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Recent Technical Advances in General Purpose Mobile Satcom Aviation Terminals

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ABSTRACT

A second general aviation ACSSB aeronautical terminal has been developed for use with the Ontario Air Ambulance Service (OAAS). This terminal is designed to have automatic call set up and take down and to interface with the PSTN through a Ground Earth Station hub controller. The terminal has integrated RF and microprocessor hardware which allows such functions as beam steering and automatic frequency control to be software controlled. The terminal uses a conformal patch array system to provide almost full azimuthal coverage. Antenna beam steering is executed without relying on aircraft supplied orientation information.

GENERAL DESCRIPTION OF THE TERMINAL

The first general purpose aeronautical satellite terminal developed by CRC for the Government of Ontario Air Ambulance Service (OAAS#1) proved the feasibity of aeronautical satcom for small aircraft by using L-Band mobile satellite technology (Ref.1). However, the technology developed for this demonstration has limited operational characteristics. The setting up and taking down of calls between the aircraft and the Medical Communications Centre in Toronto requires considerable human intervention at the Ground Earth Station. Similarly, the requirement for ultra-stable frequency control necessitated by the narrow band modulation technology and the demands of the satellite provider (INMARSAT), forced the use of an ovenized oscillator with a long stabilization time which is undesirable for a terminal designed for emergency purposes. Lastly, the use of fixed window antennas on each side of the aircraft limited the azimuth angle of satellite coverage, EIRP, and the effective G/T of the terminal. Unless the pilot was willing to steer the aircraft in a usually less than favoured direction, achieving reliable satellite communications proved to be difficult.

The purpose in developing a second air ambulance satcom terminal was to address these operational limitations. Our solution was to design a call set up and take down system which would be automatic and allow channel access to be arranged by a Carrier Sense Multiple Access protocol. The protocol would work from a hub controller located at the Teleglobe Canada Ground Earth Station in Weir, Quebec. In order to minimize the long frequency stabilization times experienced with the first terminal, the second terminal would use a satellite pilot derived frequency reference that would reduce waiting time from 15 minutes to less than one. Finally, the second terminal was to be designed to provide the aircraft with almost full azimuth coverage by using a configuration of low cost, low drag conformal patch antennas that would surround the aircraft with a series of steerable high gain beams.

The terminal (OASS#2) was built in the fall of 1989 with software development and testing starting in the spring of 1990.

ANTENNA AND RF SYSTEM

A block configuration of the terminal is shown in Figure 1. The antenna system is comprised of three microstrip patch array antennas each equipped with a diplexor, low noise amplifier, and for those antennas having multiple beams, a coaxial switch. This configuration of front end RF was chosen because it maximized the G/T and EIRP. A small phased array was considered but the losses of such a system would have resulted in poorer performance.The antenna system implemented generates 9 beams that provide the aircraft with about 320 degrees of useable coverage (Figure 2).Over this azimuth angle the G/T of the terminal varies from -8 to -18 dBK. Similarly, the EIRP goes from 48 to 58 dBm, resulting in a received C/No of 40 to 50 dBHz at the ground earth station.

The multiple beam patch antennas are mounted on the port and starboard aft fuselage of a Beechcraft King Air 200 airplane. A third antenna is mounted in the nose of the aircraft above the radar. The forward antenna almost completely fills the forward keyhole left vacant by the patch arrays. All the antennas are made of air dielectric microstrip patch elements and are 1.25 inches thick. The port and starboard antennas are conformally mounted on the skin and protected by a radome that measures approximately 18 by 24 inches having a height of about 1.5 inches, resulting in negligible air drag. The port and starboard antennas each produce 4 beams having gains that range from 13 to 16 dBic. The forward antenna located in the nose of the aircraft has a gain of 12 dBic. The gains are measured from 1550 to 1650 MHz. The beams are squinted at elevation angles of 20 degrees, corresponding to the satellite look angle in the Northern and Western Ontario service area of the ambulance.

The diplexor/low noise amplifier switch boxes are mounted within 10 inches of the antennas. This assembly is light weight (approx. 2 lbs.) and has a receive path insertion loss of 1.0 dB and a transmit path loss of 1.3 dB. Each receive RF path is a concatenation of antenna, 10 inches of 0.141 semirigid coaxial cable, 4 to 1 low loss coaxial switch (the nose antenna does not need a switch), circulator, 6 pole cavity filter, an 0.8 dB noise figure low noise amplifier, followed by the RF cable that can be anywhere from 5-30 feet long directing the signal back to the main terminal where a final 3 to 1 coaxial switch is encountered. The transmit path begins with a 6 pole transmit filter located next to the power amplifier, a 1 to 3 coaxial switch, RF cable, circulator, 4 to 1 switch and finally the feeder coaxial cable and antenna.

The desired beam was chosen by first switching the 3 to 1 coaxial switch to select either the port, starboard, on forward antennas. If the port or starboard antenna is selected the 4 to 1 switch is used to select the individual beam. The total switching time is 25 milliseconds. The loss in a coaxial switch is less than 0.1 dB over the 1550 to 1650 MHz band.

The up and down conversion system and L-Band voltage controlled local oscillator are constructed of low complexity microstrip circuitry. The design considerations here were for low cost and robustness, to satisfy the eventual land mobile applications for these circuits. The L-Band local oscillator has an output of 13 dBm at 1472.750 Mhz, a tuning range of approximately 10 KHz, and a phase noise specification of -95 dBC/Hz at 1 KHz. The RF power amplifier is a commercially available (Canadian Astronautics Limited) class AB linear L-Band device capable of delivering a peak output power of 49 dBm. To accomodate the linearity requirements of the Amplitude Companded SSB modulation, the amplifier is set at an average output of 43 dBm.

SIGNALLING AND ACCESS PROTOCOLS

The modems and protocol controller of the terminal are off-the-shelf ACSSB channel units procured from Skywave Electronics Limited. The units were modified to accept DTMF signalling and redesigned with a robust access protocol that would ensure operation at low C/No. The DTMF signalling was chosen because of its implementation simplicity and robustness. The probability of successful signalling with the DTMF tones is approximately 78.7 % at 33 dB Hz and 99.8 % at 38 dB Hz. This coupled with the observation that the limit of intelligible ACSSB is about 38 dB Hz, has caused us to set this as the lower limit of terminal operation.

The terminal is designed to work in a carrier sensed multiple access system controlled by a 386 microprocessor family computer. The computer is linked with channel units that service air ambulance calls. The system mediates PSTN signalling and controls call set up and take down between the Medical Communications Center in Toronto and the aeronautical terminal. The computer also collects usage information for billing purposes and controls forward link EIRP from the satellite. It is located at the Teleglobe Canada Weir Ground Earth Station and has a single INMARSAT 25 KHz - 21 dBW EIRP L-Band channel allocated to it. The channel is subdivided into three 8.33 KHz channels that are shared on a demand assigned basis by 2 Air Ambulance terminals (OAAS #1 and #2) and 18 briefcase portable ACSSB/DMSK terminals used for the Canadian MSAT trials program.

SATELLITE TRACKING FACTORS

There were several factors motivating the design of the beam steering hardware and software for the terminal. One factor was the need to maintain the the best C/No for the received signal. The operating margins for the forward and return links are minimal and even these change on a daily basis as the INMARSAT satellite becomes loaded with maritime traffic. The second factor driving the design was the limited lifetime of the coaxial switches for the antennas. These switches are rated for one million switching operations which is a number that can be quickly reached, especially if the terminal dithers excesively from beam to beam.

PILOT TRACKING HARDWARE

The terminal tracks the INMARSAT Standard A System channel 110 BPSK pilot. This pilot is common to the worldwide maritime satcom service and will be present as long as the Standard A service remains viable. The pilot has a low forward EIRP (only 13 dBW) and, as a consequence, is difficult to monitor. The BPSK signal is detected by a quadrature demodulator which produces signal level and frequency information.The demodulator contains a phase lock loop that has a tracking range of 300 Hz and a loop bandwidth of 50 Hz. The output of these circuits is fed into a 8 Bit A/D and a microcontroller where signal analysis is performed. The BPSK pilot signal can be detected and measured to a C/No of 24 dB Hz, though the limits for terminal operation are set at 27 dB Hz. It should be noted that the BPSK pilot has a mean power 8 dB below the average power of the ACSSB communications signal. As such, since the lower limit of ACSSB operation is set at 38 dB Hz, the BPSK pilot must be useable down to at least 30 dB Hz.

The sampling interval is 200 milliseconds long, over which time measurements were continually taken and averaged by the microcontroller. This interval was chosen to accomodate a 5 Hz ripple in the signal power of the BPSK. The ripple is due to the repitition of an unchanging identity work on the INMARSAT Standard A.

BEAM STEERING

Unlike the commercial aviation L-Band satellite terminals that are being currently developed, the OAAS#2 terminal does not switch antennas using orientation information provided by the aircraft. Steering information is derived solely from the quality of the received pilot signal and switching decisions are made on the basis of the quality of the received signal dropping below thresholds which are adaptively determined by the terminals' microprocessor.

Adaptability of switching thresholds is a key requirement with this terminal because of antenna beam scalloping and gain variation. The 9 antenna beams have gains which vary from 12 to 16 dBic. These gains and the symmetry of the patterns are also altered by the metallic structure of the aircraft. Additional complications arise from the fact that each beam represents a unique RF signal path, which can vary independently in both noise content and gain over time and temperature. To counter these variations the terminal bases its decision processes solely on the basis of received C/No. Each beam, from the onset of terminal activation, is calibrated for noise density and this calibration is continually updated and averaged every 10-16 seconds for the beam that is currently used. Similarly, the received pilot signal is sampled and averaged over six 200 millisecond intervals taken within a 2 second period. These averages are used to create a mean C/No value for the current beam, representing the quality of the signal over the previous 2 seconds. Experiments with the stationary OAAS#2 terminal have shown this sampling system capable of measuring the mean C/No to an accuracy of +/- 0.5 dB over a 20 dB dynamic range from 28 to 48 dB Hz. The nominal pilot signal level with a 14 dBic beam would be 39 dB/Hz.

TRACKING ALGORITHM

Ideally, the tracking algorithm should switch whenever the pilot signal is higher in an adjacent rather than current beam. Each beam (labelled n, where n=1....9) has two thresholds T(n+1) and T(n-1) with adjacent beams or beam pattern keyholes. These thresholds are determined by the terminal as it operates, and are updated with each successful switching that the terminal makes. When a threshold is reached the terminal determines the C/No in the current beam, then switches to the adjacent beam and samples the signal in it for an interval of 400 milliseconds. If this latter sample promises to exceed in C/No that of the original beam, sampling for a full 2 second interval is maintained. Providing the new sample is greater than one in the original beam, a threshold is created by calculating the difference between the two samples and adding half of this to the lower sample. The thresholds are further reduced by about 1-1.5 dB to increase the probability of switching success by increasing the probable difference between the current and adjacent beam samples (see Figure 3).

One difficulty that exists with this algorithm is that the terminal has only a 50% chance of moving to the correct beam whenever the signal level is between thresholds. That is, given that the level of the signal is S in beam (n), we have two possibilities:
T(n+1) < S < T(n-1) or
T(n-1) < S < T (n+1) (Figure 3).

As an example of a wrong more, the signal in the current beam may be entering the beam on its side adjacent to the n+1 beam, however this signal may be below T(n-1). Unless some preventative action is taken, the terminal will switch after each sampling cycle to the n-1 beam, where the signal is virtually non-existent. Switching will then oscillate with the periodicity of the sampling /switching cycle until the signal either goes below the T(n+1) threshold or above T(n-1). This situation will occur half the time. The other half of the time the signal will occur on the other side of the beam where the move will result in a greater signal.

A closer examination of this problem reveals that nothing can be done to prevent such oscillations, other than extracting additional information from the received signal which would indicate the direction of aircraft turn. This level of processing was not attempted with the current terminal. Instead we opted for a solution which would inhibit the terminal from making incorrect moves by dynamically varying the interval of time between wrong switching decisions. Thus after one wrong move the terminal will wait for two sampling cycles to elapse before undertaking a second wrong move. After the second wrong move the terminal will wait 10 sampling cycles after which wrong moves will be allowed only every 14 cycles (28 seconds). If the terminal moves above the threshold forcing the incorrect moves then it will quickly remove the inhibition. If the terminal successfully changes beams, then all the inhibitions for the previous beam will be set to zero.

The lost signal threshold for the terminal is set at 38 dB Hz (30 dB Hz for the BPSK pilot). No matter what level of switching inhibition the terminal is in, if the lost signal threshold is reached the terminal goes into a signal search mode beginning its scan with the adjacent beams. A complete scan of the 9 beams can be achieved in about 1.8 seconds. At times, these may be unsuccessful in acquiring the lost signal, especially if the aircraft is flying with the signal entering a keyhole. During such instances, the scan times are slowed to one every thirty seconds.

FREQUENCY CONTROL

In the design of the frequency control system for the OAAS#2 terminal it was decided that ovenized oscillators were not to be used. In consideration of future low cost terrestrial mobile terminal applications, a frequency control system using a satellite based pilot reference was preferred.Pilot reference systems using either frequency or phase lock loop techniques combine the advantages of a single, ultra-stable long term system reference with the low phase noise characteristics achievable using low cost crystal or SAW oscillators resident within the terminal.

To lower the complexity of a pilot based frequency acquistion and control system, we combined simple microstrip multiplier circuits with a microcontroller, D/A, and voltage controlled crystal oscillator to produce a frequency locked reference that is able to lock and track the Standard A BPSK pilot to an accuracy of +/- 50 Hz at a C/No of 27 dB Hz.

FREQUENCY ACQUISTION

The INMARSAT Standard A BPSK pilot at 1537.750 MHz has an absolute uncertainty of +/- 200 Hz. The pilot is detected using a 2 stage downconverter feeding the BPSK demodulator and microprocessor. The microprocessor monitors the demodulated pilot centered at a baseband frequency of 9600 Hz and provides frequency correction using a voltage controlled crystal oscillator. The 9600 Hz signal is actually a square wave whose periodicity is easily determined by the microcontroller by a simple counting routine. Offset of the 9600 Hz represents the difference between the satellite pilot and the terminals main local oscillator.

An L-Band multiplier takes the output of the oscillator and produces the 1467.750 MHz local oscillator of the terminal. Using a voltage controlled crystal oscillator was advantageous because it eliminates the need for any phase-lock loop circuits and in conjuction with the microstrip circuit multiplier, provides a highly stable, low cost L-Band reference. The circuits provide very quick frequency acquisition. At a pilot level of 27 dB Hz the INMARSAT pilot could be detected and used as a terminal reference within 30-45 seconds 90 % of the time.

The total absolute error of the terminals local oscillator after lock-up is in the order of 2.4 parts per 10(7) and is attributable to three factors, the absolute error of the INMARSAT pilot (+/- 200 Hz), the resolution of the 8 bit microprocessor system (+/- 50 Hz), and the uncertainty of the second LO in the downconversion chain (+/- 70 Hz). Secondary errors due to the drift in the temperature compensated voltage controlled oscillator were on the order of 30 Hz prior to stabiliztion of the terminal. This latter error is corrected out by periodic frequency recalibrations of the terminal flight.

The terminal acquires frequency lock to the INMARSAT pilot during those moments when the aircraft powered up. The aircraft at such moments is relatively stationary allowing the terminal to acquire a pilot free of Doppler offset. As the aircraft flies there are occasions when its orientation toward the satellite is such that Doppler offset on the received pilot is minimal. During these occasions the port or starboard antenna beams 3 or 7 are in use (see Figure 2) and the microprocessor takes advantage of this situation to perform minor frequency corrections. This procedure in reality worsens the absolute frequency error of the terminal by the acquired Doppler error (approx 90 Hz) , but it reduces the relative error between the terminal and the satellite pilot and as well, corrects any minor drift problems associated with the temperature compensated voltage controlled L-Band local oscillator.

Experiments with frequency resolution were tried with the frequency monitoring system of the terminal. The counter used for frequency measurements in the microcontroller has a 16 bit resolution allowing the pilot to be measured to a 0.5 Hz accuracy. Such accuracy could allow the terminal to quickly determine whether the aircraft is turning either toward or away from the satellite simply by monitoring the change inthe Doppler frequency of the pilot. It is proposed that incorporating this information with the steering algorithms could provide significant improvement in antenna steering performance especially in preventing moves into incorrect beams when as discussed earlier. Developing terminals and algorithms to do this processing is a future endeavour for us.

CONCLUSIONS

The above brief description has not covered many of the background functions of the terminal such as its call set up and take down processing, RF power control, and a temperature control system which ensures terminal operation over a wide range of operational and environmental conditions. Many of these functions are controlled by the same microcontroller that controls sampling, beam steering, and frequency correction.

The OAAS#2 terminal demonstrates that elements of operation such as frequency control and beam steering can be carried out using relatively simple hardware. The key to the success being control and monitoring by a microprocessor and its associated software.

Future L-Band terminals will have an even greater integration of beam steering and frequency control hardware and microprocessor software. Ultimately the goal will be to provide a simple,low cost RF system that use baseband signals at a frequency where they can be digitally signal processed without any intermediary hardware such as hardware demodulators or voltage controlled oscillators.

REFERENCES

1. Butterworth, J. S. 1988. Satellite Communications Experiment for the Ontario Air Ambulance Service. Proceedings of the Mobile Satellite Conference May 3-5, 1988. JPL Publication 88-9

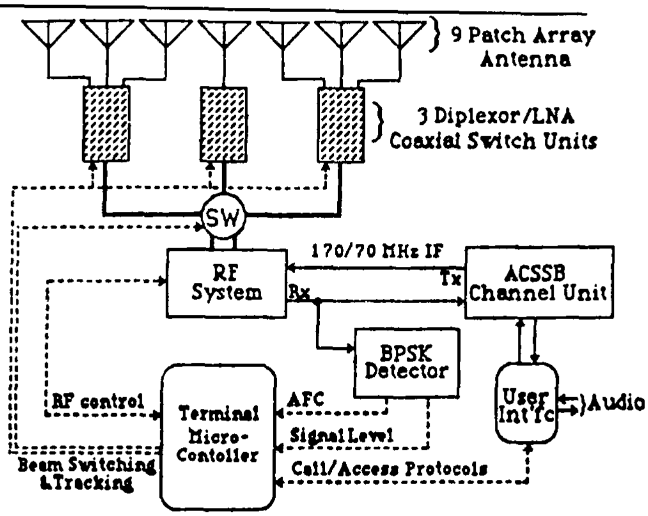

Figure 1

OAAS #2 Block Level Organization

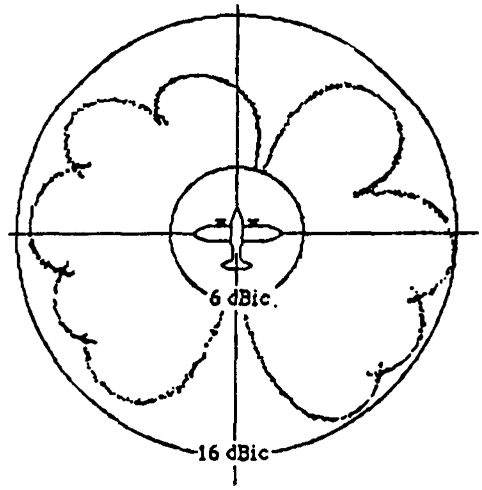

Figure 2
9 Beam Antenna Pattern of OAAS#2

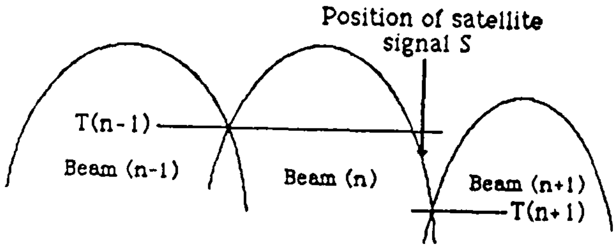

Figure 3
T(n-1)< S < T(n+1) Condition for Switching Oscillation into Beam (n-1)