with the INMARSAT, ICAO and AEEC standards. The service is expected to contribute significantly in the coming years to enhance safety and economy of air transport and to provide communication services for airline passengers.

TABLE I

MAJOR SATELLITE AIRCOM SYSTEM CHARACTERISTICS

SYSTEM CHARACTERISTIC	FULL OPERATIONAL SYSTEM
Aircraft earth station antenna gain	0 dBi and 12 dBi
Communications Services	
- ATS voice and date	Air-to-ground and ground-to-air
- Public correspondence voice	Air-to-ground and ground-to-air
- Public correspondence data	Air-to-ground and ground-to-air
- Airline operations	Air-to-ground and ground-to-air
Ground earth station interconnection	Full interconnection within and between ocean regions (i.e. inter-ground earth station and inter-network coordination station links)
Channel assignment	Pre-assigned plus common network coordination station pool
Data and signalling channel rates:	Medium-rate and high-rate
- Forward channels	600,1200,2400, 4800 and 10,500 bit/s (selectable)
- Return channel	600, 1200, 2400, and 10,500 bit/s
Voice channel rate	1/2 rate coded: 21.000 bit/s
Channel bandwidth	2.5-17.5 kHz
Voice coding rate:	9.6 kbit/s initially (other bit rates may be available in the future, eg. 2.4 to 16 kbit/s)
Channel access method:	
- Voice	SCPC
- Forward data and signalling	TDM
- Return data and signalling	RA (slotted-Aloha) and Reservation-TDMA
Channel modulation/coding method:	
- Voice	A-QPSK rate-3/4 or 1/2 FEC
- Data/Signalling	A-BPSK(A-QPSK at higher channel rates) rate 1/2 FEC (FEC consists of convolution encoding with Viterbi decoding with k=7)

TABLE II

TYPICAL GROUND EARTH STATION CHARACTERISTICS

G/T (SHF-band)	32.0 dB(K^{-1}) min.
(UHF-band)	2.0 dB (K^{-1}) min.
Antenna gain (SHF-band)	54 dBi min., transmit 50.5 dBi min., receive
(UHF-band)	29.5 dBi min., transmit 29.0 dBi min., receive
Polarization (SHF-band)	RHCP transmit/LHCP receive
(UHF-band)	RHCP transmit and receive
Operating bands: (SHF-band)	6425 - 6443.0 MHz transmit 3600 - 3623.0 MHz receive
(UHF-band)*	1530-1559 MHz (receive) 1626.5-1660.5 MHz (transmit)
Tracking System	STEPTRACKING accuracy 0.01 degrees RMS or better
Transmit sidelobe (SHF-band) pattern	G = 32-25 log ϕ for $1^{o} \le 0 \le 48^{o}$ G = -10 for $\phi > 48$
(UHF-band)	G = 40-25 log ϕ for $6^{o} < 0 \le 40^{o}$ G = 0 for $\phi > 40$
Aeronautical Ground Terminal (earth stations) (AGT) Equipment	Conforms to INMARSAT and AEEC 741 specifications

* These bands will be available at the ground earth station only for automatic frequency control tests and monitoring purposes.

TABLE III

TYPICAL AIRCRAFT EARTH STATION CHARACTERISTICS

G/T	-26 $dB(K^{-1})$ with low gain antenna -13 $dB(K^{-1})$ with high gain antenna
Antenna gain: (receive/transmit)	0 dBi low gain antenna 12 dBi high gain antenna
Polarization:	RHCP for both receive and transmit
Operating bands:*	1530-1559 MHz (receive) 1626.5-1660.5 MHz (transmit)
Coverage Volume:	Azimuth, 360° Elevation, between 5° and 90°
Aircraft Avionics Communication Equipment	Conforms to INMARSAT and AEEC 741 (FDMA variant)

* The bands 1530-1544 MHz and 1626.5-1645.5 are available to stations on board aircraft only for distress and public correspondence purposes (RR 963 and 3571).

ANNEXE III

INMARSAT AERONAUTICAL SATELLITE SYSTEM SUMMARY

This Annex contains a technical summary of the aeronautical satellite system being implemented by Inmarsat and its Signatories.

1. INTRODUCTION

The definitive description of the system is contained in the Inmarsat document "Aeronautical System Definition Manual (SDM)". /INMARSAT, 1989/

Inmarsat is committed to ensuring that the SDM accommodates the system technical and operational requirements for communications related to safety and regularity of flight as defined by the ICAO's Special Committee on Future Air Navigation Systems (FANS), the Standards and Recommended Practices (SARPS) being prepared by the ICAO Panel on Aeronautical Mobile Satellite Service (AMSS), and the Minimum Operating Performance Standards (MOPS) being developed by RTCA.

The Inmarsat system design is intended to accommodate anticipated needs for at least the next ten years, and therefore contains features that are unlikely to be implemented immediately. Inmarsat has selected a subset of the full system capabilities for initial implementation, referred to as the "Initial System". These form the basis for initial procurements of ground-based and airborne equipment. Other features of the system design will be implemented in response to demand by users. Enhancements to the initial capability will be progressively incorporated in the "Enhanced System".

Inmarsat has developed a detailed aeronautical satellite system design that is able to make use both of existing Inmarsat satellites and those under construction and due for launch during 1989/90. In addition it takes advantage of future satellites with enhanced capabilities such as spot beams. The system provides initially for voice and data services, with various provisions for future upgrades such as navigation facilities.

Full global operations are planned to begin in 1989. Users of the voice and data services will include airlines (for operations control and administrative traffic) air traffic services (for air traffic control and dissemination of safety-related information), corporate and executive aircraft users (for telex, facsimile and computer-to-computer communication) and the travelling public. Techniques new to aviation such as Automatic Dependent Surveillance (ADS - automatic reporting of position by aircraft) will be feasible worldwide.

2. SERVICE CAPABILITIES

2.1 Service Requirements

The system design is based upon the requirements for aeronautical communications traffic, as defined by potential users. These requirements will continue to be refined as familiarity with aeronautical satellite communications grows, and experience with the use of these communications becomes more widespread. Services are required for all types of aircraft, from the largest commercial airliners, to small corporate and general aviation aircraft.

2.2 Operational and Air Traffic Communications.

The communication requirements to meet operational and air traffic control needs include:

- Air-to-ground data communications. A message could be initated automatically, or when required by the flight crew. Typical message lengths will be from 100 to 2000 bits, with an undetected message error rate requirement of 10^{-9} (E-9) or better. For airline purposes, between 5 and 30 messages per hour would be required, but for ADS the volume could rise to 2 messages per minute, or even higher for short periods.

  Priority for safety-related traffic is mandatory, and processing time should be kept to a miminum, a maximum of 3-5 seconds between initiation of a message and its receipt being typical for urgent messages.

- Ground-to-Air data communications. The messages would be typically fewer and shorter than for the air-ground direction. Messages would be from 100 to 1000 bits, of which a high proportion would be interrogation or polling requests. There will also be a substantial number of broadcast messages.

- Voice communications. Good quality (high intelligibility) crew voice communications would be required for Air Traffic Control (ATC) and Airline Operations Control (AOC) purposes. Full duplex communications are necessary, and in some circumstances there may be a need for two crew members to communicate concurrently.

2.3 Passenger Communications

Requirements for passenger communications include:

- Voice Communications. Near "toll-quality" telephone communications, with an automatic connection to the International Switched Telephone Network.

- Data Communications. A capability to transmit and receive data, including telex and facsimile.

Up to six passenger voice channels per aircraft will be required.

2.4 Types of Service

Several types of data service will be available. These include: Packet-Mode Connectionless Service/Message Transmission.

Packet Mode "Connection Oriented" Service

This mode is characterised by the exchange of information at the establishment of the link, between the calling user equipment, the called user equipment, and the intervening satellite and terrestrial networks. Following initial establishment of the link, all subsequent data packets carry abbreviated address and control information and individually carry much less overhead than connectionless packets. This type of service is appropriate for enquiry/response dialogues, and there is no limit on length of individual messages.

"Circuit-Mode" Services

Circuit-mode data connections provide a transparent end-to-end data-transmission 'pipe' of a defined bit rate, to which the user must apply his own protocols. Circuit-mode transmission therefore provides none of the syetem standard packet-data interfaces or error control procedures, but can be useful for certain applications such as facsimile.

2.5 Application Specific Data Services

Special data services include polled-mode and associated aircraft to report specified data either once or at regular intervals. Examples are ADS (Automatic Dependent Surveillance) messages and reporting of engineering status information.

Polling is expected to be a basic application of air traffic control services. In its simplest sense, polling permits a ground controller to issue an instruction to an aircraft to report its position immediately. Other modes of polling operation are 'epoch-based', with aircraft instructed to report periodically in seqence. Aircraft may also report randomly at their own discretion. The applicability of each of these modes of operation will be selected in due course, following from the work begun in FANS. The INMARSAT system design is able to support all the modes identified by FANS.

3. VOICE SERVICE CAPABILITIES

Voice services are suitable for cockpit and cabin use. Cabin voice calls may be pre-empted or barred by cockpit calls at the discretion of the pilot.

The system carries voice in digital form. The voice coding rate has been initially set at 9.6Kbit/s, although the system design permits a wide range of rates to be implemented in accordance with the quality desired and the capability of the technology. Voice coding is described in more detail later.

3.1 Public Telephony, Air-to-Ground

For all airborne users, the public telephone is used just as a normal office telephone for international calls. An international number is called, beginning with the international prefix, followed by the country code and the called number, and the satellite system automatically sets up the call. The dialling and subsequent progress of the call, as perceived by the calling and called parties, follows the pattern of a terrestrial call. In the case of airline passenger calls, a means of charging for the call will be present on the telephone; usually a credit-card reader. Where a credit card is used, the system transfers relevant details of the card to the ground, where they are combined with recorded details of the call for billing purposes; authorization and validity checks on the card may be made either on the aircraft or on the ground.

For cockpit use (or cabin use for corporate aircraft) charging is accompanied by recording satellite usage at the GES. The identify of the aircraft and duration of the call are the main parameters for this purpose, and they are recorded by monitoring the internal system signals used in setting-up and clearing-down calls.

3.2 Public Telephony, Ground-to-Air

Although they can be handled by the system, ground-to-air public correspondence calls are not currently permitted for airline passengers. The reasons for this include; the problem of finding the called party on the aircraft; no presently defined means of identifying a particular flight/aircraft by a public telephone number; and security considerations. Ground-to-air calls to the cockpit (or to the cabin of non-airline aircraft) are made either from private line or by special arrangements (call authentication by the GES) from the public network.

4. TECHNICAL ASPECTS OF THE SYSTEM DESIGN

This section presents a discussion of the technical aspects of the system design.

4.1 Aircraft Antennas

The aircraft terminals will operate at 1.5/1.6 GHz. In satellite communications, link power is at a premium, and for aircraft, this is compounded by limitations on performance of airborne antennas due to problems of mounting, drag, and weight. A compromise must be achieved in terms of the maximum antenna gain (which means minimum space segment charges) for an acceptable carriage penalty (capital cost plus cost of uplifting and maintaining the equipment).

For the system design, the assumption was made that services could be roughly grouped into two categories: occasional data transfers or very low-rate voice messages in low volume; and a combination of frequent data transfers and voice traffic.

For the former, an aircraft owner should be able to fit an antenna with an absolute minimum of carriage penalty, on the understanding that this may incur higher usage charges than a higher gain antenna system. A minimum antenna gain of 0dBiC will ensure that data transfers at rates of 300bit/s are feasible using all current and planned 1.5/1.6 GHz mobile satellites, and can be achieved with a relatively small, unsteered aircraft antenna; this value has therefore been adopted. Antennas of this gain may be constructed as a helix, patch, or drooping dipole, with suitable radomes. A patch would measure about 15x15 cm, and a helix could be accommodated in a blade of about 20 cm height. An antenna system of this type could be fitted to satisfy backup or mandatory requirements, or for other situations where traffic is expected to be light.

Higher-rate data, and voice services of good ('near-toll') quality should be available through all existing and planned spacecraft, which essentially means through 'global-beam' 1.5/1.6 GHz service. Following an extensive period of trade-offs, a minimum antenna gain of 12dBiC has been derived as a value which will produce a carriage penalty which is acceptable in terms of the new voice and data services, but will permit a user charge low enough to encourage wide take-up of the system. The progressive implementation of new spacecraft, making use of spot beams to serve high-density traffic areas, has the potential to permit gradual reductions in the cost of provision of services.

Antennas of 12dBiC gain have a beamwidth of about 60 degrees, and require steering to accommodate aircraft motion (typically roll of ± 30 degrees, pitch of +/- 15 degrees). They can be built in a number of ways, including: mechanically steered element; top-mounted phased array; a blade containing multiple phased arrays. Different types are expected to have application on different aircraft types.

Most services, especially passenger voice communications, are expected to be carried on the 12dBiC 'high-gain' antenna, with circular polarization (axial ratio better than 6dB0 and peak sidelobe level under all steering conditions 13dB below the main beam in the direction of any satellite spaced 45 degrees or more in or more in orbit from the wanted satellite.

4.2 Physical Channel Characteristics

The aeronautical satellite physical channel comprises 1.5/1.6 GHz links between the aircraft and the satellite, and feeder links between the satellite and the fixed aeronautical earth stations. Owing to the aircraft antenna limitations, the 1.5/1.6 GHz links are characterised by low signal to thermal noise ratios, and by the presence of multipath fading. The feeder links do not exhibit multipath fading, but suffer from precipitation fading depending on their frequency. 3/6 GHz feeder links suffer least, while 11/14 GHz links can be severely affected. (The present system design assumes 3/6 GHz feeder links, because all INMARSAT satellites are so equipped, but the assumption is not fundamental and other feeder-link frequencies can readily be accommodated).

The 1.5/1.6 GHz band multipath arises from reflections from the sea (less so from land) or from the airframe, and has been studied and measured in depth over the past 20 years. Recent studies include [ESA, 1985; DFVLR, 1987]. The conclusion from this and other work is that multipath effects become significant at elevation angles of 15 degrees or less, and that the system design should be able to accommodate carrier to multipath ratios (C/M) of about 10dB, with fading bandwidth of 30 Hz and above.

4.3 Transmission Bit Rates

To accommodate the wide variety of service requirements, the two types of aircraft antenna, and the different capabilities of the satellites which will be available to users as the aeronautical system evolves, a range of bit rates is necessary. A basic constraint is the need to be able to operate all services through global-beam satellites which limits transmission rates per RF carrier to a few tens of kilobit/s with a high-gain aircraft antenna, and to a few hundred bits/s with a low-gain aircraft antenna. In the ground-to-air direction, channels can be bundled onto a high-rate time-multiplexed channel, but this imposes a fixed bundle size and uses a corresponding fixed bandwidth which must be accepted for the entire lifetime of the system, and for this and other reasons this has not been adopted in the system definition.

4.4 Voice Quality

The economics of provision of voice for passenger or crew use dictate a transmission rate in the range 4800-9600 kbit/s. No CCITT or other widely-established voice coding standard exists for these rates at present, and it will take some years before any particular voice coding technique becomes established as a standard for this application. For purposes of initial service provision, INMARSAT has adopted a voice codec having a rate of 9600/bit/s. Strong interest has also been expressed in 8000 bit/s. Work in this area continues very actively, and it is possible that 4800bit/s coders will emerge as having adequate voice quality in the next 2-3 years.

4.5 Modulation and Coding

This corresponds to the "physical layer" of the satellite link. Two modulation techniques have been selected, to cover RF channel rates of 600-2400bit/s, and above 2400bit/s respectively. Up to 600bit/s, a binary scheme is preferred for its robustness to phase noise, multipath distortion, and filter imperfections, even at the expense of bandwidth efficiency. This is because such a rate is likely to be used mainly for initial access procedures or for backup to a higher-rate channel (for example, in case of loss of high-gain antenna). The scheme selected is 'symmetrical' differential BPSK, in which a 90 degree carrier phase is successively inserted and removed with each transmitted bit in order to limit the envelope variations of the RF signal. [Winters, 1984]. This permits filtering of the signal before a nonlinear power amplifier, while limiting the spectrum spreading after the amplifier. When this modulation method is combined with the particular channel filtering defined for these bit rates (root 40% raised-cosine) it is termed 'Aviation Binary Phase Shift Keying' (A-BPSK).

Above 2400bit/s, a quandrature technique has been adopted to achieve higher bandwidth efficiencv. consistent with the fast-fading characteristics of the channel. This is a form of offset QPSK [Fang, 1981] which, as for the binary case, limits RF signal envelope fluctuations and permits incorporation of a nonlinear amplifier in the transmission channel. For use in the aeronautical application, a standard channel filter has been defined (root 100% raised cosine), and the resulting technique standardised as 'A-QPSK' (Aviation Quadrature PSK). The design of A-BPSK and A-QPSK modulators and their associated pulse-shaping filter characteristics and power spectral-density bounds are illustrated in Figures 4 to 9.

4.6 Channel Coding and Interleaving

This is also in the physical layer of the satellite link. The aircraft antenna gains available (0 and 12 dBiC), taken with the need to operate with 'global' spacecraft antennas (beamwidth about 17 degrees, gain about 17.5 dBiC at edge of coverage -5 degrees elevation), lead to very low-margin links between satellite and aircraft, so it is necessary to protect transmissions with forward error correction coding. The availability of future spacecraft with high-gain spot beams will raise these margins and permit a trade-off between bandwidth and transmission power, but at present both voice and data are protected by FEC.

The technique is for rate -1/2 convolutional coding, constraint length of 7, with interleaving to accommodate the bursty nature of the errors on the multipath-dominated channel. There is provision to switch out this coding in non-power-limited situations, and to increase the rate to 3/4 in intermediate situations.

The end-to-end transmission channel error criteria are different for voice and data transmissions. Data must be of high integrity, and this implies a maximum user's bit error rate of 1 in 10^5 after FEC decoding. For voice, on the other hand, an error rate of 1 in 10^3 will be adequate to give near-toll quality. (Many voice coders will work down to 1 in 10^2 average BER, since their manufacturers build-in error protection for the critical parts of the voice coding frame. However, the quality in these circumstances does not normally approach toll quality).

Convolutional coding will only work effectively if the channel error bursts are randomised by interleaving. This has been adopted in the system design, and the link design permits a multiplicity of data rates using a common interleaver structure to achieve a constant interleaver 'depth' (randomising power) for all bit rates used for data transmission. Interleaving does however introduce delays of the order of a second, which is not acceptable for voice transmission, so for this a shorter interleaver delay of the order of 30msec has been introduced, accepting that the effectiveness of the interleaver will be limited thereby.

4.7 Data Link Layer Transmission Format - Signal Units

Given the nature of the multipath fading channel, it is vital to design the transmission format to ensure the maximum resistance to repeated short interruptions. This implies consistent detection of link errors and associated recovery procedures. The way this has been handled in the System Design at the link level is to format all data, including system control and signalling as well as user data, into standard packets of predefined length, termed 'Signal Units'. This concept is familiar as a standard technique for sending signalling messages between exchanges in the terrestrial public networks.

In the present context, a standard signal unit offers the advantages of a known and controllable package error performance applicable to all data, and a standard technique for disassembling all data packets, whether they carry user data or system control/singalling. For signal units of predefined size, the error characteristics become much more predictable than for variable-size packets.

4.8 Data Applications (Network Layer Interface)

It is a normal requirement nowadays for any new data link design to support the ISO layered transmission model. In practice, the more flexibility is built into a system design to accommodate this, the heavier the burder of overheads in addressing and control data. Power and bandwidth are at such a premium in a satellite link that some compromises in layering may be necessary, at least in layers 4 and above of the model. As part of the satellite system design, it was accepted that full support of the layered structure must be supported up to an including layer 3 - the network layer. This has been achieved by means of variable-length packets at the network layer to carry user data and addressing, and the ability to establish virtual circuits. The standard network/transport layer presented by the system accords with ISO 8202.

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TABLE I

MAJOR 1.5/1.6 GHz BAND PARAMETERS OF 1ST & 2ND GENERATION INMARSAT SATELLITES

SATELLITE/ PACKAGE	EIRP dBW	G/T dB/K
MARECS	34.5	-11.2
MCS	33.0	-13.0
MARISAT	27.0	-17.0
INMARSAT 2	39.0	-12.5

TABLE II

CHANNEL TRANSMISSION CHARACTERISTICS SUMMARY

Channel Rate (bit/s)	Channel Spacing (kHz)	Modulation	Modulation Symbol Duration	
			Microseconds	Samples/Sym. with 5.04 MHz clock
28000	22.5	A-QPSK(1)	71.43	360
21000	17.5	A-QPSK	95.24	480
14000	12.5	A-QPSK	142.86	720
10500		A-QPSK	190.48	960
7200	7.5	A-QPSK	277.78	1400
6000	5.0	A-QPSK	333.33	1680
5250	5.0	A-QPSK	380.95	1920
4800	5.0	A-QPSK	416.67	2100
2400	5.0	A-BPSK(2)	416.67	2100
1200	5.0/2.5(3)	A-BPSK	833.33	4200
600	5.0/2.5	A-BPSK	1666.67	8400

(1) See Ref.

(2) See Ref.

(3) It is possible to have 2.5 kHz in the air-to-ground direction

TABLE III

SPECIMEN P-, R- AND T-CHANNELS LINK BUDGETS

FORWARD LINK BUDGET FOR 600 bit/s DATA CHANNELS (P-CHANNEL) AT 5° ELEVATION

Satellite	MCS	MARECS	INM-II	Example Spot Beam
Link Requirement				
Required Link C/No (dBHz)	35.7	35.7	35.7	35.7
Uplink (GES to Satellite)				
Frequency (GHz)	6.42	6.42	6.42	6.42
GES Elevation (deg)	5	5	5	5
Path Loss (incl. Atmos)(dB)	201.3	201.3	201.3	201.3
Satellite G/T (dBK)	-14.0	-14.0	-14.0	-14.0
GES EIRP (dBW)	62.0	62.0	62.0	62.0
Uplink C/No (dBHz)	75.3	75.3	75.3	75.3
Satellite				
Satellite gain (dB)	161.3	161.3	161.3	174.3
Satellite C/IMo (dBHz)	67.8	67.8	67.0	48.0
Downlink (Satellite to AES)				
Frequency (GHz)	1.54	1.54	1.54	1.54
AES Elevation (deg)	5	5	5	5
Path Loss (incl. Atmos)(dB)	188.9	188.9	188.9	188.9
Satellite G/T (dBK)	-26	-26	-26	-26
Satellite EIRP (dBW)	22	22	22	23
Downlink C/No (dBHz)	35.7	35.7	35.7	36.7
Link Performance				
Achieved C/No (dBHz)	35.7	35.7	35.7	36.4
Margin (dB)	0.0	0.0	0.0	0.7

Note: When received by an AES with high gain antenna and G/T of -13 dBK the link margin will be significantly higher

RETURN LINK BUDGET FOR 600 bit/s DATA CHANNELS (R- & T-CHANNELS) AT 5° ELEVATION

Satellite	MCS	MARECS	INM-II	Example Spot Beam
Link Requirement				
Required Link C/No (dBHz)	35.7	35.7	35.7	35.7
Uplink (AES to Satellite)				
Frequency (GHz)	1.64	1.64	1.64	1.64
AES Elevation (deg)	5	5	5	5
Path Loss (incl. Atmos)(dB)	189.4	189.4	189.4	189.4
Satellite G/T (dBK)	-13.0	-11.0	-12.5	-3
AES EIRP (dBW)	13.5	13.5	13.5	13.5
Uplink C/No (dBHz)	39.7	41.7	40.2	49.7
Satellite				
Satellite gain (dB)	150.9	151.3	158.0	167
Satellite C/IMo (dBHz)	43.8	46.5	59.8	60
Downlink (Satellite to GES)				
Frequency (GHz)	4.2	4.2	3.6	3.6
GES Elevation (deg)	5	5	5	5
Path Loss (incl. Atmos)(dB)	197.6	197.6	197.6	196.3
GES G/T (dBK)	32.0	32.0	30.7	30.7
Satellite EIRP (dBW)	-25.0	-24.6	-17.9	-17.9
Downlink C/No (dBHz)	38.0	38.4	45.1	54.1
Link Performance				
Achieved C/No (dBHz)	31.1	36.3	38.9	48.1
Margin (dB)	-0.6	0.6	3.2	12.4

TABLE IV
SPECIMEN C-CHANNEL LINK BUDGETS

FORWARD LINK BUDGET FOR 21000 bit/s VOICE CHANNELS (C-CHANNEL) AT 5° ELEVATION

Satellite	MCS	MARECS	INM-II	Example Spot Beam
Link Requirement				
Required Link C/No (dBHz)	47.9	47.9	47.9	47.9
Uplink (GES to Satellite)				
Frequency (GHz)	6.42	6.42	6.42	6.42
GES Elevation (deg)	5	5	5	5
Path Loss (Incl. Atmos)(dB)	201.3	201.3	201.3	201.3
Satellite G/T (dBK)	-14.0	-14.0	-14.0	-14.0
GES EIRP (dBW)	62.0	62.0	62.0	62.0
Uplink C/No (dBHz)	75.3	75.3	75.3	75.3
Satellite				
Satellite gain (dB)	161.3	161.3	161.3	161.3
Satellite C/IMo (dBHz)	67.8	69.0	67.0	60
Downlink (Satellite to AES)				
Frequency (GHz)	1.54	1.54	1.54	1.54
AES Elevation (deg)	5	5	5	5
Path Loss (Incl. Atmos)(dB)	188.9	188.9	188.9	188.9
AES G/T (dBK)	-13	-13	-13	-13
Satellite EIRP (dBW)	22	22	22	22
Downlink C/No (dBHz)	48.7	48.7	48.7	48.7
Link Performance				
Achieved C/No (dBHz)	48.6	48.6	48.6	48.6
Margin (dB)	0.7	0.7	0.7	0.7

RETURN LINK BUDGET FOR 21000 bit/s VOICE CHANNELS (C-CHANNEL) AT 5° ELEVATION

Satellite	MCS	MARECS	INM-II	Example Spot Beam
Link Requirement				
Required Link C/No (dBHz)	47.9	47.9	47.9	47.9
Uplink (AES to Satellite)				
Frequency (GHz)	1.64	1.64	1.64	1.64
AES Elevation (deg)	5	5	5	5
Path Loss (Incl. Atmos)(dB)	189.4	189.4	189.4	189.4
Satellite G/T (dBK)	-13.0	-11.0	-12.5	-3
AES EIRP (dBW)	25.5	25.5	22.5	13.5
Uplink C/No (dBHz)	51.7	53.7	49.2	49.7
Satellite				
Satellite gain (dB)	150.9	151.3	158.0	167
Satellite C/IMo (dBHz)	55.0	57.5	60.8	60
Downlink (Satellite to GES)				
Frequency (GHz)	4.2	4.2	3.6	3.6(?)
GES Elevation (deg)	5	5	5	5
Path Loss (Incl. Atmos)(dB)	197.6	197.6	196.3	196.3
GES G/T (dBK)	-32.0	-32.0	-30.7	-30.7
Satellite EIRP (dBW)	-13.0	-12.6	-8.9	-8.9
Downlink C/No (dBHz)	50.0	50.4	54.1	54.1
Link Performance				
Achieved C/No (dBHz)	47.0	48.2	47.8	48.1
Margin (dB)	-0.9	+0.3	-0.1	+0.2

FIGURE 1

AERONAUTICAL SATELLITE SYSTEM

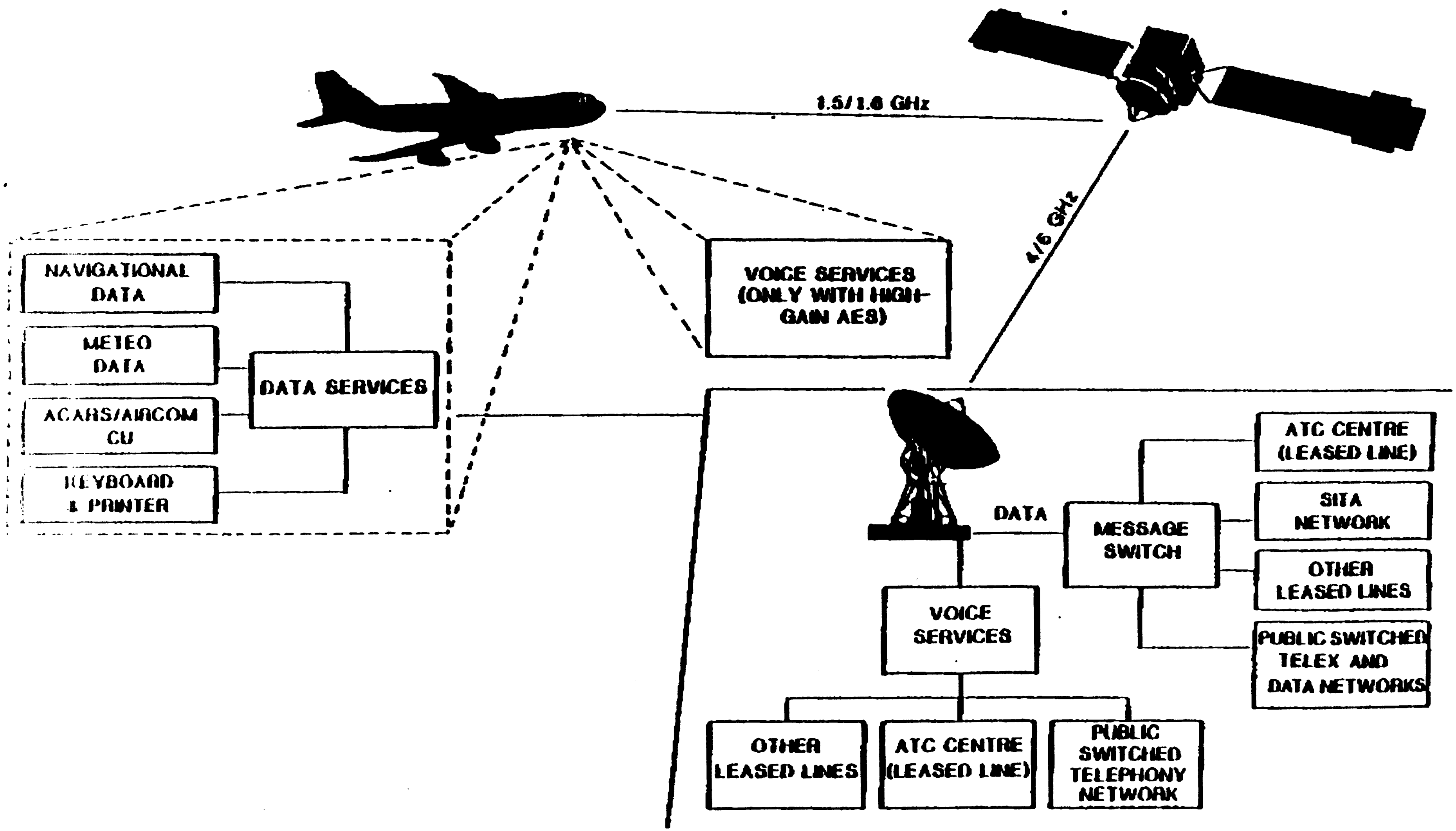


FIGURE 2

AERONAUTICAL FREQUENCY SPECTRUM

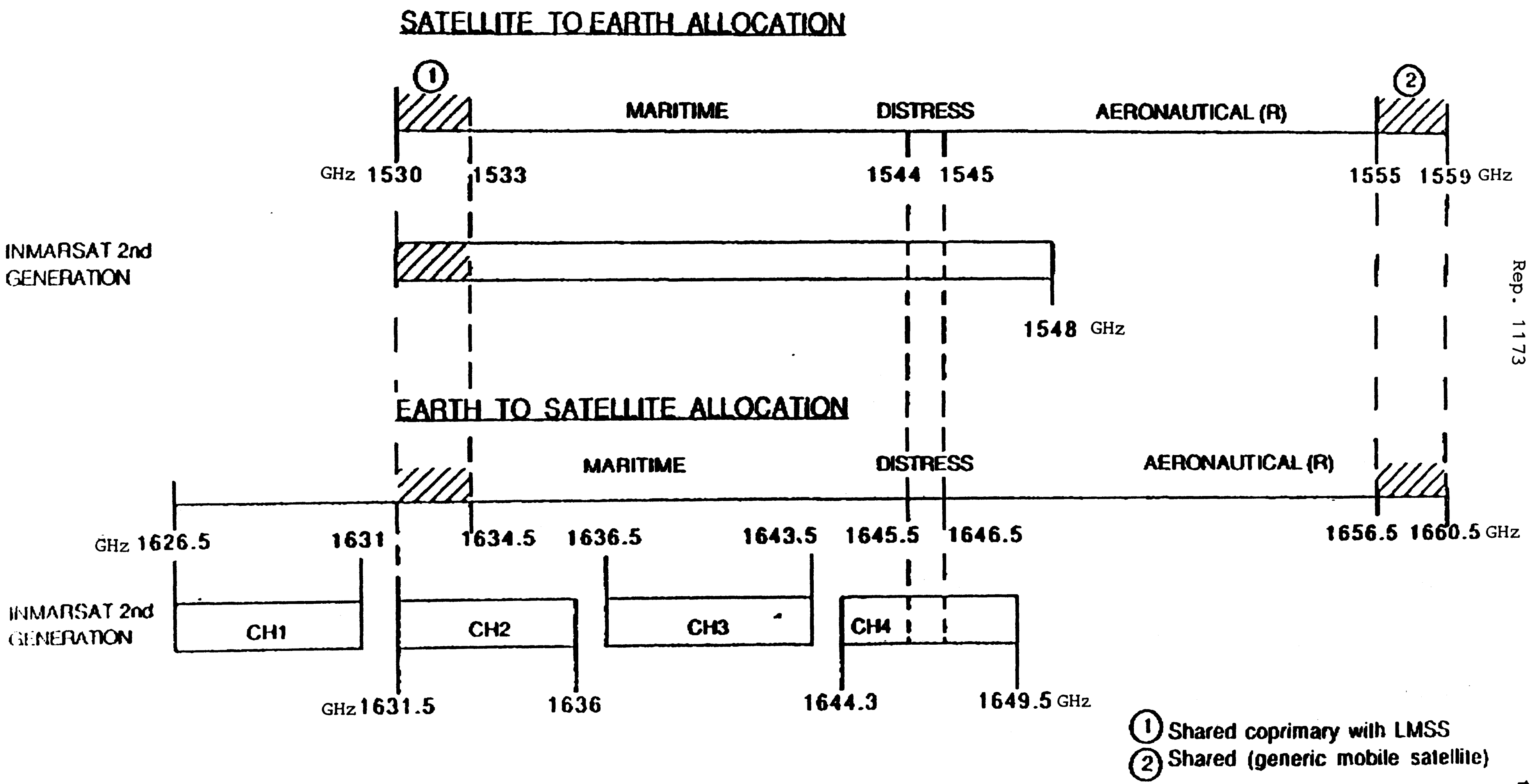
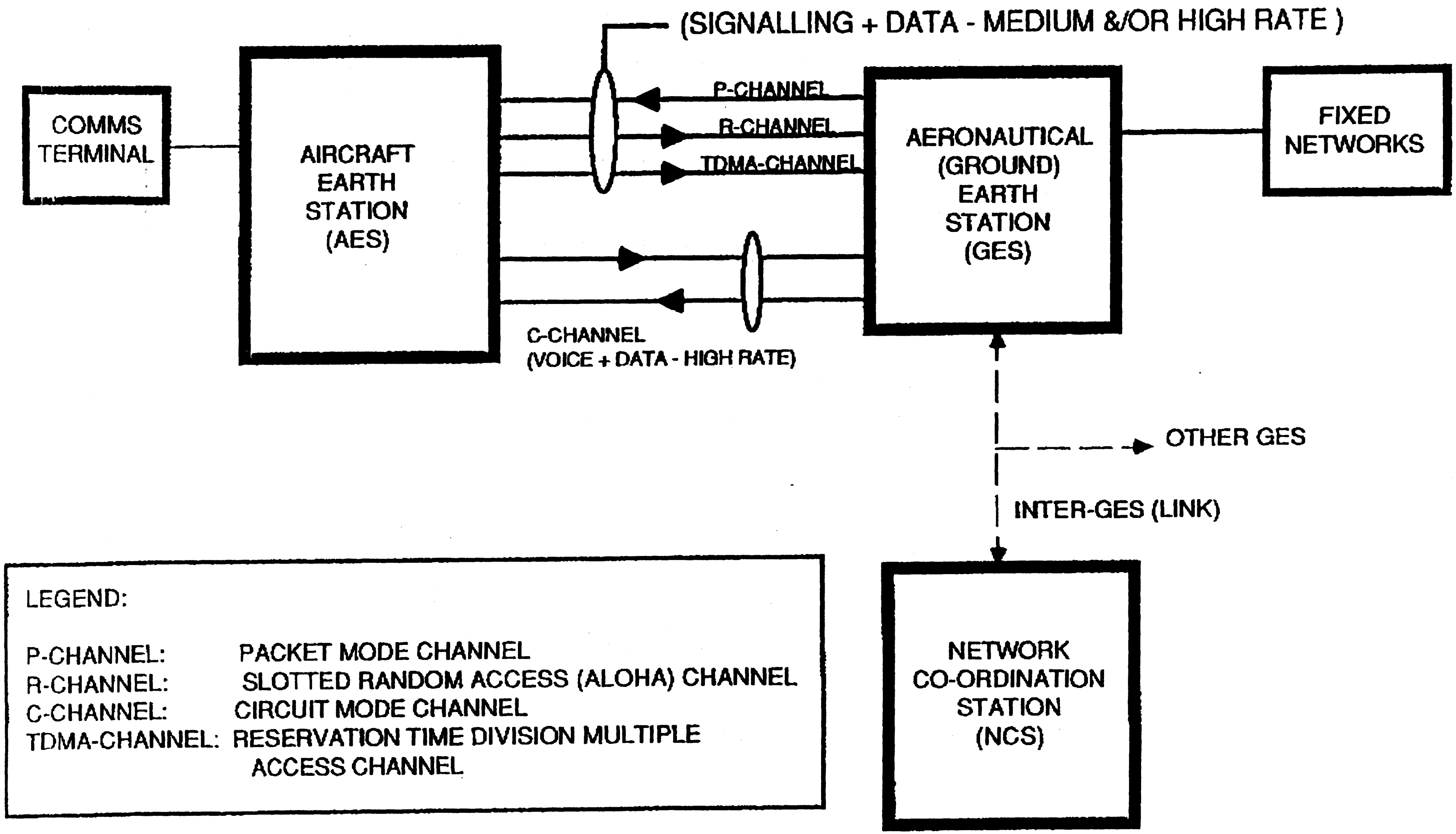
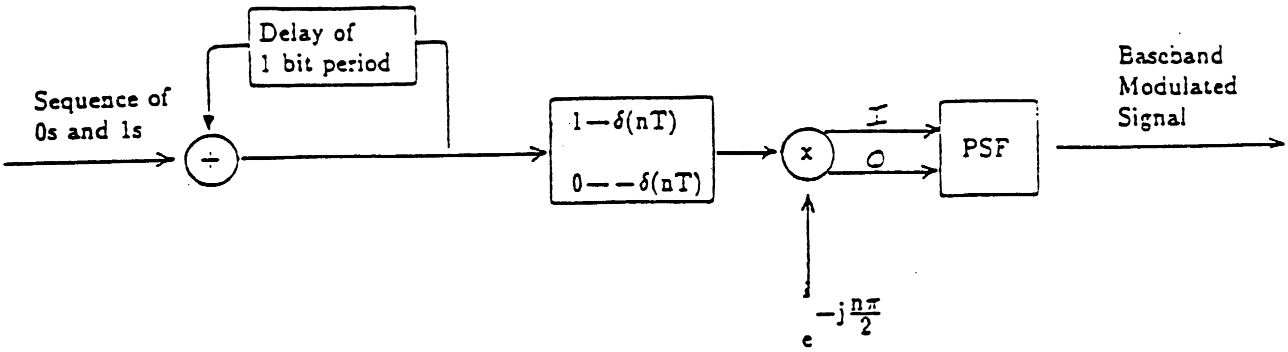


FIGURE 3

AERONAUTICAL NETWORK CONFIGURATION ENHANCED SYSTEM





⊖ modulo 2 addition
PSF pulse shaping filter
δ(t) ideal impulse

FIGURE 4 - A-BPSK modulator

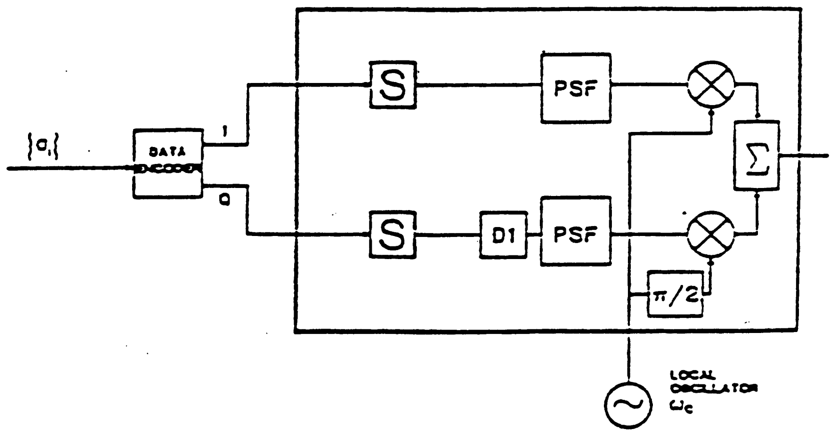


FIGURE 5 - A-QPSK modulator

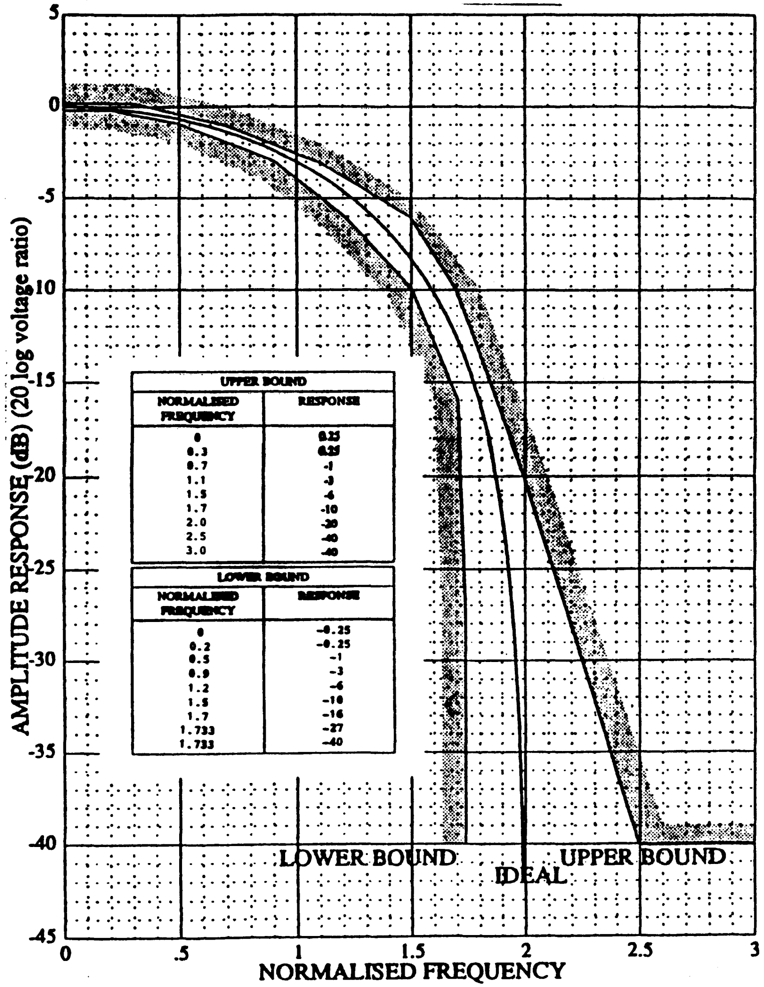
$\{a_i\}$ is input data sequence. Bit rate = 2/T for A-QPSK

$\{a_i\}$ is mapped into two bit streams on the I and Q lines, each with bit rate 1/T

Sampler S runs synchronously with I and Q data bits, and generates ideal impulses at rate 1/T

Delay D1 = T/2 for A-QPSK

A-QPSK: BOUNDS ON AMPLITUDE CHARACTERISTIC OF FREQUENCY RESPONSE OF PULSE-SHAPING FILTER

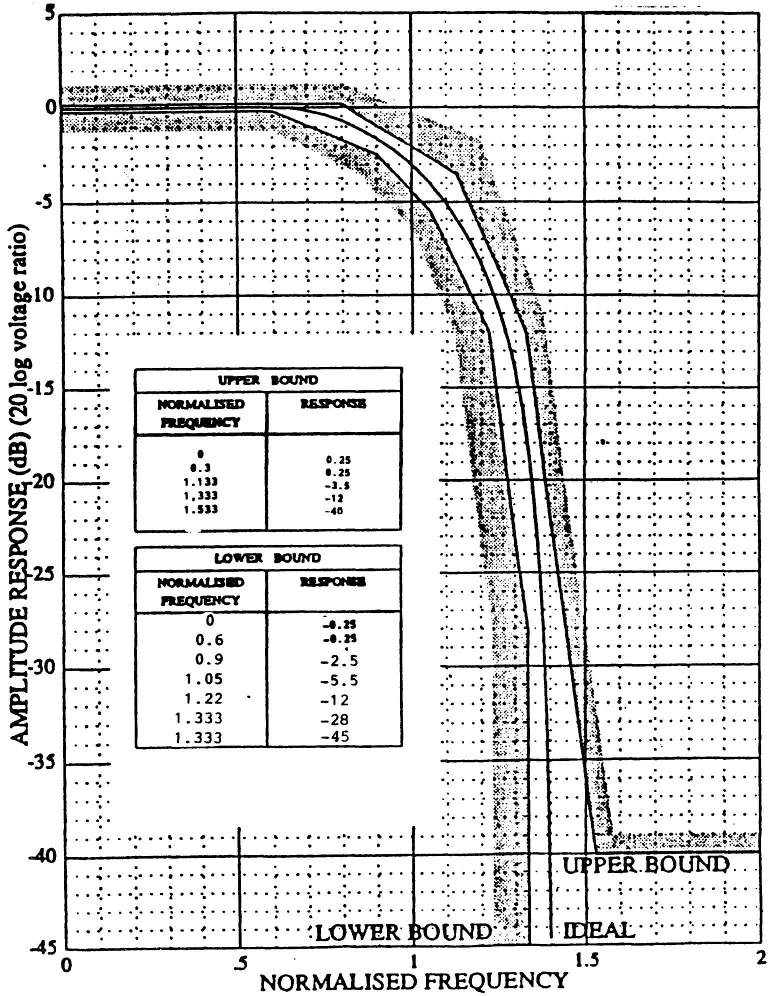


UPPER BOUND	
NORMALISED FREQUENCY	RESPONSE
0	0.25
0.3	0.25
0.7	-1
1.1	-3
1.5	-6
1.7	-10
2.0	-20
2.5	-40
3.0	-40

LOWER BOUND	
NORMALISED FREQUENCY	RESPONSE
0	-0.25
0.2	-0.25
0.5	-1
0.9	-3
1.2	-6
1.5	-10
1.7	-16
1.733	-27
1.733	-40

FIGURE 6

A-BPSK: BOUNDS ON AMPLITUDE CHARACTERISTIC OF FREQUENCY RESPONSE OF PULSE-SHAPING FILTER



UPPER BOUND	
NORMALISED FREQUENCY	RESPONSE
0	0.25
0.3	0.25
1.133	-3.5
1,333	-12
1.533	-40

LOWER BOUND	
NORMALISED FREQUENCY	RESPONSE
0	-0.25
0.6	-0.25
0.9	-2.5
1.05	-5.5
1.22	-12
1.333	-28
1.333	-45

FIGURE 7

A-BPSK & A-QPSK: BOUNDS ON PHASE DEVIATION FROM LINEARITY OF FREQUENCY RESPONSE OF PULSE-SHAPING FILTER

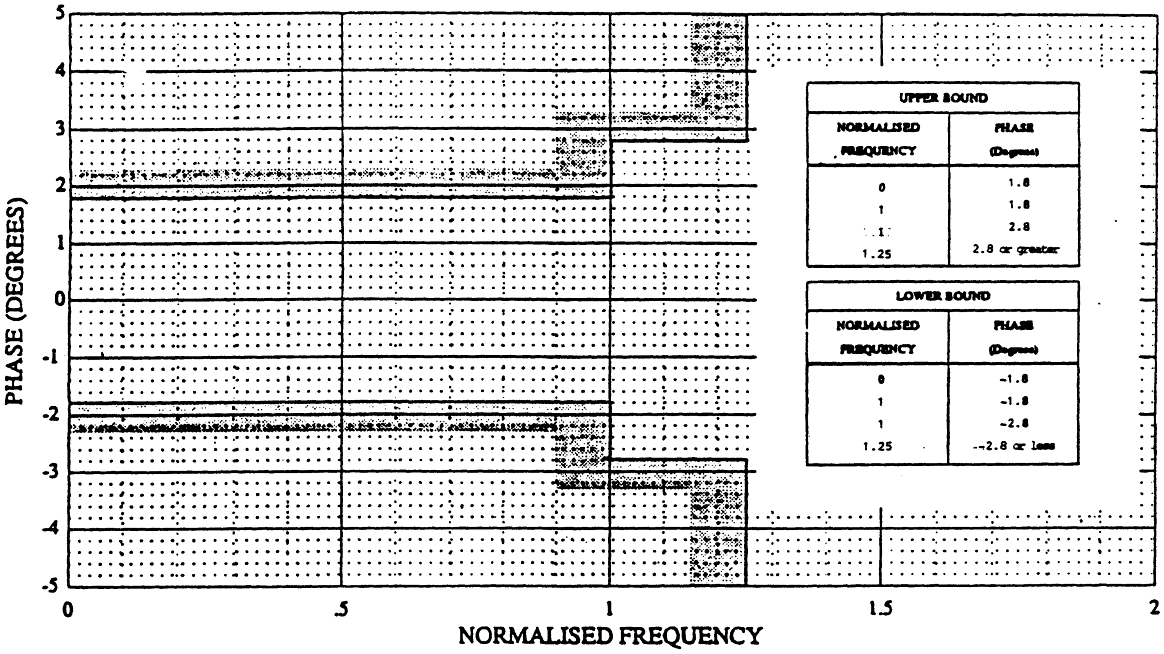
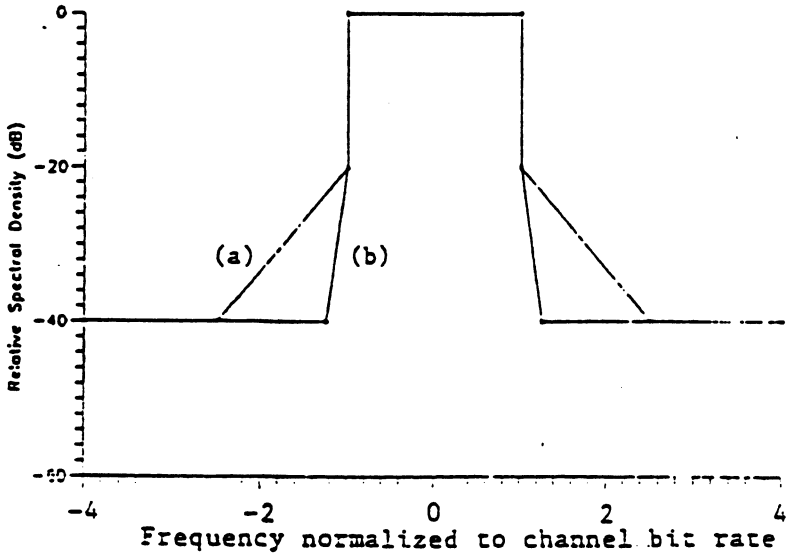


FIGURE 8



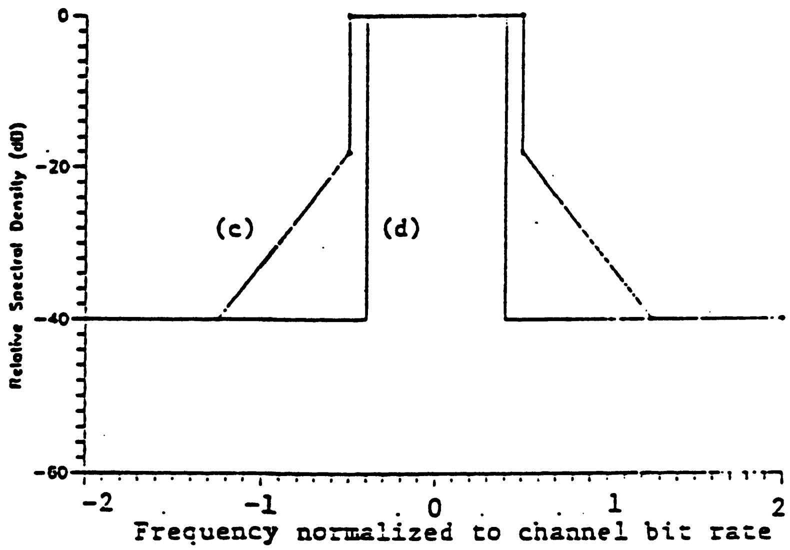


FIGURE 9 - **Bounds on radiated power spectral density.**

(a) A-BPSK transmitted from aircraft
(b) A-BPSK transmitted from ground
(c) A-QPSK transmitted from aircraft
(d) A-QPSK transmitted from ground