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FREQUENCY SHARING BETWEEN PASSIVE SENSORS AND AERONAUTICAL RADIONAVIGATION SYSTEMS EMPLOYING GROUND TRANSPONDERS IN THE BAND 4.2 - 4.4 GHz

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FREQUENCY SHARING BETWEEN PASSIVE SENSORS AND AERONAUTICAL RADIONAVIGATION SYSTEMS EMPLOYING GROUND TRANSPONDERS IN THE BAND 4.2 - 4.4 GHz

I. Introduction

The frequency band between 4.2 and 4.4 GHz has been internationally allocated for use by the Aeronautical Radionavigation Service for many years. By informal agreement, the usage of this band has been limited to radar altimeters in most of the world. Report 694 of the CCIR, published in 1978, evaluated sharing considerations and protection criteria for passive sensors operating in this band, and demonstrated that practical radiometers could share the band with existing and projected radar altimeters. At the General World Administrative Radio Conference (GWARC), held in Geneva in 1979, the frequency allocation tables of the ITU Radio Regulations were amended, by Footnote 3743A, to authorize passive sensor operation within the band. However, no protection would be provided for passive sensors from radio or radar altimeter emissions. Footnote 3743A also officially reserves the 4.2 to 4.4 GHz band for radio altimeters aboard aircraft and for associated transponders on the ground. CCIR Report 694 had previously analyzed band sharing between passive sensors and radio (radar) altimeters aboard aircraft, but did not evaluate the efects of associated ground transponders. This paper describes a radar altimeter system which utilizes associated ground transponders and analyzes the feasibility of co-channel operation of such a system with a typical passive sensor.

II. RA-PRS System Description

Radio or radar altimeters of the past have not required ground transponders in order to perform their function. However, the U.S. Navy is currently evaluating a proposed modification to the AN/APN-194 which would use a shipboard transponder to enable that particular altimeter to perform precision ranging functions for Navy and Marine Corps VSTOL aircraft and helicopters operating from shipboard platforms.

The AN/APN-194 is a standard Navy pulsed radar altimeter, now in production, and presently installed on many VSTOL aircraft and helicopters. A simple modification has been developed which adds a forward looking antenna, a range computer and tracker, and other related electronics for sequencing and detection, and allows the system to function as an airborne, short range, precision approach radar. One frame of each 20 altimeter transmitter pulses is "stolen" and used to drive the forward-looking ranging antenna. The emitted transmitter pulse is received by the shipboard transponder and used as an interrogation pulse to trigger an amplified, band shifted, transponder reply. The transponder reply is received by the forward-looking antenna and receiver circuitry aboard the aricraft. The time interval between the transmitted and received pulses at the aircraft is then precisely measured and used to drive a display of the slant range between the aircraft and the flight deck. Figure 1 is a block diagram depicting the functional flow of radio frequency emissions. Note that the addition of the ranging function does not disrupt the altimetry functions, since the two are time division multiplexed. The modified system has been referred to by the vendor as the RA-PRS, for radar altimeter-precision

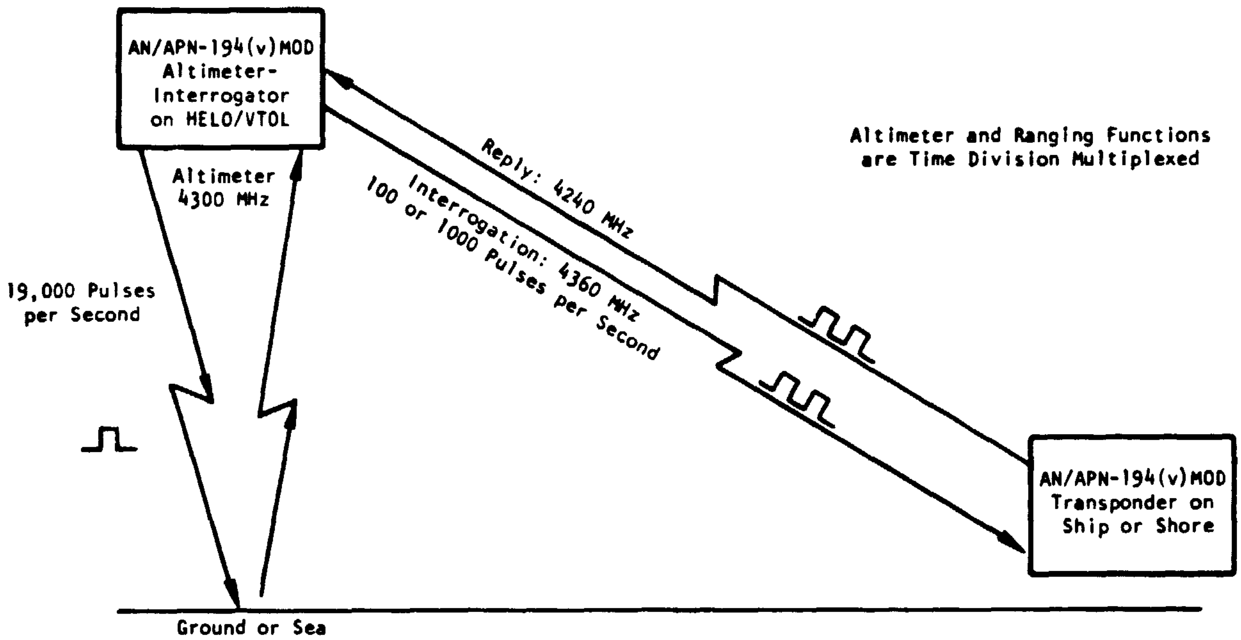

Figure 1. Radar Altimeter-Precision Ranging System

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ranging system. In this report the abbreviation PRS is used to identify that equipment which has been added or changed to allow precision ranging to be performed, while the abbreviation RA-PRS refers to the complete, modified AN/APN-194 for one aircraft.

The operating characteristics of the modified AN/APN-194 altimeter, and the associated PRS interrogater and transponder, which affect band sharing by passive sensors are tabulated in Table 1.

Table 1. Modified AN/APN-194 Operating Characteristics

System Characteristics:

System Range:	5 naut. miles
Channels:	20 channels with a 2 pulse code
Interrogation Rate:	Variable, max. is 1 KHz at close range and 100 Hz for ranges greater than a mile
Tracking Rate:	240 knots max.

Transmitter Characteristics:

	APN-194 Altimeter	PRS Interrogator	PRS Transponder
Peak Power	5 W	5 W	5 W
Pulse Width	20-200 nsec	50 nsec	50 nsec
Rise/Fall Times	<15 nsec	<15 nsec	<15 nsec
PRF	19 KHz	1 KHz	-
Type Modulation	1 Pulse	2 Pulse Code	2 Pulse Code
Transmitter Frequency	4.30 GHz	4.36 GHz	4.24 GHz
RF Switch Isolation	Greater than 30 dB		

Antenna Characteristics:

	APN-194 Altimeter	PRS Interrogator	PRS Transponder
Gain	12 dB typical 7.5 dB min. at ±22.5° from boresight	10.5 dB	15 dB
Beamwidth	40° min. E and H plane	45° min. E and H plane	0-20° elevation ±60° azimuth

III. Analysis Approach

Each operating airborne RA-PRS installation contributes to passive sensor interference through its altimeter emissions and through its rangefinder emissions. In addition, the shipboard transponder emits a signal upon interrogation by an airborne unit, which adds to the overall electromagnetic interference.

Ships which have a PRS transponder installed are capable of supporting simultaneous landing approaches by many aircraft. While the maximum number which can be expected to be operating with any given ship will vary with the ship's mission, the number can be on the order of ten or more around an aircraft carrier.

The total interference power, P_H (watts), is the sum of that due to the alimeters, P_A (watts), that due to the PRS interrogator, P_p (watts), and that due to the PRS transponder, P_t (watts),

$$P_H = P_A + P_p + P_t.$$

If the aircraft operate at relatively small separations from each other, when compared to the distance between the aircraft and the radiometer,

$$P_H \simeq n_A p_A g_A a_e / 4\pi r_A^2 + n_p p_p g_p a_e / 4\pi r_p^2 + p_t g_t a_e / 4\pi r_t^2 \qquad (1)$$

where:

n_A is the total number of altimeters in view of the satellite

p_A is the average output power of an altimeter in watts

g_A is the antenna gain of an altimeter

a_e is the radiometer antenna effective area in the direction of the interfering transmitter in square meters

r_A is the radiometer/altimeter separation distance in meters

n_p is the number of PRS interrogator units in view of the satellite

p_p is the average output power of a PRS interrogator in watts

g_p is the PRS interrogator antena gain

r_p is the radiometer/PRS interrogator separation distance in meters

p_t is the average output power of a PRS transponder unit in watts

g_t is the PRS transponder antenna gain

r_t is the radiometer/PRS transponder separation distance in meters.

The interference predictions will assume 15 aircraft are approaching an aircraft carrier for a landing. A total effective isotropically radiated power will be evaluated for the group of aircraft and the ship transponder. Equation (1) will then be used to establish a peak allowable number of interfering systems, where each system consists of 15 aircraft and one ship, by setting P_H equal to, or less than, the sensor interference threshold as given in CCIR Report 694. Other parameters will be chosen to reflect typical or average values.

IV. Interference Threshold

Table 1 of CCIR Report 694 gives −158 dBW as an acceptable interference power threshold for a passive sensor operating near 4 GHz. The Report also estimates the maximum number of conventional radar altimeters in view of the satellite at any one time as 750 (for a satellite altitutde of approximately 500 Km), with an average power output per altimeter of −7 dBW, each coupled to the radiometer through a transmitter antenna backlobe gain of −5 dBi. The effective area of the radiometer antenna sidelobe was given as −48 dBm^2 and the average slant distance as 1300 to 1400 km, i.e., the spreading loss is 134 dB/m^2. Thus, the interference power contributed by the conventional altimeter is:

$$P = 10 \log 750 - 7 - 5 - 48 - 134 = -165 \text{ dBW}, \ (.316 \times 10^{-16} \text{ W})$$

Since the total allowable threshold is −158 dBW, ($.158 \times 10^{-15}$ W) the limit available for budgeting to the RA-PRS is:

$$.158 \times 10^{-15} - .0316 \times 10^{-15} = .126 \times 10^{-15} \text{ W}.$$

or −159 dBW.

V. Interference Geometry

Considering the emissions from the airborne portions of the RA-PRS, either alone or multiply, there are three general geometric configurations of interest (see Figure 2). In the first (Case I), radio frequency energy is coupled from the RA-PRS sidelobes to a radiometer antenna sidelobe. In the second (Case II), radio frequency energy is coupled from one or more RA-PRS antenna mainbeams to a radiometer sidelobe. Finally, in Case III, radio frequency energy is coupled from RA-PRS sidelobes into the radiometer mainbeam.

In actual interference episodes, coupling from multiple aircraft could involve all three geometries simultaneously. Interference calculations have been made for several examples, however, to demonstrate the relative severity when one of the three coupling modes predominates over the others. Each case is examined in turn.

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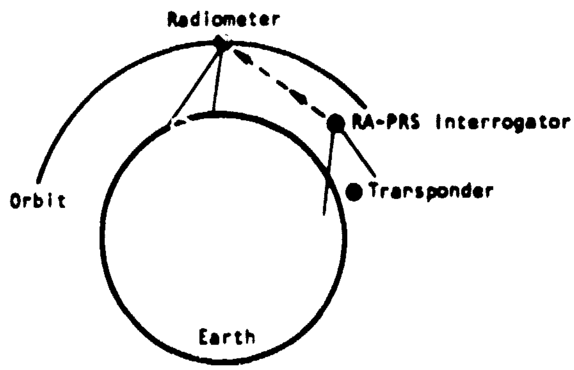
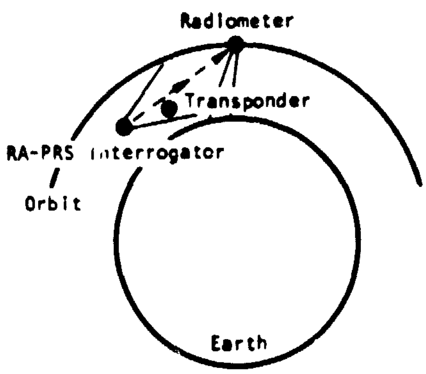
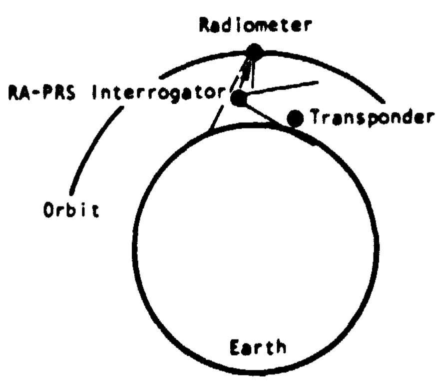


Case I: RA-PRS Sidelobe to Radiometer Sidelobe



Case II: RA-PRS Mainbeam to Radiometer Sidelobe



Case III: RA-PRS Sidelobe to Radiometer Mainbeam

Figure 2. Radiometer to RA-PRS Interference Path Geometry

VI. Interference Calculations

Case I

Interference power predictions for a single RA-PRS system, i.e., one shipboard transponder operating with 15 aircraft, and where Case I coupling predominates, are tabulated in Table 2. These calculations have assumed that only 1 of the 15 approaching aircraft is employing the high prf (2000 pps) applicable to short range operations. The combined emissions produce a total effective isotropically radiated power (EIRP) of -10.1 dBW. The allowable threshold power level for such interference is -159 dBW. Adjusting for propagation effects, we have:

$$-159 \geq 10 \log (n_p p_p g_p a_e / 4\pi r_p^2)$$

or

$$-159 \geq 10 \log n_p + EIRP + A_e - L_s \qquad (2)$$

where, from CCIR Report 694,

$$A_e = 10 \log a_e = -48 \text{ dBm}^2 \text{ (corresponding to a sidelobe gain of } -14 \text{ dBi)}$$

and

$$L_s = 10 \log (4\pi r_a^2) = 134 \text{ dB/m}^2$$

The number of systems each consisting of 1 ship and 15 aircraft and no more than -10.1 dBW EIRP, which could operate acceptably within view of the radiometer just exceeds 2000.

Table 2

RA-PRS System EIRP Where RA-PRS Sidelobe to Radiometer Sidelobe Interactions Predominate

Emitter	No. of Emitters	Emitter Peak P (W)	Emitter PRF (pps)	Emitted PW (μs)	Total Emitted Average Power (dBW)	Estimated Average Emitter Antenna Gain* (dBi)	Total Emitted EIRP (dBW)/(W)
Transponder	1	5	4,800	.05	-29	0	-29 /.0012
Interrogator @ < 1 nmi	1	5	2,000	.05	-33	0	-33 /.0005
Interrogator @ > 1 nmi	14	5	200	.05	-32	0	-32 /.0007
Altimeter	15	5	20,000	.20	-5.2	-5	-10.2/.095
RA-PRS Total	31	NA	NA	NA	NA	NA	-10.1/.0974

*Emitter antenna gain values are estimated levels consistent with the interference geometry.

Case II

An example where Case II coupling predominates has been evaluated in Table 3. Here, seven of the total 15 aircraft have been assumed to be illuminating the radiometer with RA-PRS mainbeams. The mainbeam gain is 10.5 dBi. Furthermore, the shipboard transponder has been assumed to be irradiating the radiometer simultaneously with its mainbeam (worst case situation). The total EIRP for this situation is -8.55 dBW. The spreading loss is assumed to be 139 dB/m^2 for Case II since the RA-PRS mainbeam axis will be pointed at or near the horizon. If the radiometer satellite is at an altitude of 500 km, the slant distance to the horizon will be approximately 2500 km. Thus, from equation (2), when Case II coupling predominates, more than 4500 RA-PRS systems can operate within view of a satellite radiometer before the acceptable threshold is exceeded.

Actually, simultaneous illumination of the radiometer antenna by the aircraft and the transponder mainbeams is unlikely, if not impossible. Figure 2 can be used to explain the reason for this observation. The interrogator antenna beam is a 45 degree cone with a gain of ~10 dBi. The transponder antenna beam is 120 degrees (±60 deg) wide by 20 degrees in elevation with a gain of ~15 dBi. In normal operation, the two beams are pointed more or less toward each other. The aircraft is trying to find the ship and the ship is trying to assist it. In order to do that they orient their antennas toward each other. Even when the antenna axes are considerably misaligned, they are generally pointed toward each other (see Figure 3). In order for an aircraft antenna mainbeam and the ship transponder antenna mainbeam to simultaneously

Table 3

RA-PRS System EIRP Where RA-PRS Interrogator Mainbeam to Radiometer Sidelobe Interactions Predominate (Transponder Mainbeam)

Emitter	No. of Emitters	Emitter Peak P (W)	Emitter PRF (pps)	Emitted PW (μs)	Total Emitted Average Power (dBW)	Estimated Average Emitter Antenna Gain* (dBi)	Total Emitted EIRP (dBW)(W)
Transponder	1	5	4,800	.05	-29	15	-14 /.0398
Interrogator @ < 1 nmi	1	5	2,000	.05	-33	0	-33 /.0005
Interrogator @ > 1 nmi	7	5	200	.05	-34.5	10.5	-24 /.00398
Interrogator @ > 1 nmi	7	5	200	.05	-34.5	0	-34.5/.00035
Altimeter	15	5	20,000	.2	-5.2	-5	-10.2/.095
RA-PRS Total	31	NA	NA	NA	NA	NA	-8.55/.1396

*Emitter antenna gain values are estimated levels consistent with the interference geometry.

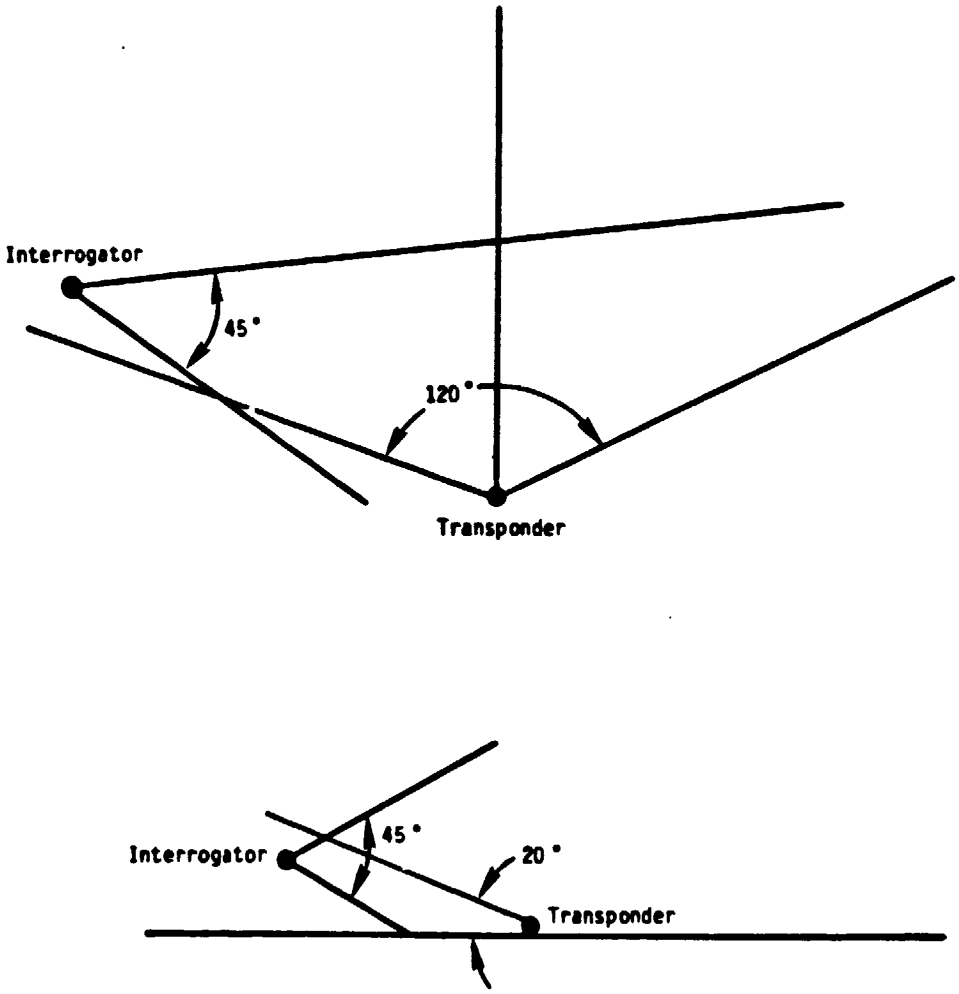


Figure 3. Beam Orientations for RA-PRS Ranging

irradiate a distant point in space, more or less at the elevation of the horizon, the aircraft must approach the transponder from the wrong side, i.e., it will not receive the maximum transponder signal level. This is unlikely in a normal or routine operation and would be an accidental occurance if it did.

The calculation of the interference EIRP in the case of RA-PRS mainbeam to radiometer sidelobe interactions has been repeated in Table 4 with a transponder antenna gain of -5 dBi. The resultant EIRP is -10 dBi. Using equation (2) with a spreading loss of 139 dB/m^2 and a radiometer antenna effective area of -48 dBm^2 (from CCIR Report 694), just over 6300 such systems would be required in view to exceed the radiometer interference threshold.

Case III

The final geometric configuration of interest (Case III) can be evaluated using the total EIRP predicted in Table 2 (for RA-PRS sidelobe emissions). However, the spreading loss in this case is only 125 dB/m^2 (approximately 500 km). The radiometer antenna effective areea is approximately +12 dBm^2 (corresponding to +46 dBi). The pencil beam of the radiometer antenna is quite narrow, viewing only a small spot ($\sim$2.6 km long) at the Earth's surface. Thus only one RA-PRS system is likely to be directly viewed by the radiometer mainbeam at one time. The interference level due to one system would be:

$$-10.1 + 12 - 125 = -123.1 \text{ dBW}$$

While this is above the interference threshold, the duration of this signal level is only a few milliseconds, at most. This is considered to be insignificant when compared with the durations of Cases I and II.

Table 4

RA-PRS System EIRP Where RA-PRS Interrogator Mainbeam to Radiometer Sidelobe Interactions Predominate (Transponder Sidelobe)

Emitter	No. of Emitters	Emitter Peak P (W)	Emitter PRF (pps)	Emitted PW (μs)	Total Emitted Average Power (dBW)	Estimated Average Emitter Antenna Gain* (dBi)	Total Emitted EIRP (dBW)/(W)
Transponder	1	5	4,800	.05	-29	-5	-34 /.000398
Interrogator @ < 1 nmi	1	5	2,000	.05	-33	0	-33 /.0005
Interrogator @ > 1 nmi	7	5	200	.05	-34.5	10.5	-24 /.00398
Interrogator @ > 1 nmi	7	5	200	.05	-34.5	0	-34.5/.00035
Altimeter	15	5	20,000	.2	-5.2	-5	-10.2/095
RA-PRS Total	31	NA	NA	NA	NA	NA	-10 /.1002

*Emitter antenna gain values are estimated levels consistent with the interference geometry.

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VII. RA-PRS Population Predictions

The Navy proposes to develop the RA-PRS system as a modification to approximately 150 existing or planned AN/APN-194 altimeters. The system is intended for use as an approach and landing aid for military VSTOL aircraft and helicopters using abbreviated landing areas, only. As it is currently conceived, the RA-PRS fulfills a specific requirement for precision range measurements at relatively short ranges, to support aircraft capable of landing in very small areas. The planned operating range (5 nmi) limits its utility to normal fixed wing aircraft, especially high speed aircraft. Furthermore, the system does not at present fulfill a general need within the National Airspace System, being defined for the United States by the FAA and military air control agencies.

The concept could become attractive for non-military helicopters and VSTOL aircraft, but it is not known if it will grow to the numbers predicted in Section VI as necessary to cause harmful interference. Any attempt to answer such a question must be subjective and highly qualified. However, given the wording of the allocation; that is, that the transponder must be associated with radio altimetry, extensive procurement of the system, or others like it, seems unlikely. The concept appears to have a usefulness only for helicopters, VTOL and VSTOL aircraft. Although precise, the operating range is more limited than for DME or precision DME used by commercial aviation. Thus it does not appear to be useful for point-to-point navigation or area navigation systems. Furthermore, as an approach and landing aid it is not as broadly useful as the commercial Instrument Landing System or the new Microwave Landing System (MLS), now under development. The specifications for MLS have been written by an international coordinating committee in an attempt to develop a world standard MLS concept, data format and signal specification. While there has been disagreement on MLS specifications and implementations, the RA-PRS concept, or any other altimeter/transponder approach alone, wuld not appear to offer any unique or comprehensive capabilities for navigation or approach and landing standards. The system could find use ashore but most probably with users of VSTOL, VTOL aircraft at small area, restricted landing sites. It is doubtful that all helicopters or VSTOL or VTOL aircraft would even be equipped with RA-PRS equipment. Thus the Navy's estimate of 150 airborne systems is probably accurate through 1985. It should be noted that 150 aircraft might require only 10 to 15 ship or ground transponders. Thus the number of operating systems, as defined in this report, is only 10 to 15 initially. The ultimate global population of operating systems would probably be less than 1000. Of this number far fewer, perhaps less than 1/3 of the total could be expected to be in operation simultaneously.

VIII. Conclusions

Sharing between radio altimeters employing ship or ground transponders and passive radiometers is feasible in the band 4.2 to 4.4 GHz. While there is no protection provided to passive sensors, existing altimeter system concepts and predicted interferor populations provide no significant threat of high level or long duration interference levels. Furthermore, the projected growth in use of altimeters and altimeter transponder systems will not cause harmful interference in the foreseeable future. Other applications for radar altimeter precision ranging systems could arise, such as for helicopter traffic to building roofs, to off-shore oil rigs, to commercial shipping and in other military operations than those involving aircraft carriers. However, the numbers of aircraft employed in these applications are likely to be smaller than in aircraft carrier operations. Therefore the foregoing analysis is assumed to describe the worst case.