

PUBLIC MOBILE TELEPHONE SERVICE WITH AIRCRAFT

(Question 74/8)

(1986-1990)

1. Introduction

1.1 This report deals with the general principles of a public mobile telephone service to aircraft and, in particular, with operational and technical characteristics which are important for satisfactory operation.

1.2 Public mobile telephone systems considered in this report are defined as aircraft systems for public correspondence which are connected to the international public switched telephone network (PSTN).

1.3 Several systems are in operation or are under consideration by different administrations to provide this service. Terrestrial systems offer some advantages over satellite-based systems. Satellite systems will have greatest application over large bodies of water or land masses that cannot be served by land-based systems. Frequency reuse in a terrestrial system, using cellular-like geometry, can yield far more channels than satellite coverage, even assuming multiple satellite spot beams. In heavily populated areas where a high volume of local aircraft movement requires high channel capacity, terrestrial systems will be the most practical.

1.4 Features of the terrestrial system developed in Japan are presented in Annex I.

1.5 Features of the terrestrial experimental system currently operated in the United States and Canada and as proposed for implementation in Australia are given in Annex II.

1.6 Outline features of the terrestrial system selected for interim use in the United Kingdom, and forming one of the approaches under review by the European Telecommunications Standards Institute (ETSI) for use in Europe, are given in Annex III.

2. General operational considerations for public mobile telephone service with aircraft

2.1 The system should be fully compatible and capable of interfacing with the international public switched telephone network, and simple in operation.

2.2 An adequate number of channels should be provided to meet the foreseeable demand for the service.

2.3 The system should be modular in design, with the capability of meeting single or multiple channel requirements.

2.4 The Quality of Service should be comparable to that of the public switched network (voice and data).

2.5 The system should provide, in so far as possible, uninterrupted coverage throughout the designated service areas with the capability of coordinated operation across national borders.

2.6 A capability to call to and from aircraft is desirable.

2.7 Automatic setting-up and administrative handling of calls to and from the mobile stations should be provided.

2.8 The system must have no adverse influence on the safe operation of the aircraft.

3. System technical characteristics for public mobile telephone service with aircraft

3.1 Frequency band

3.1.1 The WARC MOB-87, under footnote 731B, allocated the frequency bands 1 593 - 1 594 MHz and 1 625.5 - 1 626.5 MHz also to the aeronautical mobile service in Region 1 (except Syria and Tunisia) on a primary basis and in Regions 2 and 3 (and Syria and Tunisia) on a secondary basis. The service is limited to public correspondence with aircraft and is subject to the provisos in footnotes 731A and 731D, that it shall not claim protection from or cause interference to stations of the aeronautical radionavigation and radionavigation services, as applicable, or cause harmful interference to stations of the fixed service operating in the countries listed in footnote 730 (see also Recommendation No. 408 MOB-87).

3.1.2 Although WARC MOB-87 allocated the 1 593 - 1 594 MHz and 1 625.5 - 1 626.5 MHz under certain conditions for terrestrial systems, Recommendation 408 noted that these frequencies would be adequate for pre-operational and experimental systems, and would cause considerable difficulties in some countries. In addition, Recommendation 408 also invited the CCIR to identify technically preferred alternative frequency bands for a future world-wide terrestrial system. Thus, decides 4.6 of Decision 81 directs IWP 8/14 to determine what technically preferred alternative frequency bands could be allocated for such a system.

3.1.3 Recommendation No. 408(MOB-87) also invited the CCIR to study urgently the necessary sharing criteria between terrestrial APC systems operating in the bands 1 593 - 1 594 MHz and 1 625.5 - 1 626.5 MHz and the other services in the same and adjacent frequency bands.

3.1.4 Interference considerations with the Global Positioning System (GPS) are addressed in Report 766, and for the RDSS in Report 1050, Annex II.

3.1.5 The terrestrial systems as referenced under items 1.4 and 1.5, and described in Annexes I and II operate in band 9 in the 800 MHz to 900 MHz frequency range.

3.1.6 The terrestrial system as referenced under item 1.5 and described in Annex III utilizes the frequency band as defined in section 3.1.1.

3.2 Modulation

3.2.1 Various types of modulation, for example, FM, PM, ACSSB (Amplitude Companded SSB), SSB-AM, GMSK (Gaussian Minimum Shift Keying) and BLO-QPSK (Band Limited Offset-QPSK) with TDMA option have been proposed. Each method has advantages and disadvantages in communication quality, spectrum efficiency and economy. Further study is needed to aid in reaching international agreement regarding the types of modulation to be used.

3.3 Signalling

3.3.1 A completely automatic public mobile telephone system for use with aircraft requires an advanced signalling method for call control and channel acquisition.

3.3.2 Examples of such signalling systems are contained in Report 742.

3.4 Voice and data encoding

3.4.1 To be determined.

3.5 Airborne equipment

3.5.1 Size and weight of equipment should be minimal.

3.5.2 If possible, the equipment should make provision for other communication functions.

3.5.3 The airborne equipment must be electromagnetically compatible with other aircraft systems in accordance with appropriate regulatory requirements.

3.5.4 The system should have minimal impact on aircraft engineering, maintenance and operations.

3.6 Propagation and Doppler shift considerations

3.6.1 Annex IV presents an analysis of propagation and Doppler shift considerations.

4. Conclusion

4.1 It is recognized that this report represents only an initial step in defining the operational and technical factors to be considered regarding a public mobile telephone service with aircraft. Further study is needed on many aspects of the proposed system to facilitate arriving at international standards.

4.2 APC-systems operating in the band 1 559 - 1 625.5 MHz may cause interference to the GPS, GLONASS and RDSS system, and the reception of signals in the radionavigation service operating in the same band. This subject requires further study.

4.3 APC-systems operating in the band 850 - 895 MHz in Region 1 could cause interference to the Pan-European digital cellular radio network (GSM). Currently, however, this band cannot be used in Region 1 for APC systems.

ANNEX I

PUBLIC MOBILE TELEPHONE SYSTEM WITH AIRCRAFT IN JAPAN

1. Introduction

In Japan, a public mobile telephone system with aircraft has been developed. This system is economically realized through partial joint operation with the land mobile telephone (cellular) network. Moreover it is configured in the form of an integrated mobile communication system.

2. Operational features

Operational features are as follows:

- fully automatic direct-dial operation in conjunction with the public switched telephone network (PSTN);
- roaming : location registration and remote file access;

- hand-off;
- speech/non-speech service;
- service for not only airlines but also for general aviation use;
- coverage of almost all regular domestic air routes.

3. System functions

The system configuration is shown in Fig. 1.

The system functions are as follows:

- the system is composed of mobile station equipment installed on board aircraft and land station equipment on the ground;
- the land station equipment consists of the following components:
 - transmitters and receivers for transmission of various signals over a radio path;
 - mobile control station equipment for controlling the speech path set-up;
 - exchange equipment for connecting the mobile network and public switched telephone network (PSTN);
- the mobile control station and exchange equipment are used in common with the land mobile telephone system;
- speech path set-up control for both air-to-ground and ground-to-air calls is realized by a single radio channel, and the control messages are fully digitized;
- speech quality that meets the requirements for public telephone service is obtained.

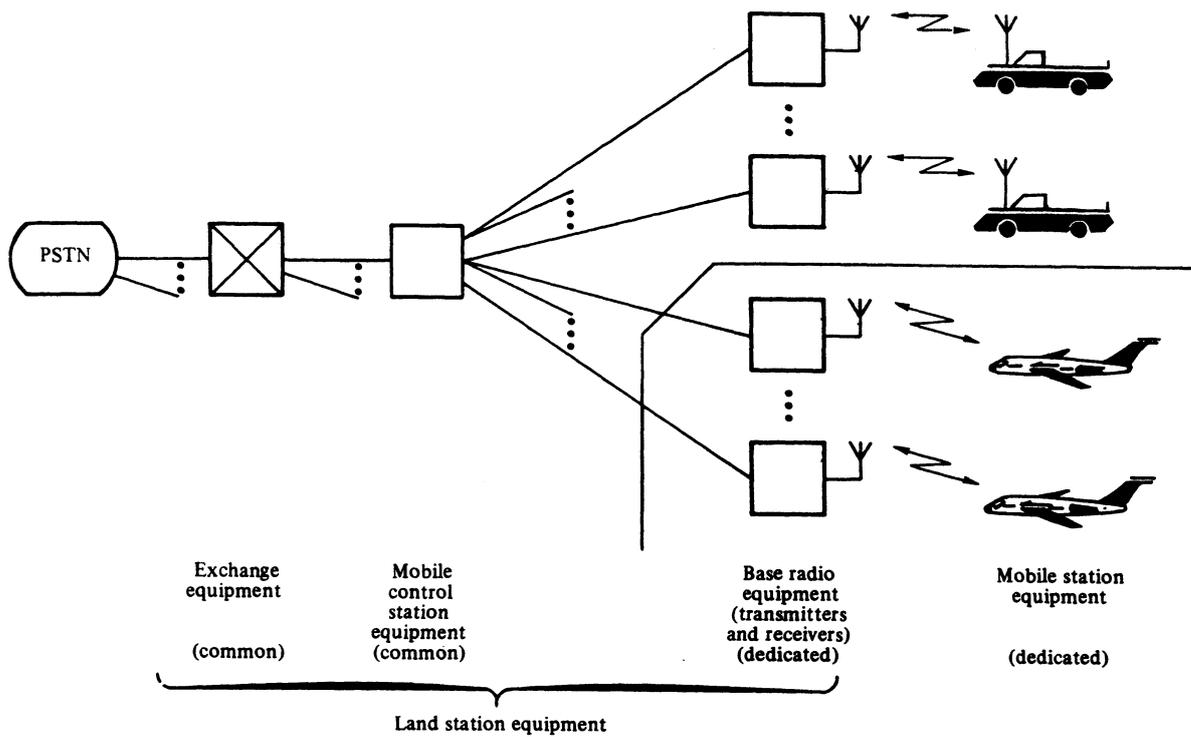


FIGURE 1 – System configuration

4. Technical characteristics

Technical characteristics are based on the land mobile telephone (cellular) system (see Report 742-1 and Ogawa, 1987).

The major characteristics are shown in Table I.

TABLE I – Technical characteristics

Frequency (MHz)		800-900
Channel spacing (kHz)		25
Total number of duplex channels		80
Type of modulation		PM
Power output (W)	Base station	40
	Mobile station	10

The modulation type is phase modulation, which is better than SSB-AM in that less receiver input power is required, especially for non-speech digital signal transmission. Also, transmission quality degradation due to Doppler shift is negligible and equipment cost is low.

5. Operations

This system began operation in 1986.

REFERENCES

OGAWA, K. [Oct. 1987]. Present and future mobile communications services, JTR, pp. 65-93.

ANNEX II

Public correspondence on commercial aircraft
in the United States and Canada1. Introduction

An advanced terrestrial air-ground public correspondence system is currently operated in the United States and Canada in the UHF frequency band based on service agreements with United States and Canadian domestic air carriers that serve over 90% of the North American air passenger market on an experimental basis. As of December 1988, approximately 900 commercial aircraft were equipped for air-ground service with either an average of two aircraft transceivers for narrowbody aircraft or four transceivers for widebody aircraft. Approximately 600 more installations are planned for 1989. This terrestrial air-ground system will provide experience for the development of operational guidance for communication services offered to airline passengers and evidence of passenger demand for such services. Technical details on that system are set forth herein.

2. Technical2.1 System architecture2.1.1 Frequency reuse

The air-ground public telephone system's use of 4 MHz is split into two 2 MHz bands, one for the air-to-ground link and another, separated by 45 MHz, for the ground-to-air link. Each of the two bands are divided into ten 200 kHz sub-bands providing a total of 310 channels and 10 pilot frequencies with guard bands. The ten sub-bands are used in a matrix covering the continental United States and major air routes in Canada.

The system is configured to reuse frequencies in a manner similar to that used by cellular radio telephone service. However, while the reuse in land mobile is based on interference-limited operation, the geometry in the air-to-ground case and the comparatively slow rate of change of path loss with distance, necessitate reuse in air-to-ground systems to rely on horizon-limited control, not power limited control of interference.

The cell size and separation are dictated by the minimum and maximum flight altitudes of the serviced aircraft. For approximately 10,000 feet (or 3,000 metres) altitudes the maximum cell radius would be near 150 miles (or 240 kilometres). Each ground station has an operating radius of up to the radio-horizon distance which depends on aircraft altitude (e.g. for 45,000 feet or 13,700 metres the horizon distance is about 300 miles or 480 kilometres), and typically allocates voice channels to meet demand created by airline flight routes.

Actual cell separations are influenced by additional issues such as ground station altitudes and antenna heights, propagation margins, knowledge of aircraft locations, and topographical considerations. Combining these considerations with analysed traffic requirements enables the construction of an efficient frequency plan allowing different groups of cells to share the same frequencies with an appropriate frequency reuse pattern.

2.1.2 Trunking radio link modulation

The system utilizes Single-Sideband modulation (SSB) for all voice and data communications in a 6 kHz channel.

2.1.3 Trunking radio link channel selection

The air-ground nation-wide telephone network is made possible by a series of ground stations installed across the country. Each ground station has an operating diameter of approximately 500 miles, and can handle up to 31 simultaneous calls. Each station collects the billing data for all calls channelled through it. The stations also monitor all airborne equipment and, should any component malfunction, the ground station automatically notifies a central site so that the problem may be corrected quickly.

The system consists of two sub-systems:

- a) active components of the airborne equipment include the Airborne Computer Unit ("ACU"), Common Unit ("CMN"), air-ground transceivers (RT), Cabin Handset Holder ("CHH") and cordless handsets;
- b) terrestrially located base stations consisting of a Ground Control Unit (GCU), public switched network interface and ground-air transceivers (RT).

Each ground station is assigned one of the ten 200 kHz sub-bands which would then be further divided into 31 sub-channels plus a single pilot channel.

Each base station incorporates a continuously operating pilot channel transmitter which constantly broadcasts a list of the available voice channels in the group within which the pilot channel is located. When an aircraft transceiver "seizes" an available channel to place a call, the base station removes that channel from its broadcasted list.

The system is designed so that the ground transceivers always operate on fixed frequencies; the aircraft transceivers are frequency-agile and are tuned to pair with a ground transceiver's frequency, under control of an Airborne Computer Unit (ACU).

In telephone-equipped aircraft the pilot frequencies are scanned regularly to find a base-station signal for initiating the next telephone-call process. This scan occurs every three minutes, requiring only a few seconds to complete. One of the transceivers installed on each aircraft is used for the scan; if all transceivers are engaged in telephone conversations, further access to the public switched telephone network must await a transceiver becoming available for initiating a scan.

The choice of which base station's channels will be accessed is determined by assessing the signal strengths of all detected pilot channels, and also by measuring their Doppler shifts. An aircraft flying toward a base station will receive the pilot signal at a frequency higher than its actual frequency; if flying away from a station, the received signal will be at a lower than actual frequency. The ACU compiles a table of signal strengths and Doppler frequency shifts and selects the most appropriate ground station according to a preprogrammed selection algorithm that ensures maximum connect time for a customer. This connect time is typically between 20 to 40 minutes, and it is very rare for a call to be lost because of an aircraft flying out of range of a base station.

To accurately sense Doppler, the system frequency standards (one on each aircraft and one at each base station) must be quite accurate. The Doppler frequency shift is approximately one hertz per megahertz for aircraft speeds of 600 mph (or 965 kms/hr); a jet flying directly towards or away from a ground station will sense a Doppler shift of about 800 Hz in the 900 MHz band. The gross Doppler shift is determined via FM detection (in a transceiver) of the base station pilot frequency carrier.

Each base station has an operating reach of approximately 200 miles (or 320 kilometres), depending on highest flying altitude. Hand-off from one ground station to the next is not presently needed; rather than handing off a conversation, the system is designed to preferentially place calls according to a selection algorithm to maximize connect time.

Effective power control of the aircraft transmitters is required in order to control intermods and prevent aircraft at close range to the ground base station receivers from overpowering weak signals from more distant aircraft transmissions on adjacent sub-channels. AGC and AFC is used in the aircraft to adjust the gain and correct Doppler shift of the aircraft receivers and transmitters. As a result, the ground receivers require no AFC and only a moderate amount of AGC because Doppler and power control are performed by the airborne transceiver for the air-to-ground link.

The air-ground public telephone system will permit the same direct dialling and access to directory information that is available from a ground phone. The airborne caller will be able to make a call using any major credit card. The system is not presently configured to permit incoming calls to the aircraft in order to avoid disruption to normal airline cabin procedures and service.

2.2 System hardware

Standard blade-type monopole antennas are used on equipped aircraft. One antenna will accommodate two transceivers; therefore, on narrowbody aircraft only one antenna is required. The best mounting for the antenna is on the underside of the fuselage, centered along a cut defined by the wing span, with the fuselage acting as a ground plane whose dimensions are many wavelengths in any direction.

2.2.1 Cordless handsets

The Airborne Computer Unit (ACU) is mounted in the electronics bay of the aircraft. The ACU contains a microprocessor used for control purposes and a set of base station radio channels which transmit to the cordless handsets in the aircraft at a frequency of 1.7 MHz at 90 milliwatts and receive at a frequency of 49 MHz. The ACU converts frequencies used by the cordless handset radio stations and/or hardwired handsets to the air-ground channel frequencies. The ACU microprocessor performs other control functions, monitors onboard equipment and collects performance data.

The Cabin Handset Holder (CHH) is a wall-mounted unit that holds the cordless handset. One handset fits into each CHH. CHHs may be located at appropriate locations within the cabin. They house a credit card reader, a microprocessor and a battery charger. The CHH reads each customer's credit card and transmits the information to the ACU, which in turn verifies the credit card and sends a "release" command back to the CHH. The CHH then mechanically locks the credit card in place and releases the cordless handset to the customer. When

the handset is later returned, the CHH, in communication with the ACU, determines that the correct handset has been returned, locks the handset in place and releases the credit card. The CHH itself does not use radio frequencies. It uses the cordless handset transceiver to communicate with the ACU. Each CHH has an alphanumeric display that prompts the customer and gives display error messages when appropriate.

2.2.2 Seat back handsets

In order to increase passenger accessibility to telephone while inflight, handsets are being installed in the seat backs. Seat back handsets are hardwired directly to the ACU. Insertion of a credit card releases the handset from its holder. Once released, a credit card is passed through a magnetic strip reader built into the back of the handset. The call processing features are similar to those of the cordless handsets detailed above.

The Common Unit (CMN) contains the RF circuitry and the power supply for all air-ground equipment in the electronics bay of the aircraft. It contains a three-phase power supply operating off the aircraft's 400 Hz power system. Fuses and redundant circuitry protect the aircraft's power system and ensure there will be no single-point power failures in the system.

Table II contains the specifications for the air-to-ground public correspondence system.

TABLE II

Technical characteristics

	<u>Aircraft station</u>	<u>Ground station</u>
Transmitter power output	+40 dBm	+40 dBm
Transmitter filter loss	1 dB	1 dB
Antenna feed loss	1 dB	3 dB
Antenna gain	0 dB	3 dB
Receiver noise figure Max.	5 dB	5 dB
Filter diplexer loss	1 dB	N/A
Transmitter combiner	4 dB	N/A
Transmitter frequency**	895 MHz \pm 1 MHz	850 MHz \pm 1 MHz
Path loss*	141 dB	140.5 dB
Receive signal level	-103.5 dBm	-108 dBm
Noise level (6 kHz BW)	-136 dBm	-136 dBm
Signal/Noise	27.5 dB	23 dB

* Altitude 9,000 m
Distance 300 km

** These frequency bands are currently used in the United States and Canada on a provisional basis. Currently these bands cannot be used in Region 1.

ANNEX III

United Kingdom approach to public mobile telephone service
for communication with aircraft1. Introduction

In the United Kingdom, studies have been conducted into methods of providing a public telephone service with aircraft. These have led to the selection of a system which is intended to make efficient use of the frequency spectrum, give comprehensive area coverage, allow maximum call continuity and provide access to up to 8 voice circuits from each aircraft (growing to 32) while keeping the weight, power and heat generation of on-board equipment to a minimum. In addition to these operational factors, the system concept is such that it will be possible to easily update the system to incorporate lower rate voice codecs. The technical and operational characteristics are described below.

2. System concept

The system is intended to use the two 1 MHz bands (1 593 - 1 594 MHz and 1 625.5 - 1 626.5 MHz) allocated by WARC MOB-87. Each of these bands will be divided into 39 channels of 25 kHz, thus providing 12.5 kHz guard bands at the edges of each 1 MHz band.

The modulation will be approximately 38 kbit/s with TDM process on the ground-to-air link and TDMA on the air-to-ground link.

Each channel will be capable of carrying four 9.6 kbit/s voice circuits.

The system will have the facility to change to 4.8 kbit/s operation on the necessary channels for those aircraft equipped with lower rate voice codecs when they become available. This will provide a maximum capacity of 312 circuits/MHz. In the nearer future, data reduction techniques may also increase the capacity by a factor of two.

2.1 Doppler shift

The speed of electromagnetic radiation is approximately one million times the likely cruising speed of aircraft using the system. Doppler shift of the signal is thus 1 Hz/MHz (i.e. 1.6 kHz) for an aircraft moving radially relative to a ground station. This figure is reduced if the track is not radial or if the range is of the same order as the altitude.

This system will make no attempt to correct the Doppler shift since the shift is a small proportion of the 25 kHz channel spacing, neither is the receive filter shifted to centre over the signal since the TDMA operation means that any channel may be used by more than one aircraft, each with a different associated Doppler shift.

The amount of signal information lost due to the Doppler shift on the wanted signal is tolerably small. Of much more importance is the amount of unwanted signal introduced into the receive filter. This is minimized by keeping the filter centred on the nominal frequency, a particularly effective method when Doppler shifted interference exists on both sides of the wanted signal.

3. Frequency reuse scheme

This system ensures that comprehensive coverage for aircraft is provided, whilst maintaining efficient use and reuse of the frequency spectrum, by adopting a three tier structure. Each tier is associated with a given transmitter power level and aircraft altitude.

Each ground station will be designated as either high, medium or low power. The high power ground stations are for en-route coverage and will be used by aircraft above about 9,000 feet (2.7 km). Medium power ground stations are for use mainly during the climb and descent phases of flight, up to about 9,000 feet. Low power ground stations are only for use when aircraft are on the ground. The power levels associated with each of these ground stations is given in section 5.

Low and medium power ground stations will only be sited at airports but high power ground stations must be distributed throughout the operational area in a manner which will provide total coverage. This will be achieved by implementing a nine frequency reuse pattern, as shown in Figure 1.

3.1 Channel assignment

Each channel is designated as either an en-route (high power) channel or an airport (medium or low power) channel. Figure 2 shows this diagrammatically. There are 12 airport channels (annotated "A" in Figure 2), six at each end of the 1 MHz bands and 27 en-route channels (numbers 7 to 34).

The en-route channels are assigned sequentially to the en-route stations so that each en-route station has three channels at 225 kHz intervals. Therefore, each en-route ground station can support 24 voice circuits at 4 kbit/s (12 circuits during 8 kbit/s operation but eventually rising to 48 circuits per ground station).

Airport ground stations can be assigned a maximum of six channels, so that only alternate airport channels are used at any one ground station. This will be done on a case by case basis to take account of the airports' requirement and proximity to other airport ground stations.

A further benefit of this arrangement is that the risk of adjacent channel interference to other services is minimized by transmitting the lowest powers at the band edges.

3.2 Ground station coverage

Figure 1 shows the layout of the en-route ground stations. They are spaced 200 nautical miles (366 km) apart. The minimum distance between stations with the same channels is 529 nautical miles (968 km) and the minimum distance between stations with adjacent channels is 346 nautical miles (633 km).

Aircraft below 46,000 feet (14 km) cannot be in line-of-sight of two en-route ground stations with the same channels, thus avoiding co-channel interference up to this altitude.

Aircraft above 8,700 feet (2.7 km) will always be within line-of-sight of at least one en-route ground station. The maximum distance to a ground station for these aircraft will be 115 nautical miles (210 km). Aircraft above 8,700 feet will always be within line-of-sight of between one and seven ground stations, depending upon the aircraft altitude and location within the hexagonal pattern. Therefore any single aircraft may have access to up to 168 circuits.

4. Operation

Circuit availability data will be transmitted by each ground station on one of its channels. An aircraft requiring voice circuits will listen to circuit availability transmissions and select channels and slots to meet its need.

The ground stations will also transmit control data which will provide instructions to the aircraft on synchronization of time slots and its required transmitter power.

4.1 Hand-over

Hand-over will be an intrinsic part of this system. This will be controlled by the aircraft so that call continuity can be achieved, signal quality improved and probability of interference reduced.

5. Power

The system en-route power budget is shown in the table below. The path loss is conservative by about 3 dB and a generous allowance has been made for cable loss between the transceiver and antenna. The 14 dB in reserve is for multipath propagation at maximum range.

POWER BUDGET	
Transmit power	+46 dBm
TX loss	-2 dB
Radiated power	+44 dBm
Aircraft antenna gain	0 dB
Path loss (370 km)	-148 dB
RX loss	-3 dB
Ground antenna gain	+6 dB
Net signal power	-101 dBm
Noise in channel	-130 dBm
RX noise figure	+3 dB
Total noise power	-127 dBm
S/N for EB/No. of 10 dB-Hz (BER 10E-4)	+12 dB
Margin	+14 dB

ANNEX IV

Propagation and Doppler effects in
terrestrial APC systems1. Air-to-ground propagation model

The basic air-to-ground propagation model consists of two paths between the transmitter and the receiver (see Figure 1). One path is the direct line-of-sight (LOS) path and the other is one reflected from the Earth's surface. At the receiver, the direct and reflected signals add constructively and destructively, [Kirby, R.S et al, 1952], depending on the phase difference between the two signals which results from the ground reflection and the refractivity profile of the atmosphere. When the aircraft is within a few miles from the base station, the separation between fades is in the order of a second with linear dependence on frequency, [Painter, J.H. et al, 1973]. Higher fading rates can be encountered in very special cases due to reflections geometry.

The magnitude of each fade is affected by the ground characteristics in the reflection region, the incidence angle and the reflected angle. The ground conductivity is generally a function of frequency with the consequence that higher frequency causes larger reflection coefficient, [Report 238-4 (Geneva, 1982)].

The ground reflection is affected by the shape and the roughness of the reflection surface in the first Fresnel zone, which is, in the present case, the intersection between the first Fresnel ellipsoid for the reflected ray and the ground. The size of the first Fresnel zone is frequency dependent.

The ground distance between the base station and the reflection point is roughly equal to the aircraft ground distance scaled down by the ratio of the height of the base station antenna (h_1) to the aircraft altitude (h_2). As the aircraft moves, the reflection point moves at a much reduced velocity (by a factor approximately equal to h_1/h_2).

The distribution of power between the specular and diffuse components of the signal depends on the terrain roughness correlated with the transmitted frequency. Doubling the frequency corresponds to raising the scattering coefficient to the fourth power, decreasing the power of the specular reflection, and increasing the power of the diffuse component. Thus, the total received signal shows smaller fades caused by specular reflections but larger fluctuations due to the diffuse component when frequency is increased. The fading rate of the signal fluctuations due to the diffuse component is related to the coherence distance of the irregularities on the ground and to the velocity of the Fresnel zone on the ground and therefore is not affected by changes in the transmitted frequency.

The Earth's atmosphere affects the propagation at UHF in mainly two ways: refraction and diffraction. The refraction, or ray bending, of UHF waves is due to gradients in the refractive index of the atmosphere. In what is called the standard atmosphere, the refractive index decreases linearly with altitude and as a result, the rays are bent downward over the spherical Earth. Using the approximation of $4/3$ earth radius (CCIR Recommendation 528), the rays may be considered straight. A correction can be made to account for variations due to altitude and atmospheric refractive index, [Robertshaw, G.A., 1986].

The atmospheric variations in temperature, pressure and humidity affect the ray paths and consequently the phase of the signal. However, for the purpose of providing reliable air-to-ground communication, the exact location of the fades is less important than the fact that these fades exist. It is not critical to consider the exact profiles of the atmospheric refractive index and free space propagation can be assumed. The refractive effect of the Earth's atmosphere is adequately taken into account by using the effective earth radius method, [Robertshaw, G.A., 1986].

The diffraction effects of the atmosphere are due to scattering by turbulence in the troposphere and abnormal atmospheric conditions. At 850 MHz, the scattered power is negligible compared to the received power. Thus, the scattering effects of the atmosphere can be neglected when there is a radio line-of-sight path which is determined by refractive effects.

The airborne antenna, attached at the bottom of the aircraft, acts as a half-wave dipole. The base station antenna is also assumed to be a half-wave dipole. The airborne antenna is located to minimize signals reflected from the aircraft surface.

The antenna directivities can cause small signal fluctuations as the aircraft moves because of the change in angles between the ray paths and the antennas. The airborne antenna is expected to be the principal contributor to this effect because the aircraft causes multiple reflections which modify the simple pattern of the ideal half-wave dipole antenna. The fluctuations of the received signal due to the antenna patterns are expected to be rather slow since the inertia of the plane limits its movements. Furthermore, the angles between the ray path and the antennas change slowly. The amplitude of these fluctuations depends on the antenna pattern. The largest fluctuations are expected when an aircraft engine (or other obstacles) shadows the paths between the airborne and base site antennas.

Figure 2 shows a received signal performance corresponding to the two paths model, as the aircraft moves away from the base station.

As frequency increases from 860 MHz to 1 600 MHz for example, the predominant effect is free-space loss, with somewhat deeper fading due to larger ground conductivity and more specular reflection. Larger apparent terrain roughness, due to shorter wavelength offsets the larger fades due to larger scatter loss for the reflected signal. Near and beyond the radio-horizon the reflected signal becomes shadowed so that the model has to be modified to apply in these regions.

2. Effects of Doppler shift

Doppler shift has a considerable effect on the air-to-ground system design and complexity. Taking maximum aircraft speed to be 600 miles per hour, and operating frequency to be 850 MHz, then maximum Doppler shift is experienced by an aircraft flying on a base site radial at maximum aircraft speed, and is 760 Hz.

Conflicting Doppler shifts can cause interference both between two aircraft operating on a common base site, and between aircraft operating on adjacent base sites, where the Doppler shift is a large percentage of the channel bandwidth. If an aircraft flying toward the base site is operating on a channel, and an aircraft flying away from the base site is operating on the next higher channel, then the aircraft on the lower channel has up-Doppler at the

base site, and the aircraft on the higher channel has down-Doppler at the base site. The received signals can overlap, causing interference at the base site. There is no equivalent interference effect on the uplink, since each aircraft experiences equal Doppler from all transmissions from a base station. Similarly, Doppler induced adjacent channel interference occurs at adjacent base sites.

There are ways to avoid these two forms of Doppler induced adjacent channel interference including using a guard band between adjacent channels greater than the maximum Doppler shift, or prohibiting adjacent channel assignments both within cells, and between adjacent cells.

Using either of these approaches leads to a serious decrease in bandwidth efficiency. A third approach precompensates for the Doppler shift at the aircraft transmitter. If the aircraft has an accurate measure of the received Doppler shift, it can apply the opposite shift (corrected for duplexing frequency offset) on the transmit. As a result of this precorrection, the signal received at the base site will be in the correct frequency band.

Doppler precompensation cannot compensate for adjacent site Doppler induced adjacent channel interference, however. Aircraft applying similar Doppler precorrections to compensate for co-site Doppler effects, will still have conflicting Dopplers at a mutually adjacent base site.

These three approaches apply with both single channel per carrier systems (SCPC) as well as multiple signals per carrier (e.g. Time Division Multiple Access) systems. With TDMA there are some additional considerations. In general, several aircraft with different Dopplers would be occupying time slots on a single carrier at a base site. If the guard band approach is taken, then it is necessary only to provide two guard bands around each TDMA carrier, so that the effects of the guard band are shared between the N voice channel time slots using that carrier. Making N large minimizes the effect of the guard bands. However, this approach imposes the burden of tracking up to N different Dopplers on the base site receiver with increased complexity as the tracking range increases due to higher frequencies. The Doppler precompensation approach can be used to eliminate the need for guard bands and mitigate the base site carrier recovery problem. The base site receiver will still have to deal with residual carrier offset between aircraft in different time slots.

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Two paths air-ground propagation model

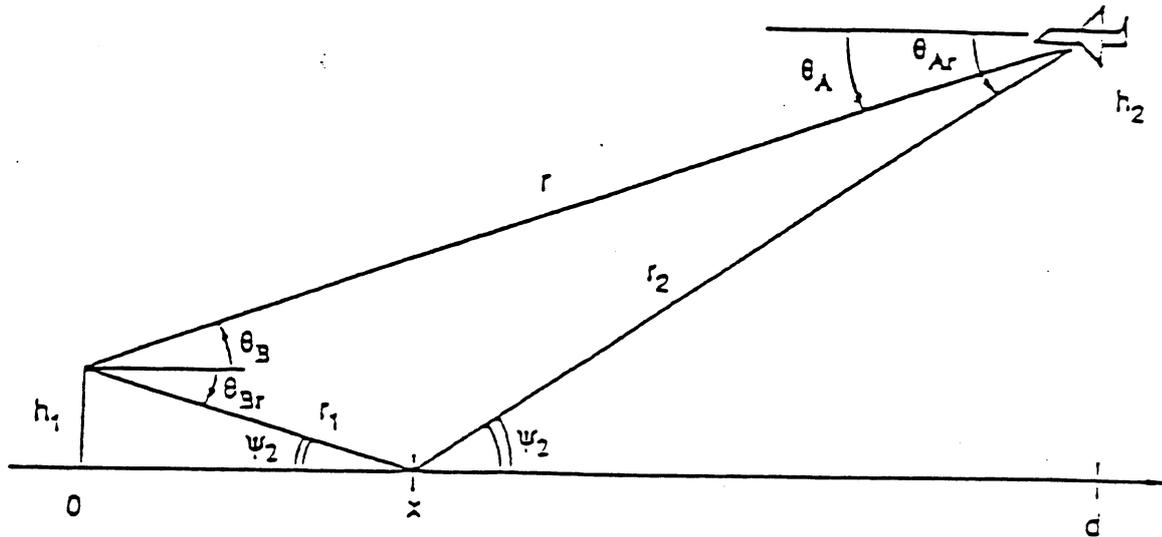


FIGURE 1

Geometry and notation for the air-to-ground propagation model

h_1 = 60 ft	Medium dry ground	h_1 = 60 ft	Medium dry ground
h_2 = 30,000 ft	r.m.s. roughness = 0.100 ft	h_2 = 10,000 ft	r.m.s. roughness = 0.100 ft
Freq = 849.0 MHz	half-wave dipole	Freq = 849.0 MHz	half-wave dipole

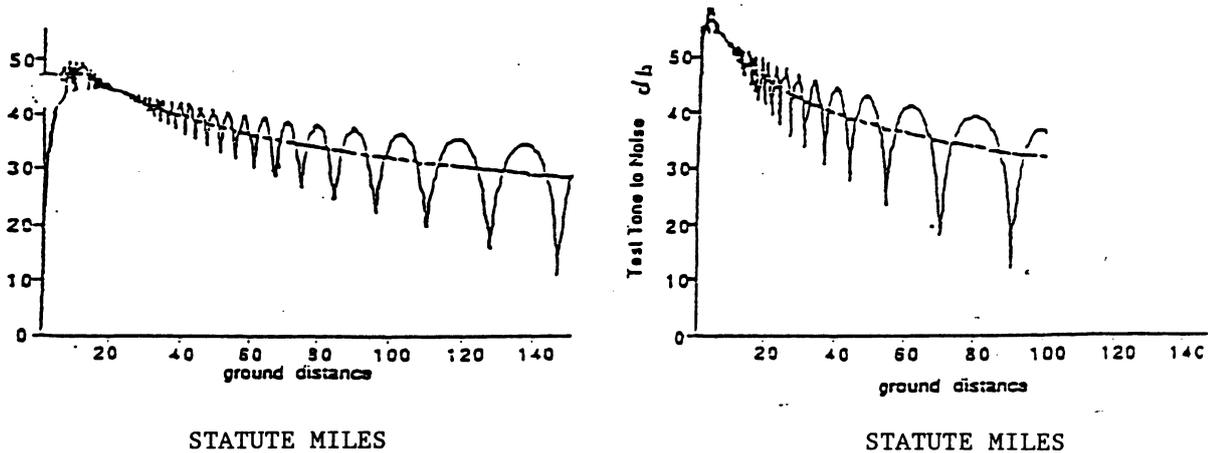


FIGURE 2

Comparison between calculated received signal patterns for two different altitudes using half-wave dipole antennas at the base station