

## WEATHER DATA DISSEMINATION TO AIRCRAFT

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Abstract

Documentation exists that shows weather to be responsible for approximately 40 percent of all general aviation accidents with fatalities. Weather data products available on the ground are becoming more sophisticated and greater in number. Although many of these data are critical to aircraft safety, they currently must be transmitted verbally to the aircraft. This process is labor intensive and provides a low rate of information transfer. Consequently, the pilot is often forced to make life-critical decisions based on incomplete and outdated information.

Automated transmission of weather data from the ground to the aircraft can provide the aircrew with accurate data in near-real time. The current National Airspace System Plan calls for such an uplink capability to be provided by the Mode S Beacon System data link. Although this system has a very advanced data link capability, it will not be capable of providing adequate weather data to all airspace users in its planned configuration. This paper delineates some of the important weather data uplink system requirements, and describes a system which is capable of meeting these requirements. The proposed system utilizes a run-length coding technique for image data compression and a hybrid phase and amplitude modulation technique for the transmission of both voice and weather data on existing aeronautical Very High Frequency (VHF) voice communication channels.

Background

The National Transportation Safety Board (NTSB) broad cause/factor assignments for general aviation accidents in the United States show weather to be the overall cause of approximately 40 percent of the general aviation accidents with fatalities occurring from 1980 to 1984 [1]. According to these data, only pilot error outranks weather as the most frequent overall cause of fatal accidents in general aviation. Similarly,

the data for United States air carriers show weather to be the overall cause of approximately 35 percent of the air carrier accidents with fatalities occurring in the same time period [2].

Not included in the above data is the August 1985 Delta L-1011 crash in which 135 persons lost their lives when the pilot attempted to penetrate a severe thunderstorm containing a microburst on final approach at the Dallas/Fort Worth International Airport. This crash led the NTSB to express concern that although the Federal Aviation Administration (FAA) had addressed nearly all of the actions proposed by the Safety Board since 1973, one important problem was not adequately being addressed. In the aircraft accident report for the Delta disaster, the NTSB identifies that problem as "the communication of hazardous weather information available from ground sensors to the flightcrew in time for the information to be useful in go/no-go decision making." The NTSB continues: "Current procedures to relay NWS [National Weather Service] information through the ATC [Air Traffic Control] system are not and will never be adequate for dynamic weather conditions" [3].

The aircraft pilot is the principal decision maker when in flight, and has the ultimate responsibility for the safety of the aircraft. Unfortunately, the information the pilot needs to make informed decisions about navigation in and around areas of severe weather simply is not available in today's National Airspace System.

Weather information is provided to users of the National Airspace System by a weather system which has been developed and is operated through a joint venture involving the FAA, the Department of Defense (DOD), the National Oceanic and Atmospheric Administration (NOAA), and the civil aviation community. Many of the weather data products utilized in the system are provided by the National Weather Service (NWS). The system is known as the Aviation Weather System, and is represented functionally in figure 1.

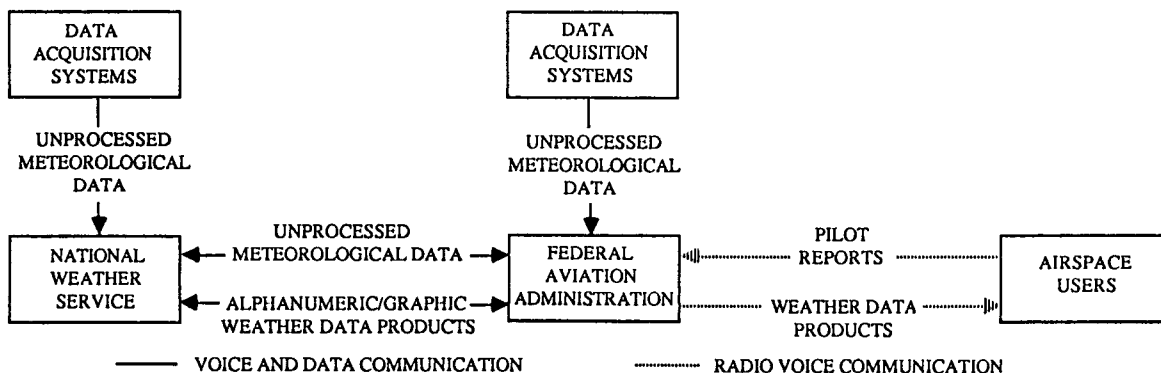


FIGURE 1 FUNCTIONAL DIAGRAM OF AVIATION WEATHER SYSTEM

In spite of significant advances in the ability to gather and disseminate weather data on the ground, the Aviation Weather System continues to rely upon voice communication for the dissemination of weather data to the aircraft. As a result, the system is severely limited in its ability to disseminate current weather data which is operationally significant to the individual end user.

The transmission of current weather data products from the ground to the aircraft by data uplink is widely recognized as a feasible solution to the weather data dissemination problem. The FAA has the responsibility to determine what meteorological services are required for aircraft efficiency and safety, and has committed to providing this service. The Aviation Weather System Plan states that at some point in the future the pilot will have in-flight access to required weather data "automatically and by request via data link" [4].

#### Requirements

##### Weather Data

Airspace user organizations and several U.S. Government agencies have expressed recommendations for the improvement of the Aviation Weather System. These recommendations are included in the Aviation Weather System Plan [5]. Recommendations with specific applicability to the uplink of weather data to aircraft are included in table 1.

Research in this area has resulted in the identification of certain weather data products

Organization	Expressed User Needs
ALPA	* NWS weather radar display
AOPA	* Timely critical forecasts * Self-briefing capability * Direct access to weather data
ATA	* Satellite images * NWS/FAA weather radar display
NBAA	* Pre-flight and in-flight weather data/briefings * Mass dissemination of Aviation Weather System data
NTSB	* Real time display and classification of precipitation and turbulence
NOAA/FAA/ NASA <sup>1</sup>	* Automated transmission of hazardous weather areas
ALPA - Air Line Pilots Association AOPA - Aircraft Owners and Pilots Association ATA - Air Transport Association NBAA - National Business Aircraft Association NASA - National Aeronautics and Space Administration <sup>1</sup> 1981 jointly sponsored workshop on meteorological and environmental inputs to aviation systems	

TABLE 1  
RECOMMENDED WEATHER DATA PRODUCTS  
FOR UPLINK TO AIRCRAFT [5]

which would improve aircraft safety and efficiency were they transmitted to the pilot by real time data uplink [6]-[8]. These weather data products are as follows:

1. Hazardous weather conditions
2. Radar precipitation reflectivity patterns
3. Surface analysis (SA)
4. Terminal and area forecast (FT and FA)
5. Critical weather maps
6. Text information:
  - Pilot Reports (PIREPS)
  - Significant Meteorological Information (SIGMETS)
  - Airman's Meteorological Information (AIRMETS)
  - Notices to Airmen (NOTAMS)
7. Satellite images

Microburst detection systems such as the Low Level Wind Shear Alert System (LLWAS) have been shown by simulation to be as much as 94 percent effective in the avoidance of microbursts if displayed graphically to the pilot. This compares to 43 percent if warnings are transmitted only by voice [9]. For such systems to provide the level of safety of which they are capable, the pilot needs to have the data available in graphical form.

Based on these facts, it is apparent that any system developed for the uplink of weather data will be required to provide some type of graphics transmission capability. Some of the more important graphics weather data would consist of real time radar precipitation reflectivity patterns and graphical microburst information. Such data would provide the pilot useful and up-to-date information about areas of operationally significant weather, and most importantly, areas of hazardous weather.

Many larger aircraft are equipped with on-board weather radar systems which provide similar information as do ground-based radar systems. These systems do not, however, have the capability of ground-based systems. Due to equipment size, cost, and weight considerations, airborne systems operate at X-Band and at lower power levels than ground-based systems. X-Band energy is more readily absorbed by precipitation and is also attenuated more in free-space than the S-Band and C-Band energy which is utilized by many ground-based systems. For these reasons, airborne systems have lesser range and are subject to greater precipitation shadowing than their ground-based counterparts. Additionally, airborne systems do not provide 360 degree azimuthal coverage. Although airborne radar systems can provide very useful precipitation reflectivity information, they cannot provide as accurate and detailed information as ground-based radar systems.

Ground-based weather radar data are currently available to the Center Weather Service Unit (CWSU) within the Aviation Weather System. Improved radar systems such as the Next Generation Weather Radar (NEXRAD) and the Terminal Doppler Weather Radar (TDWR) will provide additional information such as doppler echoes for location of windshear. The uplink of such information is certainly technically feasible and would greatly enhance the safety of the National Airspace.

### Data Transmission

Transmission of weather data to the aircraft must be accomplished in such a way as to minimize the use of an already overcrowded frequency spectrum, while at the same time provide an adequate temporal update rate for near-real time weather data dissemination. The pilot or aircrew should be able to access these weather data without expending a great amount of additional effort since workloads are already quite heavy. Additionally, the transmission mode should provide adequate spatial coverage to allow uplink of weather data at any flight altitude and especially during final approach and departure. Coverage on the ground at the terminal would be very useful for updated pilot weather briefings after departure delays. Finally, the transmission of weather data products should be a service provided by the FAA as part of the Aviation Weather System. In this way airborne equipment requirements can be standardized and transmission can be accomplished using existing aeronautical radio frequency channels without competition for transmission rights from commercial interests. As a result, quality weather data products will be available to all airspace users throughout the United States. The transmission requirements identified above are summarized as follows:

1. Near-real time transmission with spectrum conservation
2. Ease of pilot access to weather data
3. Adequate spatial coverage
4. Weather uplink service provided by FAA

An ideal weather uplink system implementation would meet all of the described requirements with a minimal additional investment on the part of the aircraft operator and with minimal equipment, facilities, and maintenance cost to the FAA.

### Mode S Data Link

The Mode Select (Mode S) Beacon System is the planned replacement for the current Air Traffic Control Radar Beacon System (ATCRBS) [10],[11]. The Mode S system has evolved from earlier development work on the Discrete Address Beacon System (DABS). The system is capable of providing radar surveillance with selective interrogation of aircraft, and also of ground-to-air and air-to-ground data exchange. The current Aviation Weather System Plan relies upon this data exchange capability for the uplink of ground-based weather data products [12]. For the reasons described in the following discussion, this system is not capable of providing adequate weather data uplink services to all users of the National Airspace.

The Mode S interrogator is capable of transmitting three classes of messages to the aircraft. These are as follows:

1. Surveillance data
2. Standard message
3. Extended-length message (ELM)

These messages consist of a 56-bit or 112-bit data

block. Included in the data block is a 24-bit discrete address overlaid with parity check bits which provides for selective interrogation of aircraft and also for error detection. The messages are transmitted at a 4 Mbit/s data rate using differential phase shift keying (DPSK). Effective utilization of the parity check bits will allow for an overall undetected bit error rate of less than  $10^{-7}$ . The interrogator is capable of servicing 700 users within the service volume, and so the overall data exchange rate is very high.

The standard message and the ELM are capable of providing general purpose data transmission. The standard message provides surveillance data along with a 56-bit data link message. This message type is intended primarily for messages not requiring large numbers of consecutive bits, and replaces the surveillance message while still providing the surveillance data. The ELM does not contain the surveillance data, and thus cannot substitute for the surveillance message. It is designed to accommodate transfer of large amounts of data, and consists of up to 16 112-bit data blocks of which 80-bits are available for the message. This results in one message block of up to 1280 bits being transmitted per ELM. Because graphic weather data products will consist of relatively large amounts of data, the ELM is the most efficient message format for the uplink of this information.

The ELM data rate available to the individual user is limited by the ability of the interrogator to service all of the users within the service volume. For terminal interrogators, the antenna scan time is approximately 4 seconds. Allowing one 16-segment ELM for an individual user in any one antenna scan would limit the individual user to 1280 bits in the 4 second scan time. The Minimum Operational Performance Standards (MOPS) for the Mode S airborne equipment require the aircraft transponder data link interface to be capable of handling this same amount of data in the same 4 second period of time [13]. Both performance criteria result in an overall effective ELM data rate of 320 bits/s for the individual user. This number is considerably less than the overall system data handling capability because the individual user is being communicated with selectively.

The Mode S selective communication capability is very important for the transfer of data used for air traffic control and would be useful for the transmission of user-specific weather data while en-route. It is not required, however, for the transmission of weather data products that affect all airspace users in a particular terminal area. In fact, the data rate limitation of a fully loaded Mode S interrogator in the terminal area could slow the transmission time of graphic weather data products at a time when access to current weather data is extremely important.

One other very important Mode S data link limitation for the uplink of weather data is the system spatial coverage. The National Airspace System Plan calls for the first 137 Mode S systems to provide coverage down to 12500 feet above mean sea level (msl) and to the ground at high density terminals. These systems are to be in place in the early 1990's. The second contract for an

additional 60 systems would then provide coverage down to 6000 feet msl by 1993 [14]. As a result, any airspace user at altitudes of less than 12500 feet msl would not have weather uplink capability unless in the vicinity of a high density terminal equipped with Mode S surveillance. After 1993, this coverage would be lowered to 6000 feet msl, but would still not provide for approaches and departures from any terminal not equipped with Mode S surveillance. This is not a significant problem for the air carriers, but leaves general aviation aircraft without weather uplink capability for approaches and departures from the terminals most often used by these aircraft.

For these reasons, the Mode S data link alone cannot meet the weather data uplink requirements for all airspace users. Although the Mode S data link capability is important for the transmission of air traffic control data and en route weather data, supplemental systems will be necessary at lower density terminals and would greatly enhance the individual user data rate capability at higher density terminals.

#### VHF Voice/Data Transmission

The continuous broadcast of weather data by VHF data uplink at the terminal area would meet the data uplink requirements and could be accomplished simultaneously with existing voice communications at these locations. The resulting system would not require any additional spectrum, would support a high data rate regardless of number of users, and would provide line-of-sight (LOS) coverage down to ground level. Additionally, the system could be implemented with only modifications to existing ground-based and airborne VHF communications equipment.

Voice and digital data can be transmitted simultaneously through the use of two independent modulations of the same carrier. Continuous wave radio communication is accomplished through the modulation of the amplitude, phase, or frequency of a continuous wave radio frequency carrier. The current VHF aeronautical radio frequency channels used for communication between the ground and the aircraft utilize amplitude modulation (AM) for the transmission of voice. In an amplitude modulated continuous wave, the phase and frequency carry no information. If phase modulation (PM) of this same carrier is accomplished by a digital data stream, then both voice and data can be transmitted simultaneously on the same carrier.

An amplitude modulated carrier can be expressed as:

$$A_c(1 + k_v m(t)) \cos(2\pi f_c t) \quad (1)$$

where  $A_c$  is an arbitrary constant,  $k_v$  is the amplitude sensitivity of the modulator,  $m(t)$  is the modulating waveform, and  $f_c$  is the carrier frequency. Similarly, a phase modulated carrier can be expressed as:

$$A_c \cos(2\pi f_c t + \theta(t)) \quad (2)$$

where  $\theta(t)$  is the phase modulation resulting from the modulating waveform. Combining amplitude and phase modulations yields the hybrid modulation waveform:

$$A_c(1 + k_v m(t)) \cos(2\pi f_c t + \theta(t)) \quad (3)$$

By letting  $m(t)$  be the voice modulation, and  $\theta(t)$  be the phase modulation resulting from a digital data stream of weather information, simultaneous communication of these data can be accomplished.

The hybrid modulated carrier can be generated and received as shown in figure 2. The described modulation technique works perfectly provided that the signal is not subject to non-linear processes such as amplitude or bandwidth limiting. Under these ideal conditions, the AM envelope detector only detects the amplitude modulated voice information. Similarly, an ideal phase detector responds only to zero crossings and is not sensitive to amplitude modulation. Thus only the phase modulated data information is detected by the phase detector. Of course, the phase information is only retrievable if the AM modulation index ( $\mu$ ) of the process is limited to values of less than 1:

$$|\mu| = |k_v m(t)| < 1, \quad \text{for all } t \quad (4)$$

It is equally important to maintain limits on  $\mu$  in existing AM systems in order to prevent over-modulation while still providing adequate sideband power levels for efficient information transmission. Specifications for ground-based aeronautical VHF transmitters require  $\mu$  to be greater than 0.7 but not to exceed 1.0 [15].

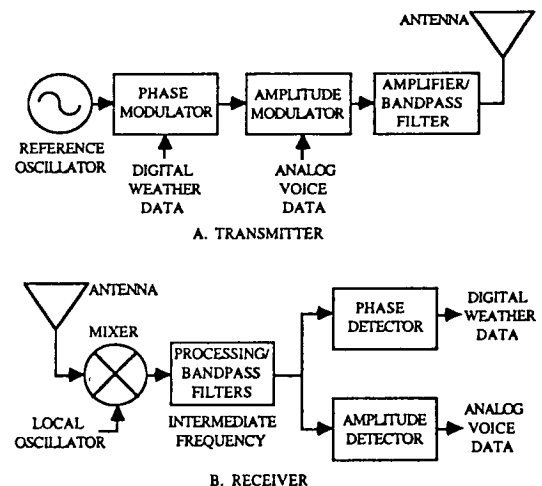


FIGURE 2  
TRANSMITTER (A) AND RECEIVER (B) FOR SIMULTANEOUS  
TRANSMISSION OF VOICE AND DATA

#### Limitations

Unfortunately, an actual radio communication system cannot achieve ideal linear conditions. Amplitude limiting occurs in modern Class C output amplifiers, and would be necessary in the receiver in order to limit the dynamic range of signals presented to the phase detector. Furthermore, filtering performs bandwidth limiting at the transmitter power amplifier output for harmonic attenuation and frequency spectrum control, and in the receiver for selectivity.

These limitations affect the performance of both the voice and data transmission. Voice transmission performance is degraded by amplitude fluctuations caused when bandlimiting removes high frequency energy from the carrier. This high frequency energy is created by the phase modulation of the carrier. Data transmission performance is affected by both bandwidth and amplitude limiting. Amplitude limiting results in a lower effective signal level present at the phase detector, and also creates an interphasor cross-talk mechanism for the digital data. Additionally, bandwidth limiting creates intersymbol interference for the digital data.

### Spectrally Efficient Phase Modulations

Before analyzing the effects of bandwidth and amplitude limiting on system performance, it is necessary to consider the specific type of phase modulation utilized. An overview of two spectrally efficient phase modulation techniques is presented here [16],[17].

Quadrature phase shift keying (QPSK) and minimum shift keying (MSK) have both received increasing attention in recent years due to the common characteristic of transmitting maximum amounts of information while occupying relatively small amounts of frequency spectrum. Both modulation techniques accomplish this by utilizing one of four possible phase states for the representation of data. Using this technique, each phase state corresponds to one symbol composed of two data bits in the modulating data stream.

### Quadrature Phase Shift Keying (QPSK)

The QPSK signal waveform can be expressed as:

$$g(t) = A_g \cos[2\pi f_c t + \frac{1}{2}(2i - 1)\pi] \quad (5)$$

where  $A_g$  is an arbitrary constant,  $i = 1, 2, 3$ , or 4 depending on the symbol transmitted by the data stream during the symbol period  $T$ , and  $f_c$  is the carrier frequency chosen to be an integer multiple of  $1/T$ . This signal is more easily analyzed in the quadrature form:

$$g(t) = g_i(t) \cos(2\pi f_c t) - g_q(t) \sin(2\pi f_c t) \quad (6)$$

where  $g_i(t)$  is referred to as the in-phase component, and  $g_q(t)$  is referred to as the quadrature component. Expressing 5 in this form:

$$g(t) = A_g \cos[\frac{1}{2}(2i - 1)\pi] \cos(2\pi f_c t) - A_g \sin[\frac{1}{2}(2i - 1)\pi] \sin(2\pi f_c t) \quad (7)$$

where  $g_i(t) = A_g \cos[\frac{1}{2}(2i - 1)\pi]$ , and similarly  $g_q(t) = A_g \sin[\frac{1}{2}(2i - 1)\pi]$ . Let  $g_i(t)$  and  $g_q(t)$  be modulated by the odd and even numbered data stream input bits respectively. Note that each quadrature component takes on values of  $\pm A_g/\sqrt{2}$  depending upon the data streams.

Since the two quadrature carrier components are coherently orthogonal signals, the two binary data streams modulating the two signals can be demodulated independently. The two QPSK quadrature carrier components  $g_i(t)$  and  $g_q(t)$  along with their sum  $g(t)$  are shown in figure 3 for the input binary data sequence 01101000.

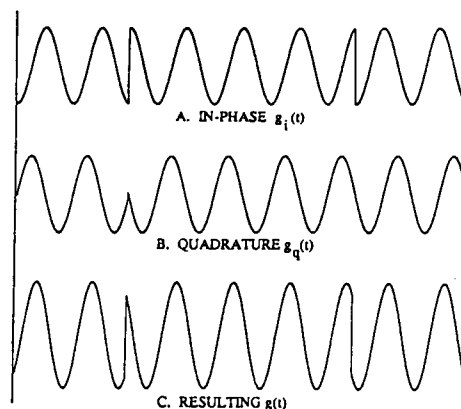


FIGURE 3  
QPSK WAVEFORMS

### Minimum Shift Keying (MSK)

Now consider a special case of QPSK where:

$$g(t) = A_g \cos[\theta(t)] \cos(2\pi f_c t) - A_g \sin[\theta(t)] \sin(2\pi f_c t) \quad (8)$$

For a given bit rate  $T_b = T/2$ ,  $f_c$  is the carrier frequency which is chosen to be an integer multiple of  $1/4T_b$ .  $\theta(t)$  is defined as follows:

$$\theta(t) = \theta(0) \pm [\pi/(2T_b)]t, \quad 0 \leq t \leq T_b \quad (9)$$

where the + corresponds to the symbol 1, the - corresponds to the symbol 0, and  $\theta(0)$  is 0 or  $\pi$  depending upon the past history of the modulating signal. In this case  $g_i(t) = \cos[\theta(t)]$ , and  $g_q(t) = \sin[\theta(t)]$ . Let  $g_i(t)$  and  $g_q(t)$  be modulated by the odd and even numbered input data stream bits as before, but introduce an offset of  $T_b$  between these two data streams. Note that each quadrature component takes on maximum values of  $\pm A_g/\sqrt{2}$  as before. In this case, however, the amplitudes of each quadrature component are sinusoidally weighted, and the two quadrature components never change phase at the same instant of time.

As for QPSK, the two MSK quadrature carrier components can be demodulated independently. For MSK, the two quadrature carrier components  $g_i(t)$  and  $g_q(t)$  along with their sum  $g(t)$  are shown in figure 4 for the input binary data sequence 01101000.

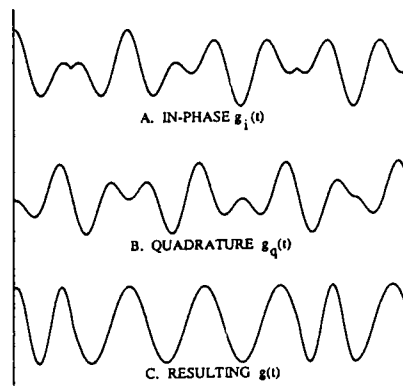


FIGURE 4  
MSK WAVEFORMS

The power spectral density of any bandpass signal  $g(t)$ , given by  $S(f)$  is, except for a scaling factor, a frequency shifted version of the baseband power spectral density  $S_b(f)$ . Therefore, the power spectral density of  $g(t)$  is given by the power spectral density of  $g_i(t) + g_q(t)$ . Because these two components are independent, the total power spectral density is given by the sum of the power spectral densities of  $g_i(t)$  and  $g_q(t)$ . For a data sequence of equally probable ones and zeroes, the baseband power spectral density of  $g(t)$  in the case of QPSK is thus:

$$S_b(f) = 4E_b \left[ \frac{\sin^2(2\pi T_b f)}{2\pi T_b f} \right]^2 \quad (10)$$

Similarly, the baseband power spectral density of  $g(t)$  in the case of MSK is:

$$S_b(f) = 32E_b/\pi^2 \left[ \frac{\cos(2\pi T_b f)}{16T_b^2 f^2 - 1} \right]^2 \quad (11)$$

Equations 10 and 11 are normalized with respect to  $4E_b$  and plotted as a function of  $T_b f$  in figure 5.

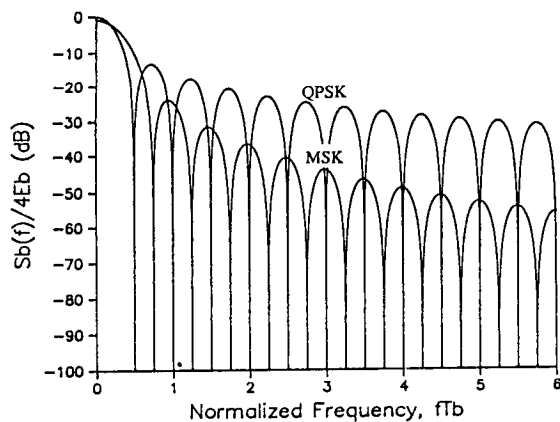


FIGURE 5  
BASEBAND POWER SPECTRAL DENSITY FOR  
QPSK AND MSK MODULATIONS

Comparing the power spectral densities of MSK and QPSK in figure 5, it can be seen that the MSK waveform contains much less high frequency energy than the QPSK waveform. This can be explained by comparing the two waveforms in figures 3 and 4. Note that the instantaneous phase of the QPSK waveform is subject to instantaneous changes, while the instantaneous phase of the MSK waveform is continuous with time. It is the instantaneous phase changes which cause the QPSK waveform to contain more energy at the higher frequencies than the MSK waveform.

Since the removal of this high frequency energy by bandlimiting produces unwanted carrier amplitude fluctuations, it is apparent that by choosing the modulation which produces less high frequency energy, this effect can be minimized. Therefore, to minimize the deleterious effects caused to the voice modulation by the data modulation, MSK is the modulation technique of choice.

In the case of a communication channel with additive white Gaussian noise, the bit error rate of a QPSK or MSK signal can be written as: [18]

$$P(\text{error}) = 2Q[(2E_b/N_0)^{1/2}] - Q^2[(2E_b/N_0)^{1/2}] \quad (12)$$

where  $E_b = (A_s^2 T_b)/2$  is the signal energy per bit,  $N_0$  is the noise spectral density, and  $Q$  is the  $Q$  function defined as:

$$Q(x) = (2\pi)^{-1/2} \int_x^\infty \exp(-t^2/2) dt \quad (13)$$

Equation 12 is plotted as a function of  $E_b/N_0$  in figure 6.

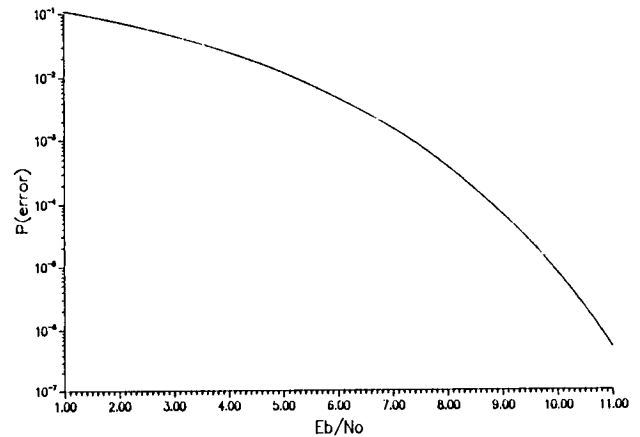


FIGURE 6  
BIT ERROR PROBABILITY FOR QPSK AND MSK  
MODULATIONS

### Analysis

A computer simulation of a combined amplitude and phase modulation communication system has been performed, and the results are available in the literature [19],[20]. The computer simulation was performed using discrete numerical techniques and sampling of the signals. Processing was performed on the equivalent baseband system. The signal was processed in blocks of 2048 samples, and was sampled at 19200 Hertz (Hz). Filtering was performed in the frequency domain, and non-linear operations such as modulation and demodulation were performed in the time domain. A Fast Fourier Transform (FFT) algorithm was used for the transformation between frequency and time domains.

The signal and system parameters were chosen to simulate transmission by hybrid modulation of voice and data on a VHF communication channel. Bandpass filtering was performed at the output of the transmitter and at the input of the receiver. The filter characteristics were as follows:

Transmitter filter - 4th order Butterworth  
3 dB bandwidth of  $\pm 7.5$  kHz

Receiver filter - 8th order Butterworth  
3 dB bandwidth of  $\pm 5.0$  kHz

The modulated signals of interest here were phase modulated at various data rates using MSK. The same signals were then amplitude modulated using a 4 second sample of an actual voice, and by a simulated voice signal consisting of the sum of

five tones as shown:

$$m(t) = \sum_{i=1}^5 a_i \cos(2\pi f_i t) \quad (14)$$

where  $a_i$  and  $f_i$  were chosen as shown in table 2. This signal and its corresponding power spectral density are shown in figures 7 and 8.

Amplitudes		Frequencies (Hz)	
$a_1$	2/9	$f_1$	468.75
$a_2$	1/3	$f_2$	937.50
$a_3$	2/9	$f_3$	1406.25
$a_4$	1/9	$f_4$	1875.00
$a_5$	1/9	$f_5$	2343.75

TABLE 2  
VALUES OF  $a_i$  AND  $f_i$  FOR SIMULATED  
VOICE SIGNAL IN EQUATION 14

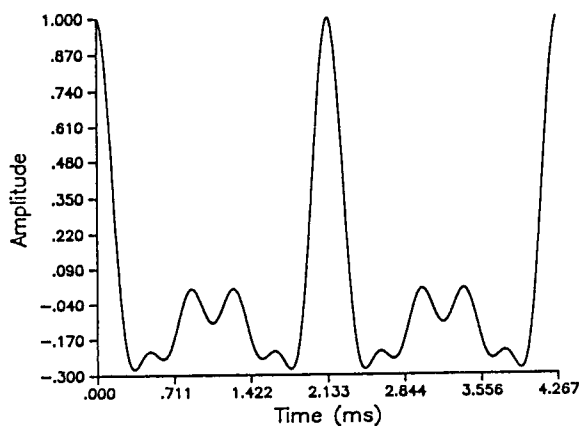


FIGURE 7  
SIMULATED VOICE SIGNAL  $m(t)$

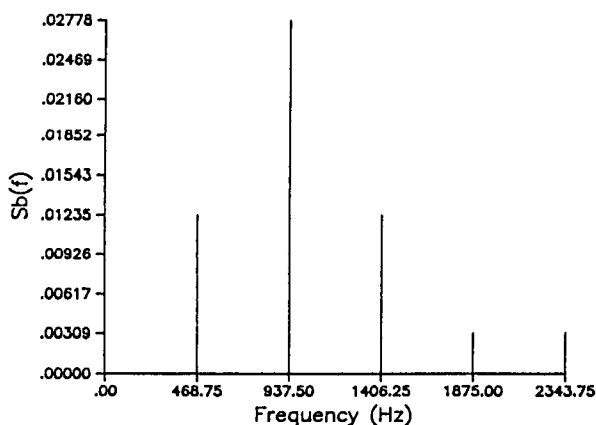


FIGURE 8  
POWER SPECTRAL DENSITY OF SIMULATED VOICE  
SIGNAL  $m(t)$  (SAME FOR NEGATIVE FREQUENCIES)

The analysis resulted in the determination of both signal-to-noise ratio (SNR) of the detected voice signal and the bit error rate for the data signal. The voice channel is assumed noiseless such that the noise in the channel is due entirely to the effects of the data modulation. For the data signal, additive white Gaussian noise is

introduced in the channel, and the overall bit error rate including the effects of the amplitude modulation is experimentally determined.

This analysis does not take into account amplitude limiting of the phase modulated portion of the carrier. Such limiting would occur in some Class C transmitter power amplifiers, and would be necessary to reduce the dynamic range of the signal presented to the phase detector in the receiver. Instead, the effects of phase detecting the amplitude modulated version of the phase modulated carrier are considered.

### Analysis Results

The voice signal SNR results for the simulated voice with  $\mu$  set to 0.8 are shown in figure 9 as a function of data rate. The same data for the actual voice signal with  $\mu$  set to 0.9 are shown figure 10. The results for the data modulation show an overall degradation of 2-4 dB in  $E_b/N_0$  as compared to an ideal infinite bandwidth and constant amplitude data modulation.

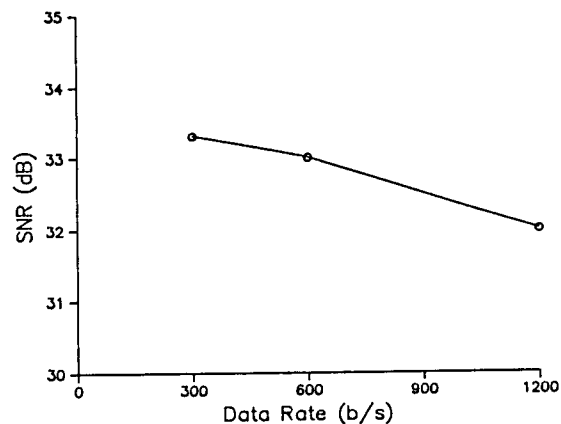


FIGURE 9  
SNR RESULTS FOR HYBRID MODULATION  
USING SIMULATED VOICE SIGNAL ( $u = 0.8$ )

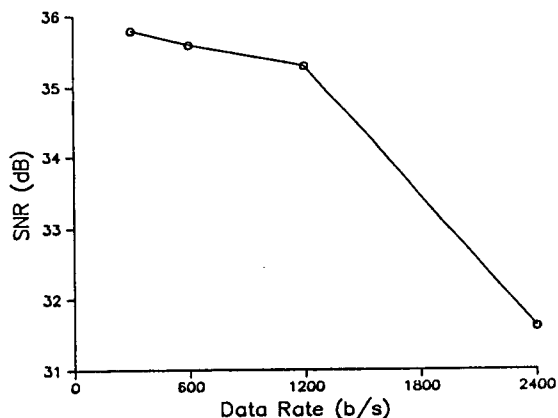


FIGURE 10  
SNR RESULTS FOR HYBRID MODULATION  
USING ACTUAL VOICE SIGNAL ( $u = 0.9$ )

### Further Analysis

If both the amplitude and bandwidth limiting effects on the data modulation are considered, further analysis can be applied to predict the

overall reduction in bit error rate. Such analysis has been performed for various cases of filter bandwidths assuming an ideal limiter characteristic [21]. The results show that despite severe distortion of data symbol shapes and the introduction of interphasor crosstalk,  $E_b/N_0$  is degraded by a maximum of 0.5 dB.

With amplitude limiting, an additional degradation of  $E_b/N_0$  can be expected since the amplitude of the data modulated carrier would be limited to its lowest value. For a carrier with constant amplitude  $A_c$ , the energy per bit is given by:

$$E_b = A_c^2 T_b / 2 \quad (15)$$

However, if the carrier amplitude is modulated by a voice signal with some known value of  $\mu$ , equations 3 and 4 show that the minimum value of the overall bit energy would be given by:

$$E_{bmin} = A_c^2 (1 - \mu)^2 T_b / 2 \quad (16)$$

Since the limiter would provide this level to the phase detector at all times, a reduction in  $E_b/N_0$ , in decibels, would be given by:

$$P_{loss} = 10 \log(E_{bmin}/E_b) = 20 \log(1 - \mu) \quad (17)$$

For  $\mu$  of 0.8, this would represent a loss of approximately 14 dB. Adding this amount to the worst-case degradation predicted due to the presence of amplitude modulation and limiting of both amplitude and bandwidth gives a total loss in  $E_b/N_0$  of:

$$14 + 4.0 + 0.5 = 18.5 \text{ dB}$$

relative to a constant amplitude carrier. This loss would result in a decreased distance of communication for acceptable system performance.

It is important to consider the spectrum requirements of the overall hybrid modulated waveform. Because the amplitude and phase modulations are statistically independent, the overall power spectral density at baseband can be found by the convolution of the power spectral densities of the voice modulation process and the phase modulation process. The baseband power spectral density of the MSK modulated carrier is given by equation 11 and shown in figure 5. If the simulated voice signal given by equation 14 is chosen to represent the voice information, then the baseband power spectral density of the voice modulated carrier is as shown in figure 8. The convolution of the two signals at the carrier frequency yields the power spectral density shown in figure 11. Also shown on the plot are the Federal Communications Commission (FCC) spectrum limits for the VHF aeronautical communication band [22]. The hybrid modulated waveform conforms to this requirement.

#### Data Redundancy Reduction

The transmission time required for the uplink of a complete weather data graphical image at a fixed data rate can be substantially reduced using image redundancy reduction techniques. Many methods exist for the accomplishment of this redundancy reduction.

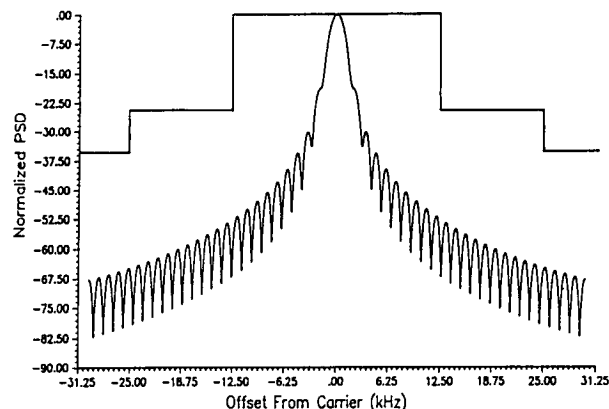


FIGURE 11  
NORMALIZED POWER SPECTRAL DENSITY OF HYBRID  
MODULATED WAVEFORM USING SIMULATED VOICE SIGNAL  
(SHOWN WITH VHF VOICE CHANNEL SPECTRUM LIMITS)

The method chosen for data redundancy reduction of graphical weather images will depend upon the characteristics of the image. For the uplink of weather radar reflectivity patterns, however, run-length encoding provides very high compression ratios and is implemented more easily than many types of image compression. Run length encoding codes runs of repeated pixel values with a starting location and a count of the number of repeated pixels. Because NWS weather radar reflectivity patterns contain only six intensity levels and these levels are usually grouped together to form weather cells, repeated pixel runs occur frequently. Thus run length encoding very efficiently compresses the amount of data necessary for the description of these images. Further compression can be achieved by not transmitting weather map overlays. Since this information is constant, and digital data storage costs are decreasing, the weather map information can be stored in the cockpit and overlaid on the current weather data.

Radar reflectivity patterns which include weather activity over large areas of the radar coverage have been compressed to 2000 bytes using run length coding and suppression of map detail [23]. Transmitting this data at 2400 bits/s would result in a total transmission time of less than 7 seconds.

#### Conclusions

Some requirements for the uplink of weather data to the aircraft have been delineated, and it has been shown that the Mode S Beacon System data link capability will not be sufficient to provide weather data uplink capability to all airspace users.

A system capable of meeting weather data uplink requirements has been described. The system uses hybrid modulation techniques for the transmission of both voice and data on an existing aeronautical VHF voice communication channel. The system is particularly well suited for the provision of weather data products to the airspace user in the terminal area where Mode S capabilities have been shown to be inadequate.



A computer analysis shows that the hybrid modulation technique would result in an  $E_b/N_0$  loss of up to 18.5 dB as compared to a phase modulated constant amplitude carrier. This loss in  $E_b/N_0$  results in an increased bit error probability as shown in figure 6. By limiting communication distance, however, acceptable performance can be maintained. The voice signal is shown to provide an SNR of approximately 30 dB when combined with the MSK phase modulation. The MOPS for VHF airborne communication equipment establishes 25 dB as the required minimum SNR when the received signal strength is well above the receiver noise floor [24]. Based on this requirement, the SNR obtained using the hybrid modulation technique would be adequate. The hybrid modulation technique would thus provide acceptable performance if the AM modulation factor is limited to the range of 0.7 to 0.9, and MSK is used for data transmission at a data rate of 2400 bits/s.

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