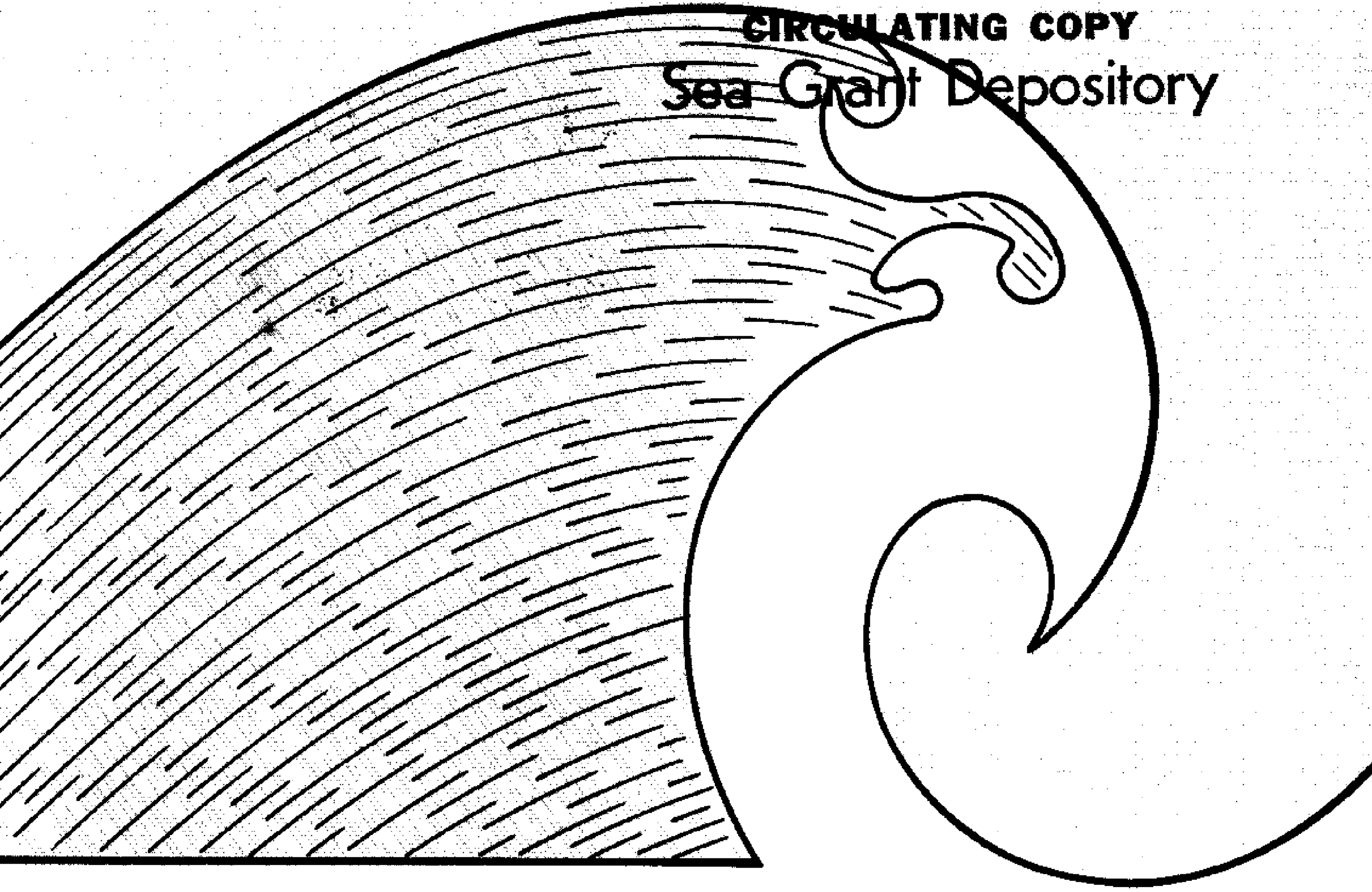

DEPARTMENT OF OCEAN ENGINEERING

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Memorandum Number 2M

DATA TRANSMISSION SYSTEMS

BY
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8 APRIL 1970

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B. Lincoln Smith, Jr.

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University of Rhode Island

8 April 1970

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DATA TRANSMISSION SYSTEMS

INTRODUCTION

When discussing any data transmission technique, we must remember that the Telemetering link is a system in its own right.

Thus, there are many tradeoffs, all which have a direct bearing on the final system configuration. Each tradeoff must be evaluated within the context of the particular system requirement. Some parameters are rigidly fixed such as the IRIG (Inter Range Instrumentation Group). Frequency allocations, while others are completely variable, such as modulation mode.

To fully evaluate these tradeoffs we must know and understand what is readily available when it comes to:

1. Types of Systems
2. Variable Parameters
3. Fixed Parameters

Therefore, it is the intention of this discussion to present enough information so that the reader will:

1. Become exposed to various systems,
2. Be able to identify the important parameters, and
3. Understand a typical systems design,

Much of the actual design will be beyond the scope of this discussion, but the handout will present sufficient references to delve in depth into most of the topics discussed.

A nine part approach will be used to fully describe the transmission system. It will consist of the following categories:

1. Various Telemetering Types
2. Basic System Description

3. Items Never Usually Mentioned, but Necessary
4. Several Typical Systems
    a. Simple (single VCO)
    b. Typical FM/FM
    c. Typical Digital System (PCM)
    d. Cost Considerations
5. IRIG Standards
6. Frequency Allocations
7. Identification of Important Parameters
8. Determination of Important Parameters

    Modulation

    S/N Ratio

    Bandwidth

    Power Requirements

    Error Introduction

    Cost, Size and Compatibility
9. Actual Design (Follow through)

1.0 VARIOUS TELEMETERING TYPES

The discussion of Telemetering types by definition must concern itself with the modes of information transferral. The basic flow diagram (See Figure 1.0) shows that Data Telemetering in general can be divided into two broad categories; analog and pulse. Each is briefly described below.

A. Analog:

Analog means that all the data will be transmitted over a system which transfers continuous information. The information is modulated onto the transmission link as either amplitude or frequency variations to a basic analog carrier.

a) AM: Standard Amplitude Modulation (Ref 1)

Standard amplitude modulation is a technique where the amplitude of some fixed carrier frequency is varied as a function of the input modulation signal

b) FM: Standard Frequency Modulation (Ref 1)

Standard frequency modulation is a technique where the frequency of a carrier is varied (deviated) slightly both above and below some arbitrary center point as a function of the input modulation signal (Ref 2). (i.e., the frequency is varied as a function of the modulation).

c) FM/FM: (Ref 2)

The FM/FM system is exactly what is sound like: two FM systems in series. The modulation signal FM modulates a single carrier frequency (Usually called a sub carrier). This varying frequency is then used to FM modulate a second, higher frequency main carrier. NOTE: Many different sub carriers can be FM modulated, mixed together, and the

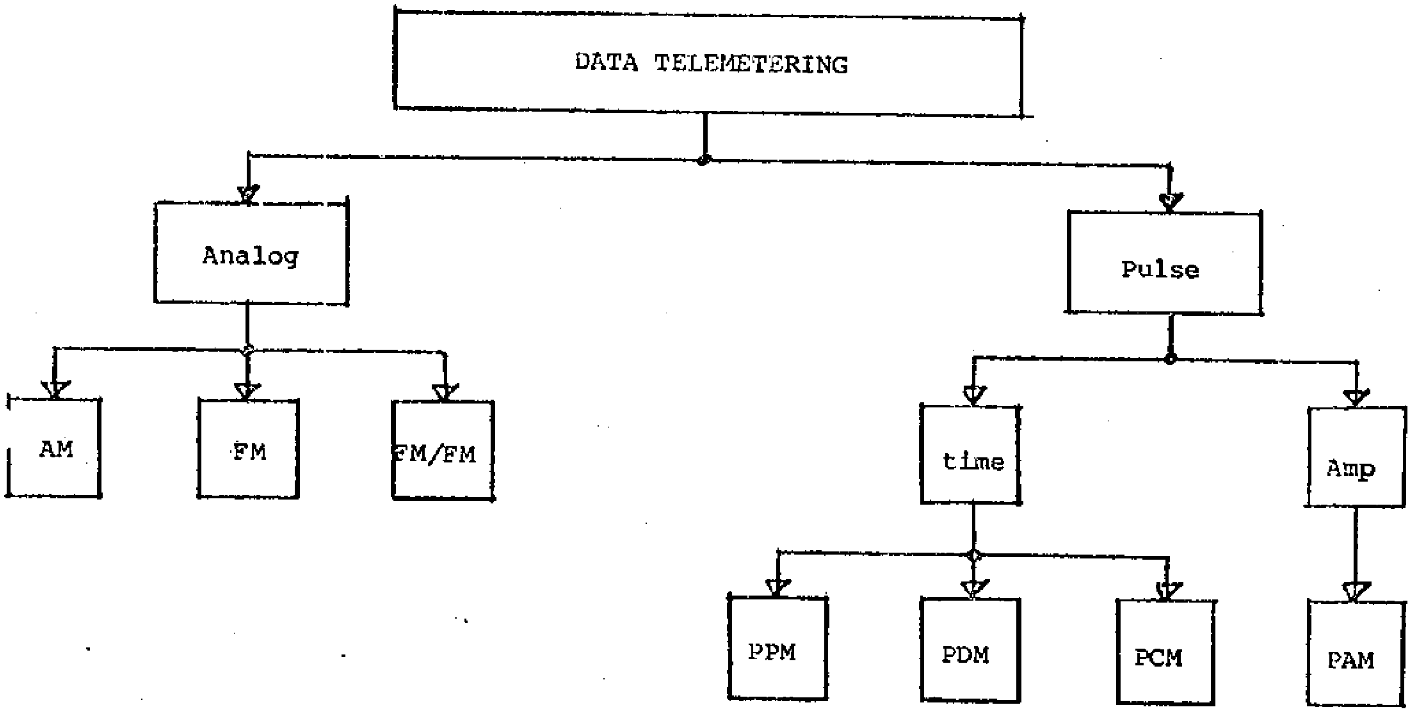

Figure 1.0 Flow Diagram of Telemetering Types

composite signal used to FM modulate the main carrier. The sub carrier oscillator (device that generates the sub carrier frequency) is called a SCO (sub carrier oscillator) and usually consists of a VCO (voltage controlled oscillator). The two terms, VCO and SCO are very often used synonomously and interchangeably, but not necessarily properly.

VCO or Voltage Controlled Oscillator.

Just briefly, a typical VCO consists of a conventional LC oscillation with some voltage sensitive element within the frequency determining loop. Figure 2.0 shows a typical oscillator of this type, where the oscillation frequency is determined by L_1, C_1, C_2, and VRC. The VRC is a varicap. (Ref 3). (eg: A capacitor whose capacitance is a function of the voltage applied across its terminals.) The whole circuit is basically an LC oscillator. When the capacitance of VRC is changed, by varying the voltage impressed across it, the total capacitance in the C_2, VRC, C_1 loop, which is effectively in parallel with L_1, is changed. This forces the frequency of the oscillator to change. Generally speaking, most commercial VCO's require a 0-5 VDC input as a modulation signal. This is applied across the varicap as shown in Figure 2.0 and forces the oscillator to vary its output frequency as a function of the input modulation signal.

Voltage Controlled Crystal Oscillator

The same cricuit as shown in Figure 2.0 can be used by substituting a crystal in place of C_2 (in the feedback loop). The same operation will prevail, except that the center frequency of the VCXO will be crystal controlled. The input modulation will "pull" the frequency slightly above and below the crystal frequency, by means of the varicap, thus making a voltage controlled crystal oscillator.

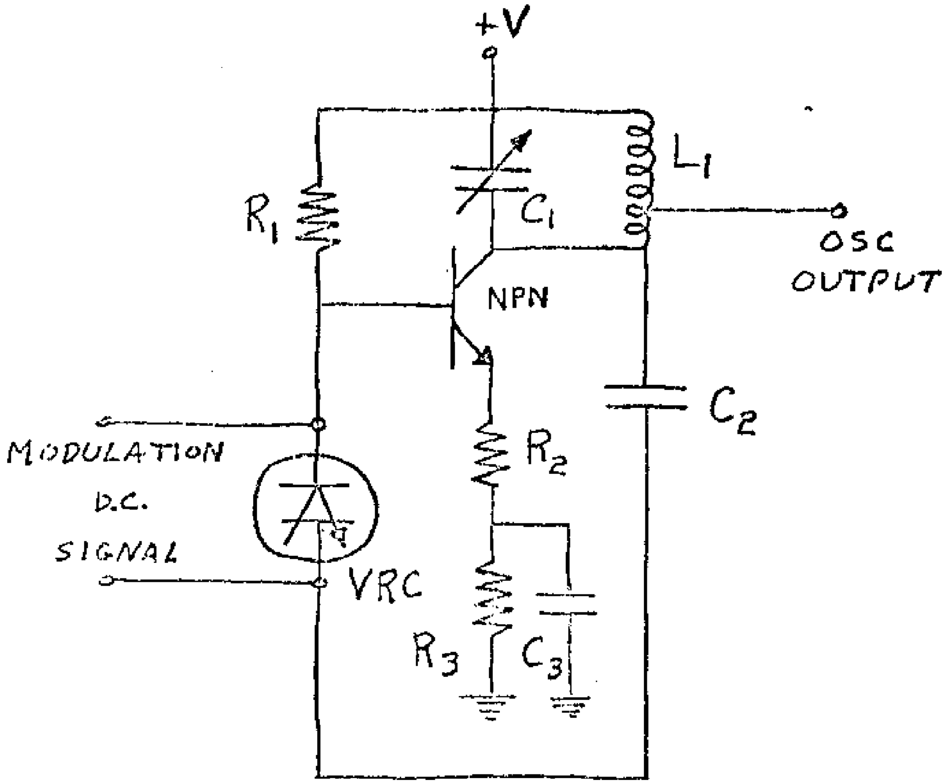

Figure 2.0 Typical VCO Schematic

Conclusion

There are some 29 SCO frequency bands designated by the IRIG standards. These constituted one of the fixed parameters mentioned before. The IRIG standards will be covered in detail in Section 3.0 and FM/FM systems will be discussed again in more detail in Section 4.0.

B. Pulse (Ref 2)

Pulse means that all the data will be transmitted, using a format of only pulse information. The broad category of pulse modulation can be divided into two groups. One group deals with the time aspect of pulses, while the other deals with the amplitude of pulses. (See Figure 1.0). The amplitude group only contains one mode so it will be discussed first, followed by the time pulse modes.

a) PAM: Pulse Amplitude Modulation

Exactly as the name implies, data is conveyed in the amplitude of a discrete pulse. A series of fixed pulses (i.e.: fixed width, PRR, etc) is generated, and the amplitude of these pulses is made to vary as a function of the input modulation signals. In general, one pulse is used for each parameter, and the intelligence is conveyed in the amplitude. The series of pulses is used for a series of parameters.

The remaining three modes are classified as pulse-time because in each case the information is contained somehow upon the time position, duration, or frequency of the pulses.

a) PPM: Pulse Position Modulation

The data is conveyed by the time position of a single pulse. The system generates a series of regular interval marking pulses which are fixed in time. The intelligence is then converted to a time delay, and the data pulse is delayed away from the interval marker pulse a duration or distance which is a function of the magnitude of the measured variable (See Figure 3.0). Figure 3.0 (a) shows a PPM signal where the value of the measured variable was larger, whereas Figure 3.0 (b) shows the same thing for a small value of measured variable. NOTE: In digital applications, the pulse position would be fixed for each level sampled. However, in analog applications, the pulse could vary back, and forth as a function of the modulation.

b) PDM: Pulse Duration Modulation

The PDM technique is much like PPM except that the pulse width is a function of the modulation. Figure 4.0 shows graphically how a small magnitude is represented (a) and a large value (b). The information is conveyed by the width of the transmitted pulse, as the signal is "on" for a duration of time, proportional to the magnitude of the telemetered signal. PDM was the best known and most widely used technique for many years (and still is in many cases) because of its;

i ability to transmit large number of channels over a single transmission link

ii high accuracy (better than 1% overall, made possible by self-calibration features)

iii inherent high S/N due to narrow bandwidths

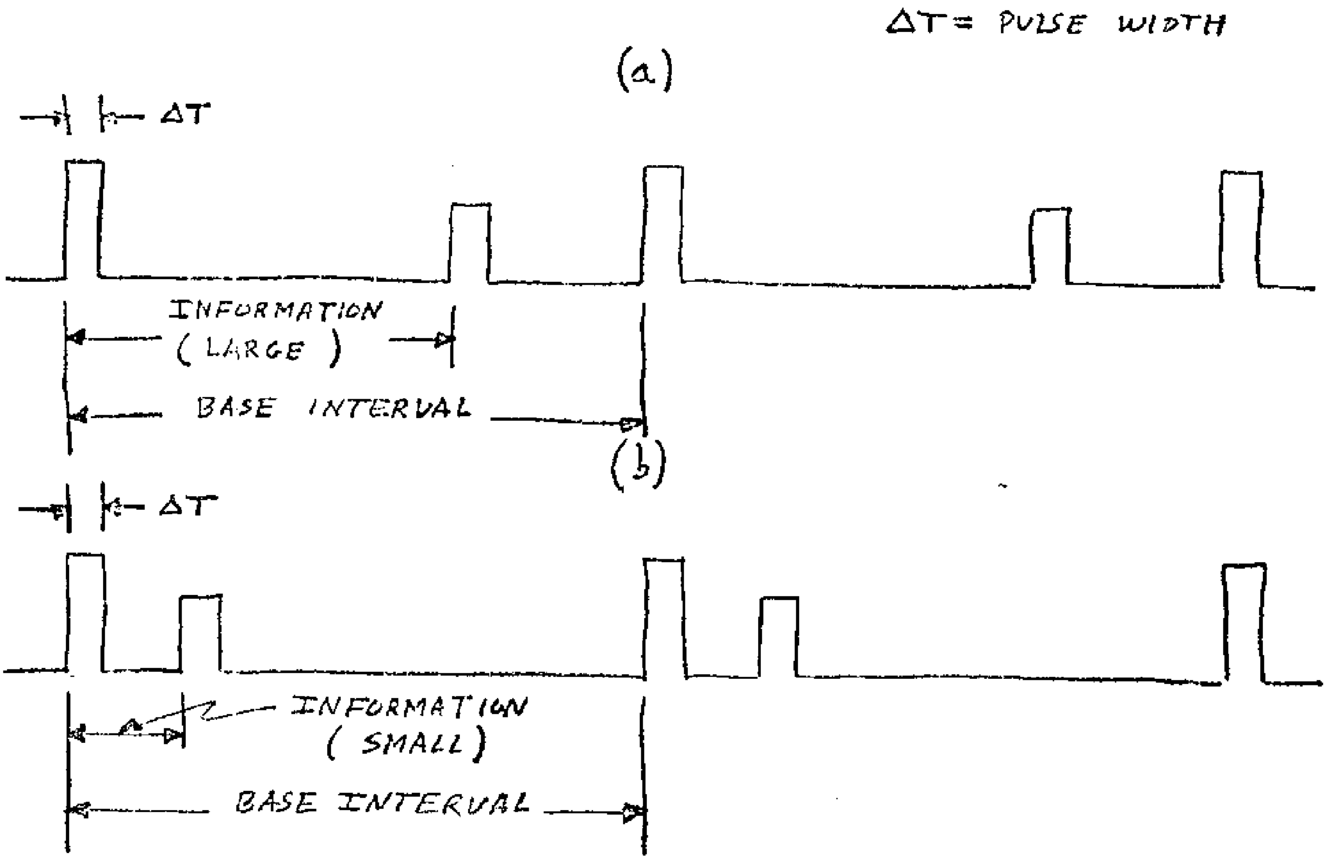

Figure 3.0 Typical PPM Waveforms

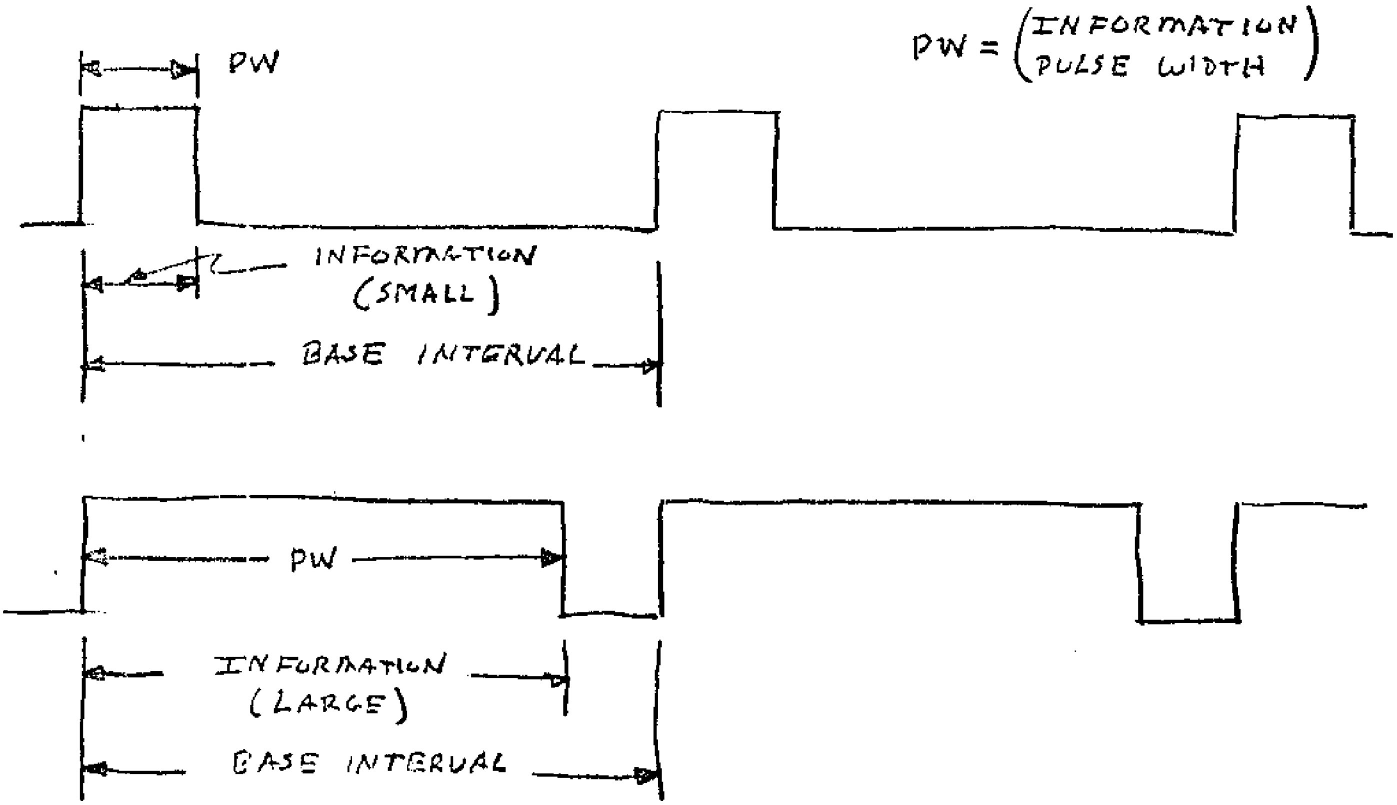

Figure 4.0 Typical PDM Waveforms

c) PCM: Pulse Code Modulation

PCM is exactly what the name implies. The data are first converted into a digital format and transmitted as a series of discrete pulses coded to indicate the magnitude of the variable. This is the first true digital system where Analog to Digital conversion is required. Inherent in this mode are all the things which are basic to the field of signal analysis. These are sampling, holding, quantizing, number of levels, information theory, etc. These are beyond the scope of this discussion but still extremely important and pertinent.

2.0 BASIC SYSTEM DESCRIPTION

The basic telemetering system can be broken down into a series of only four basic building block at both the transmitting and receiving end. Figure 5.0 identifies those blocks. It should be noticed that although the connection between the blocks is schematically shown as a radio link, it could just as readily have been depicted as a hard wire link, or a storage medium (such as a tape recorder) instead of the transmitter and receiver for intermediate storage and playback. (See Figure 5.0). This discussion, however, is concerned primarily with remote data sensing, where the radio link method is assumed the best. Subsequent discussions will address themselves to the radio link assumption.

The system itself, as shown in Figure 5.0 is very simple. The measured parameter is sensed by the block labelled sensor. This could be anything from a simple temperature sensing thermistor probe to an sophisticated in situ dissolved oxygen meter (not yet developed). The output of the chosen sensor may be a variety of things, such as a resistance, a contact closure, a DC voltage, an AC voltage, a string of pulses, etc. Unfortunately, the sensor output will probably not be

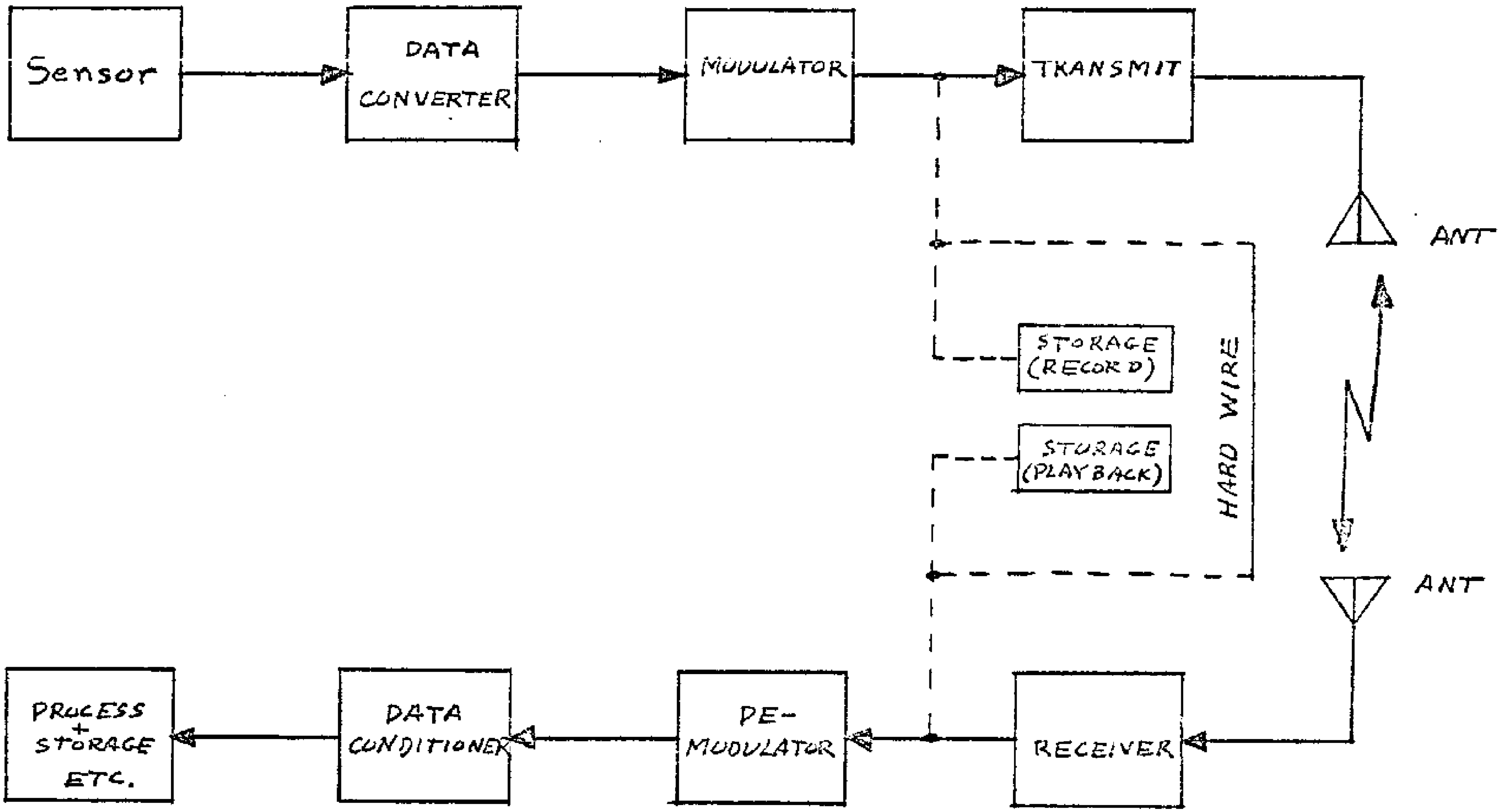

Figure 5.0 Basic System Building Blocks

compatible with the modulator's desired input. Therefore, the signal is passed through a data converter, whose only purpose is to convert the sensor output to a format compatible with the modulator's input. (In the case of an FM/FM system, this would be the 0-5 VDC dictated by the VCO input). The data converter feeds the modulator, which in turn modulates the main carrier, and applies a data filled carrier to the antenna for radiation.

The captured signal is applied to the receiver input and on into the system demodulator, where the intelligent data is separated from the carrier. The "data" is then applied to a data conditioner whose primary function it is to act as an interface for the processing and storage equipments.

Many items have been omitted for the sake of simplicity, and will be shown in more detail in Section 4.0. The building blocks in Figure 5.0 should be looked at carefully, because when studying any system, if it can be reduced to those simple blocks, then understanding its operation is elementary.

3.0 ITEMS NEVER USUALLY MENTIONED

Experience is a great teacher, but sometimes a very painful teacher. Nowhere else have I seen or do I anticipate seeing the things discussed in this Section. Any system built for remote sensing and data relay to a central station must contain at least some of the items listed below. The basic system can be designed by plugging into the correct equations and arriving at an appropriate circuit or group of circuits to substitute for the blocks of Figure 5.0. This will yield the basic system. Then, in order to avert a sure catastrophy, several system status, calibration, and on-off capability must be added. One prolonged test without them will teach anybody their importance. Described below are some of the more important ones.

a) On-Off Command

One of the most important parameters of any remote system (which cannot be plugged into the house AC power) is power consumption. Also, most monitoring or data sensing systems have an extremely low necessary duty cycle (i.e., time when they must be turned on). Therefore, it is common practice to provide means for turning the major portion of the system off when not in use. This is called an on-off command capability and is shown within the circled section of Figure 8.0. It consists of an encoder, a device which generates the interrogation code. A code is any single audio tone or a combination of up to as many as five simultaneous tones, combined as a composite modulation for the command transmitter. Upon reception, the code is identified by the decoder, and the appropriate functions are initiated.

One of these functions is to turn the entire system on. As can be seen, once the main data transmitter is turned on, the command receiver front-end will be blocked by high power RF from the data transmitter. Thus, no other commands could be received without the incorporation of an expensive antenna diplexer (the discussion of antenna diplexers, transmission line theory, stubs, etc., is beyond the scope of this discussion. The reader is directed towards reference 4). Thus it is common practice to command the system on, and time it off. An excellent choice for a timer is a modified Bulova Acutron watch movement. They are readily available from Bulova for this exact purpose. (the timer is not shown in Figure 8.0). Other methods undoubtably will come to mind, but thus far, the one above is widely used, accepted, and has proven to be satisfactory.

Thus, the on-off command system is an extremely important addition to the basic system. Omission of this capability can cause much grief.

b) In Situ Calibration

All data obtained from a remote monitoring system is as good only as the accuracy of the system measuring and transmitting it. Not all measurements can be calibrated, but the whole transmission system can be. Ideally, an in situ calibration from the sensor on would be preferred (this would be the scientific definition of a calibrated system). However, in situ calibration of most of the system can be made, which allows greater confidence in the validity of the values being obtained.

The calibration can be accomplished by using the command on-off transmitter with a code signifying a command to calibrate. The system would then step through a built-in reference system and calibrate the system from the VCO out to the final readout (See Figure 8.0). In general, the system can be calibrated from just after the measurement sensors, through to the final readout.

c) Housekeeping Sensors

The status of any remote system must be maintained at all times. Each system has its own particular critical parameters which should be watched. In general, there are a few which should probably be watched on all ocean oriented system. They are:

Leak Detector: This sensor keeps track of the moisture content inside the buoy, and if it rises above a present level, it triggers a warble oscillator. (See Figure 6.0). The warble oscillator turn on, overides ALL functions, turns on the main transmitter, and transmits a continuous warbling tone until the system is dead. This is probably the most critical housekeeping sensor for buoy applications.

Battery Status: The status of the battery pack should be monitored at all times. Battery behavior can certainly dictate the whole system's operatioh, and in many cases, predict things prior to their occurrence. The actual monitoring requires one more data channel and sensor and merely becomes an additional parameter which must be measured.

Miscellaneous Sensors

Without belaboring the point, a variety of parameters, important only to the OPERATION of the system, should be monitored. Among these are:

Temperature (Internal)
Internal Pressure
Presence of Particular Gasses
Attitude
Operating Elapse Time
etc.

4.0 SEVERAL TYPICAL SYSTEMS

Three typical systems will be discussed in this section. The simple system is merely a single VCO FM system where all sensors are sampled, and a serial readout is obtained. Next, an FM/FM system is described to show the use of VCO's, introduce a more complex approach, and show a true parallel readout system. Finally, the digital system is discussed primarily because this discussion would be incomplete without it. It should be noted that PCM and any of the pulse techniques are a form of this method.

A. Simple System (Single VCO)

Five typical initial measurement parameters have been chosen. These are current velocity, current direction, single depth temperature, wind velocity and wind direction. Unfortunately the data outputs of each standard instrument available are not compatible to the VCO input specifications. Therefore, their outputs must be converted by a data converter circuit to allow application of the data signal to the VCO. Table 1.0 lists the typical standard instruments, with their output data format. Although it would be ideal to provide a separate VCO for each parameter measured, the simplicity of the system and the limited bandwidth characteristics of the citizens frequency Band (carrier frequency at approximately 27 MHz with a B.W. controlled by FCC regulations), requires that each sensor output be sampled and driven into one common VCO. Figure 6.0 presents a detailed block diagram of the simple system. As can be seen, the output of each parameter sensor is applied to its own data converter module. The complete data converter package contains five discrete data converters; two resistance to DC voltage, one pulse to DC voltage, one contact closure to DC voltage, and one AC voltage to DC voltage. Each data converter produces a 0 to 5 VDC (typical) output which drives the VCO across its linear frequency range. The data converter outputs are placed on the segments of a data commutator (sequency timer) where each voltage is applied in turn to the VCO for a discrete time (6 seconds). A two second dwell time is used between each sampling. The modulation signal presented to the CB transmitter consists of the following information: six seconds of current direction data, two seconds of dwell time, six seconds of current velocity data, two seconds of dwell time, etc. until all five sensors have been sampled. This process is repeated three times, as dictated by the timer and operational timer, with a twenty second blank transmission between data transmissions (See Figure 7.0 for descriptive

TABLE 1.0

INSTRUMENTATION DATA OUTPUT SPECIFICATIONS

Parameter	Instrument	Data Output	Cost	Comments
Current Direction & Velocity	Bendix Marine Advisors Inc. Geomagnetic Savonius Rotor Current Meter Model Q-9	Speed = 8 pulses per rotor revolution- (10.4 pps per knot) Direction = 0 to 5000 ohms resistance	1395.00	Both speed and direction are incorporate in one instrument
Temperature	Bendix Marine Advisors Inc. Temperature Meter Model D-1	Temperature to ± 0.15°C (32.4 ohms/°C resistive	95.00	Thermister probe so that absolute resistance depends upon probe specifications
Wind Direction	Belfort type 1411A	Contact closure (every 22 1/2 degrees)	115.00	These instruments are chosen for their cost, reliability, and either no external power requirements or D.C. operation
Wind Speed	Belfort type 1420B	AC wind drive AC voltage	105.00	

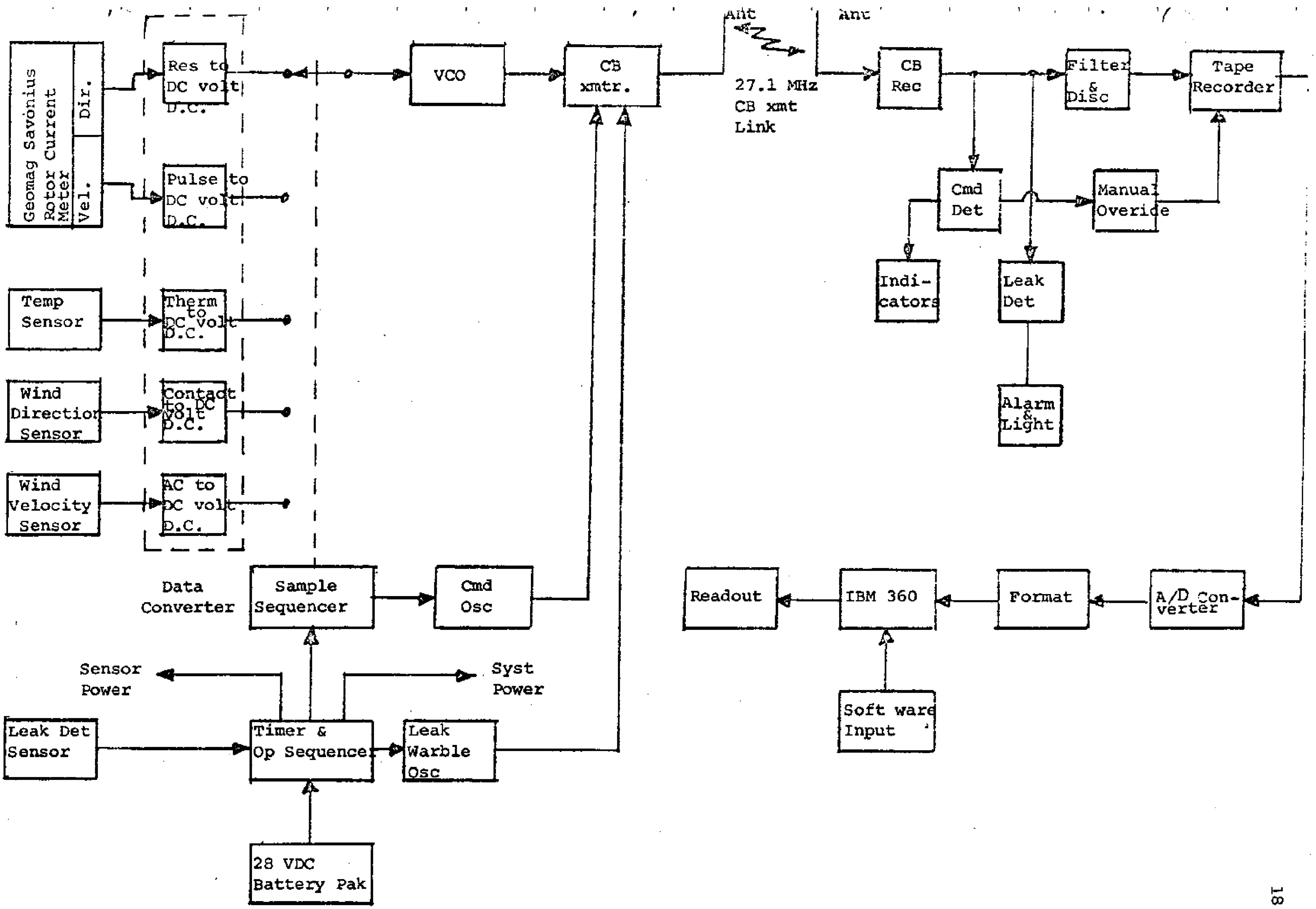

Figure 6.0 Simple System (Detailed Block Diagram)

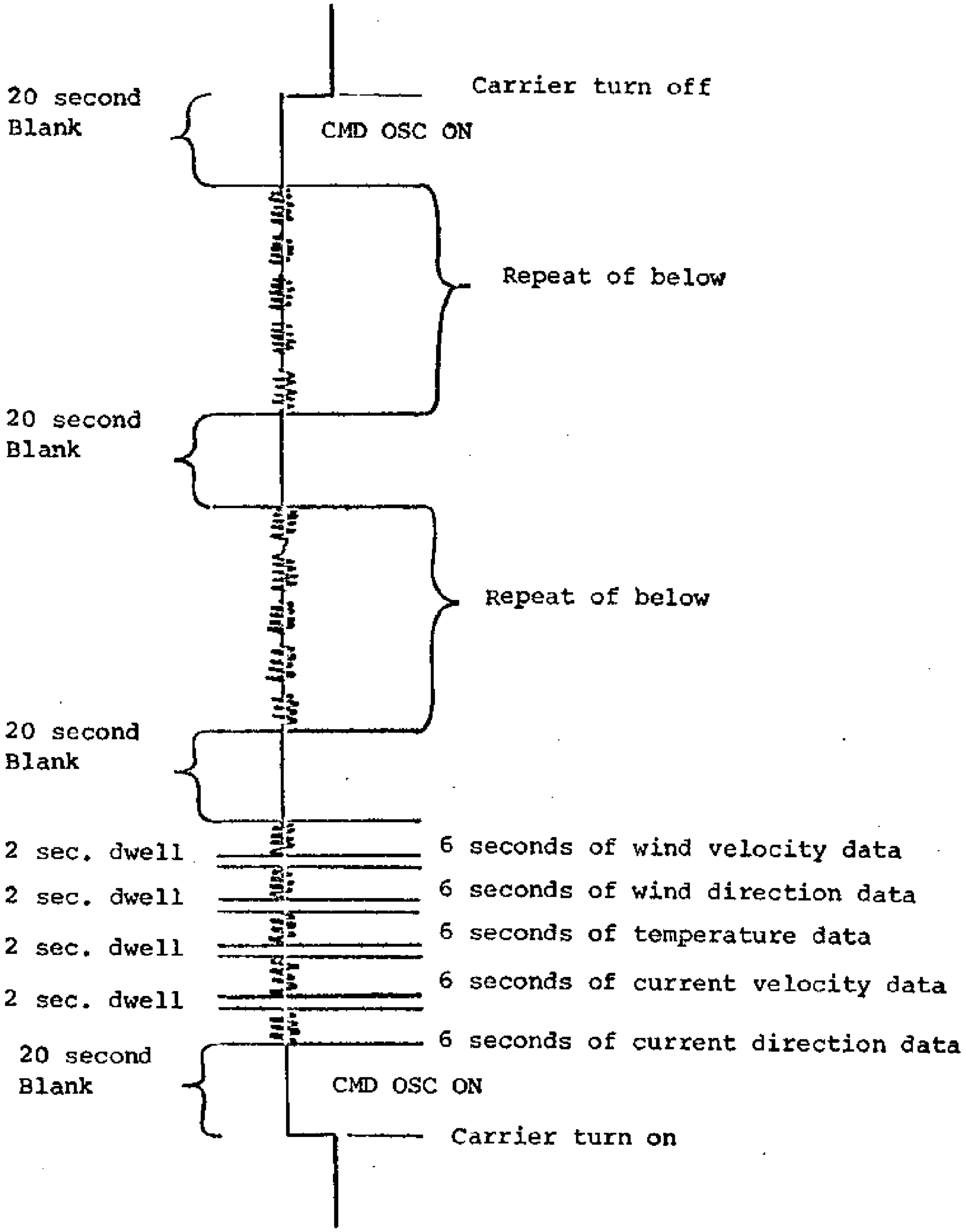

Figure 7.0 Transmission Sequence

example). This gives a total transmission time of 224 seconds, which will cycle every x hours (x is predetermined by the measurement data desired and is some integer multiple of 24/I + T where I is an integer and T is an offset time so that the sampling will process through each 24 hour period).

As has been explained, theCB transmitter receives a modulation signal as shown in Figure 7.0. There are two other modulation inputs. The first is the leak detector oscillator. If a leak occurs in the buoy, the presence of water is sensed, and the timer and operational sequencer is overriden. The leak oscillator comes on, turns on the CB transmitter, which transmits a continuous warbling tone until the batteries wear down or the system sinks. This tone will alert the shore facility attendent of impending troubles due to buoy leakage. The second is an optional command signal. When the buoy system first turns on, the command oscillator transmits for precisely ten seconds. This alerts the shore station and turns on the tape recorder if unattended operation is desired. Also, at the end of the third data transmission, it activates a second time, turning off the tape recorder, and reverting the shore station to its original stand by state.

The CB transmitter loads into a standard CB whip antenna, and transmits the information to the receiving station. On shore, a second standard CB whip receives the energy and applies it to a standard CB receiver. The receiver output is applied to three modules. First, if the command signal is present at the time of initial transmitter turn off, the command detector is activated, and if the manual override is not turned on, the tape recorder automatically starts. If the manual override is turned on, then the tape recorder must be activated by the attendant. In any case, the alarm system activates, indicated by a blinking light and audio tone (applied to a speaker). If the leak detector detects a leak, the shore facility indication shows as a flashing light and warbling tone. If the whole system is operational, the data as shown in Figure 7.0 is recorded for post analysis.

The off-line computer interface equipment could be almost anything, depending upon the desired post analysis. However, in general, the data is taken off the tape recorder, and converted into IBM computer format. This consists of analog to digital conversion, conversion into IBM 360 input format, and application to the computer along with the appropriate software program. The computer will then provide an appropriate data analysis output.

The simple system provides preliminary measurement of five oceanographic parameters. The measurement instruments in general have greater inherent accuracy than can be reproduced at the shore facility due to the errors associated with system data conversion, transmission, detection, and display. The system also provides one housekeeping sensor (leak detection) and an automatic sequencing and monitoring capability.

B. Typical FM/FM System

FM/FM transmission is defined as the composite transmission of several FM signal simultaneously. In general each sensor drives its own VCO, all VCO's are mixed, and the composite signal is frequency modulated onto a single carrier. A typical system can be seen in Figure 8.0. Each sensor output is conditioned in exactly the same manner as in the simple system. The data converter outputs drive a bank of VCO's where each sensor has its own VCO associated with it. The VCO outputs are mixed together and applied as the modulation signal for the FM transmitter. (Note: it is obvious that this system requires a wider bandwidth than the simple system. Because of this, three telemetering bands have been assigned by the FCC. These are:

a. 216-260 mHz (44-500KHz wide channels)
b. 1435-1535 mHz
c. 2200-2300 mHz)

The frequency choice for this system is the 216-260 mHz band. The transmitter feeds a simple eight inch whip antenna (easily incorporated), and radiates omnidirectional power into the air.

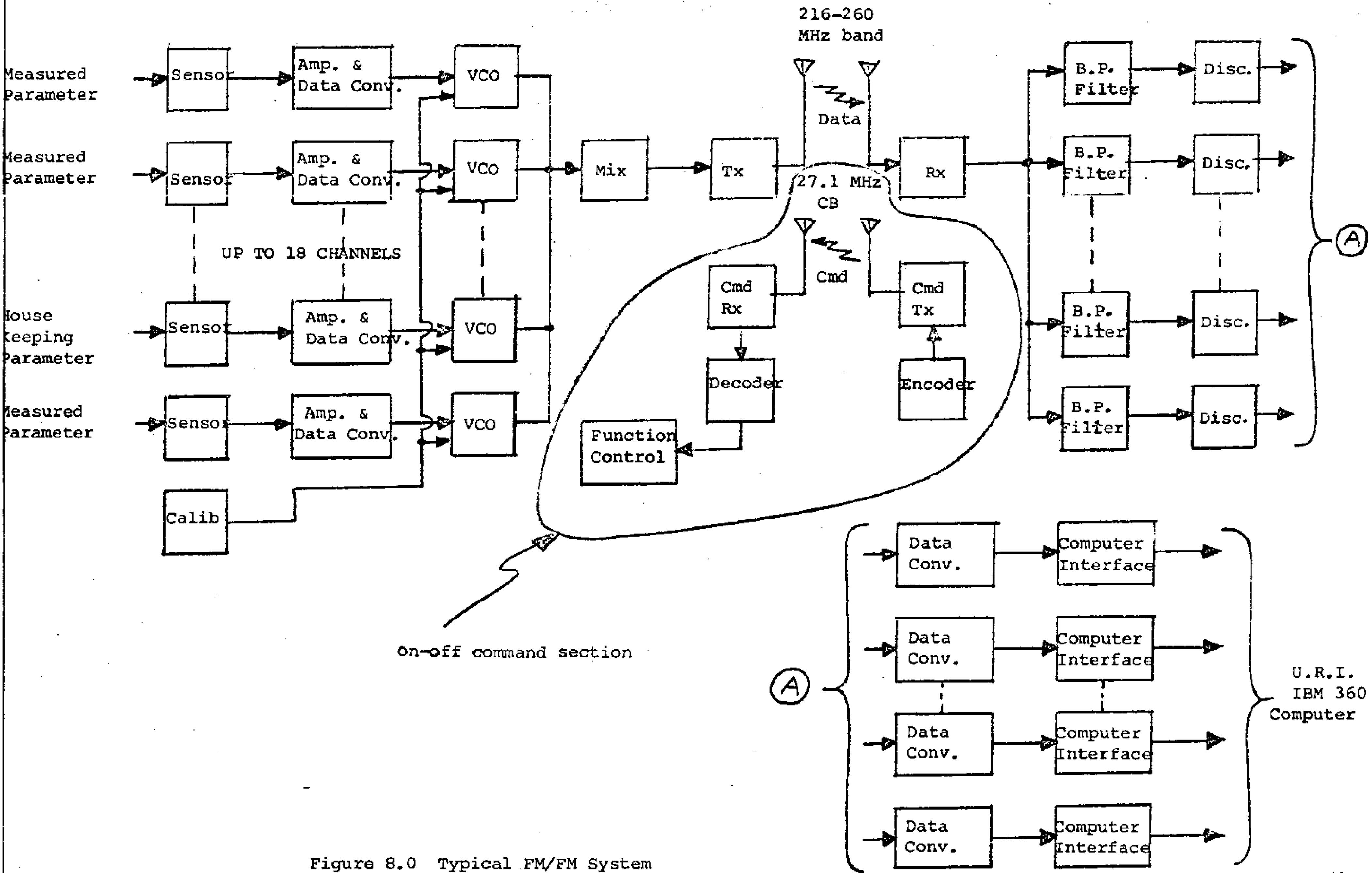

Figure 8.0 Typical FM/FM System

The UHF signal is received and demodulated by an FM discriminater. The composite VCO signal is then applied to a bank of Band Pass (B.P.) filters, which separate the individual VCO frequencies. Each VCO signal is itself FM discriminated, resulting in a DC voltage proportional to the originally measured parameter. These D.C. voltages are converted into computer format for real time analysis.

Also incorporated in this system is a 27.1 mHz citizen's band command link. The system can be turned on, calibrated, and turned off by remote command from the shore facility. (See Figure 8.0). Also, up to 18 channels can be used simultaneously, and if necessary each channel can contain sampled commutated data extending the data channel capacity to several hundred. The advantages of this system are many. They consist of:

a. Expandability to many channels
b. Multiple housekeeping sensor capability
c. Complete in-situ calibration
d. Command on-off-calib-etc capability
e. Automatically computer interfaced

The one disadvantage which makes it not much better than the original simple system is measured parameter accuracy. The only help is that in situ calibration can be incorporated which eliminates drifting errors. However, data conversion, transmission, and detection errors inherent in the system will be present such that the overall accuracy is system limited rather than instrument limited.

C. Typical Digital System

The obvious limitation to each system presented thus far is one of data accuracy. The optimum solution for this problem is to digitize the information prior to transmission. Then, the accuracy limitation becomes a function of the number of bits in each digital word and the accuracy of the analog to digital converter. The number of bits can be easily resolved. A typical measurement is the current meter. According to a typical specification sheet, current sensors have a range of 0 to 7 knots, and an accuracy of ± 0.05 knots. This means that the meter has sufficient accuracy to resolve 0.1 knot variations. Therefore, there is a possibility that 700 descrete levels would have to be measured. Simply speaking, this requires a word length of 10 bits ($2^{10} = 1024$ levels) with accuracy left over. A 10 bit analog to digital converter can certainly be obtained. Thus the system accuracy can now be instrument limited rather than system limited, which provides optimum system accuracy.

In general, because the analog to digital converter will be an expensive item, the sensors would be commutated so that the same A/D converter could be used for all sensors. This means that the data will be transmitted serially. (See Figure 9.0). The exact timing is a discrete systems design problem and will not be discussed here.

As previously stated, a 10 bit word would meet the systems accuracy criteria. However, a more suitable data format would be that of the digital computer being used for post analysis. The ideal format is an engineering trade-off and must be carefully considered during the initial design phase, because the extended number of bits may be cost prohibitive.

The system would operate in the following manner. The sensor outputs are applied to an amplifier and data converter in much the same manner as in the simple system. The data converter outputs are then switched (commutated) one at a time to the input of the analog to digital converter. The digitized serial data signal, along with appropriate synchronization and parity check pulses are applied directly to the data transmitter. Note that the bandwidth requirements are no longer critical, and a lower transmission frequency can be used than in the FM/FM system. The data is transmitted to the shore facility, resynchronized, conditioned, and applied directly to the computer for real time analysis, or stored on an appropriate storage medium. Included also in this system are the multiple housekeeping sensors, the command on-off capability, and all the other refinements mentioned earlier.

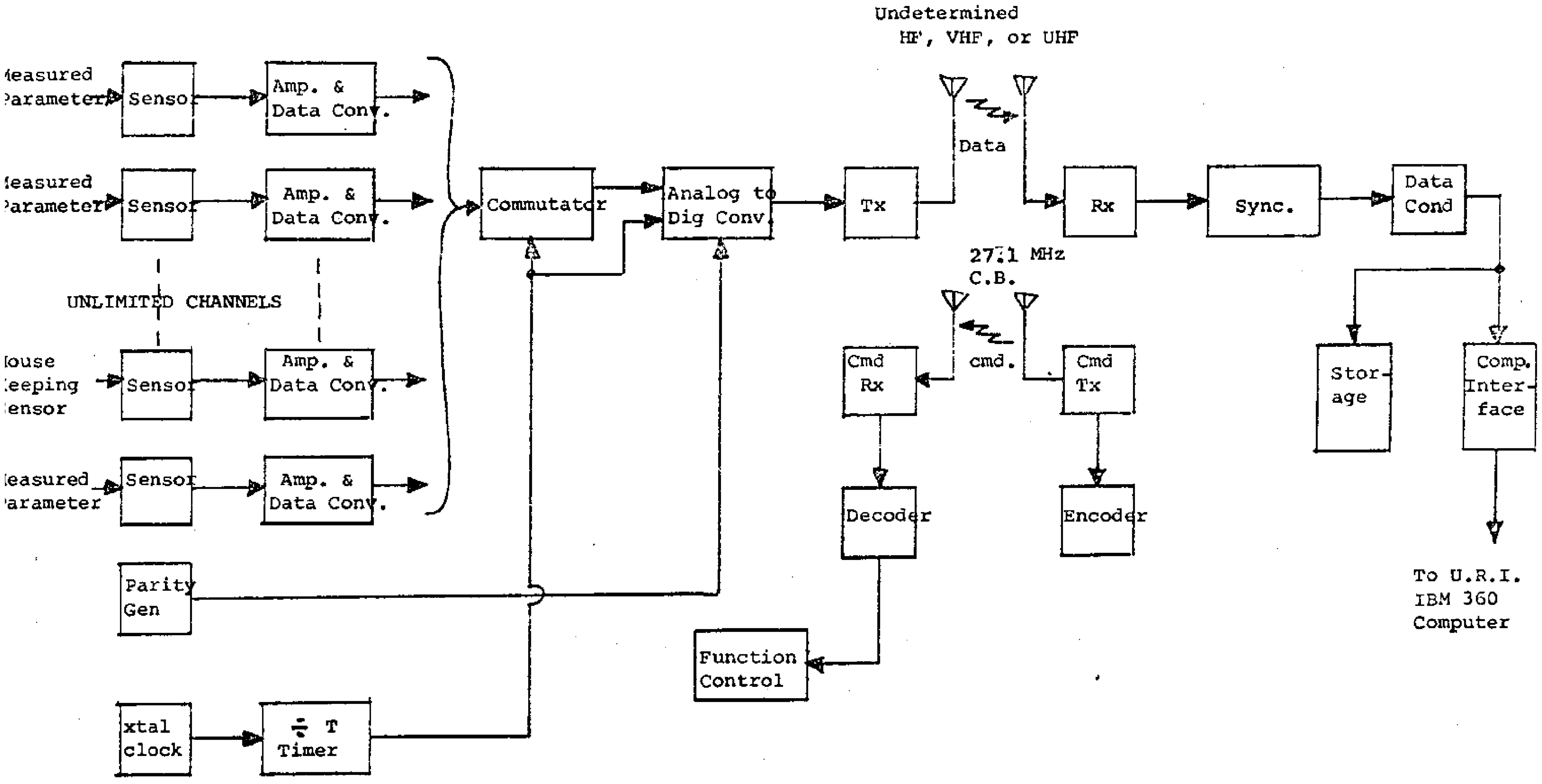

Figure 9.0 Typical Digital System

The advantages of this system are maximized. Not only does it contain all the advantages listed for the FM/FM system, but it also allows the overall system accuracy to be limited by the sensors rather than the system.

Cost Considerations

The consideration of cost is based on engineering estimates for some items and manufacturers listed prices for many others. The cost analysis is summed up in Tables 2.0, 3.0, and 4.0. Comparative values are given assuming a five sensor system, and then the cost is computed for each additional measurement mentioned. No attempt has been made to solicit manufacturer quantity price reductions. Tables 2.0, 3.0, and 4.0 show that the initial cost of a five channel simple system is $6430 as compared to $16,170 for the FM/FM system and $14,130 for the digital system. However, they also show that the next channel addition could not be readily incorporated into the simple system, while the FM/FM system would require an additional $1470 and the digital system would only require an additional $580. These figures, of course, are only estimates, but they do point out the financial trade-offs which must be considered.

5. IRIG Standards

The Inter Range Instrumentation Group at the White Sands Proving Grounds in New Mexico, have devised a set of standards for telemetering systems (Ref.5). There are two sets of standards. One is for Constant Percentage deviation frequencies. These standards are set to regulate the SCO frequencies and deviations. Table 5.0 shows this system. It shows the channel number, the center frequency of the SCO (or VCO), the deviation in Hz, the lower and upper limits, the percent of deviation (constant), and the maximum intellegence frequency, or frequency response with a modulation index of 5. Table 6.0 shows the same type of data for constant bandwidth (i.e. each SCO maintains a constant frequency bandwidth even though the percentage changes) subcarrier channels. This table shows the channel

TABLE 2.0

COST ANALYSIS (SIMPLE SYSTEM)

Item	Cost
Sensors (from table 2)	2710.00
Data Converter (5 Channels)	250.00*
VCO	195.00
Sequence timers (2 @ $150 each)	300.00
Cmd, Osc	40.00*
Warble Osc.	35.00*
Batteries	30.00
CB xmtr.	40.00
Antennas (2 @ 15 each)	30.00
CB Reciever	40.00
Cmd, Detection	20.00*
Indicaters	25.00*
Leak Detection alarms	15.00
Manual Overide	5.00*
Filler & Disc.	195.00
Hardware (misc.)	500.00*
Labor (2 months)	2000.00*
Total	
Total Cost (1st system)	6430.00
One Add Chan	
Almost impossibe without rebuilding system	+
Total Cost for one addition Channel	?

* denotes estimated costs

TABLE 3.0

COST ANALYSIS (FM/FM SYSTEM)

Item	Cost
Sensors (from table 2)	2710.00
Amp & Data converters (5 channels)	275.00*
VCO (5 @ 195 each)	975.00
Mixer	175.00
Transmitter	1795.00
Calibrator	450.00
Antennas	10.00*
Receiver	2795.00
Encader	150.00
Cmd Tx	40.00
Antennas	30.00
Cmd Rx	40.00
Decoder	150.00
B.P. filler & Disc. (5 @ 375 each)	1875.00
Data Conv. & Computer Interface	available equip.
Hardware (misc.)	1200.00*
Labor (3½ months)	3500.00*
Total	
Total Cost (1st system)	16,170.00

One additional channel	
Sensor (assume $200)	200.00*
Amp & Data converter	55.00*
VCO	195.00
B.P. filter & Discriminater	375.00
Hardware (misc.)	125.00*
Labor (2 weeks)	500.00*
Total	1,460.00

* denotes estimated cost

TABLE 4.0

COST ANALYSIS (DIGITAL SYSTEM)

Item	Cost
Sensors (from table 1)	2710.00
Amp & Data converter (5 channels)	275.00*
xtal clock	35.00*
÷ timer	55.00*
Parity generater	60.00*
Commulater	350.00
Analog to Digital Converter	5000.00*
Tx	200.00*
Antennas	50.00*
Rx	200.00*
Sync.	350.00*
Data conditioner	35.00*
Storage & comp. interface	available equip.
Encoder	150.00
C.B. Tx	40.00
C.B. Rx	40.00
Antennas	30.00
Decoder	150.00
Hardware (misc.)	1000.00*
Labor (3½ months)	3500.00*
Total	
One additional channel	14,130.00
Sensor (assume 200)	200.00
Amp & Data converter	55.00*
Hardware (misc.)	75.00
Labor (1 week)	250.00*
Total	580.00

* denotes estimeated cost

Table 5.0 IRIG CONSTANT PERCENTAGE DEVIATION FREQUENCY SYSTEM

Band	Center Frequency (cps)	Deviation (cps)	Lower Limit* (cps)	Upper Limit* (cps)	Maximum Deviation (percent)	Maximum Intelligence Frequency (Modulation Index 5) (cps)
1	400	±30	370	430	±7.5	6.0
2	560	42	518	602	±7.5	8.4
3	730	55	675	785	±7.5	11
4	960	72	888	1,032	±7.5	14
5	1,300	98	1,202	1,399	±7.5	20
6	1,700	128	1.572	1.828	±7.5	25
7	2,300	173	2,127	2,473	±7.5	35
8	3,000	225	2,775	3,225	±7.5	45
9	3,900	293	3,607	4,193	±7.5	59
10	5,400	405	4,995	5,805	±7.5	81
11	7,350	551	6,799	7,901	±7.5	110
12	10,500	788	9,712	11,288	±7.5	160
13	14,500	1,088	13,412	15,588	±7.5	220
14	22,000	1,650	20,350	23,650	±7.5	330
15	30,000	2,250	27,750	32,250	±7.5	450
16	40,000	3,000	37,000	43,000	±7.5	600
17	52,500	3,940	48,562	56,438	±7.5	790
18	70,000	5,250	64,750	75,250	±7.5	1,050
19	93,000	6,975	85,025	99,975	±7.5	1,400
20***	124,000	9,300	114,700	133,300	±7.5	1,900
21***	165,000	12,375	152,625	177,375	±7.5	2,500
A**	22,000	3,300	18,700	25,300	±15	660
B	30,000	4,500	25,500	34,500	±15	900
C	40,000	6,000	34,000	46,000	±15	1,200
D	52,500	7,880	44,625	60,375	±15	1,600
E	70,000	10,500	59,500	80,500	±15	2,100
F	93,000	13,950	79,050	106,950	±15	2,800
G***	124,000	18,600	105,400	142,600	±15	3,700
H***	165,000	24,750	140,250	189,750	±15	5,000

* Rounded off to nearest cycle.

** Bands A through H are optional and may be used by omitting adjacent bands as shown in the following table. In the process of recording the foregoing subcarriers on magnetic tape at a receiving station, provision may also be made to record a tape-speed-control tone and tape-speed-error-compensation signals.

Band used	Omit bands—
A	13, 15 and B
B	14, 16, A and C
C	15, 17, B and D
D	16, 18, C and E
E	17, 19, D and F
F	18, 20, E and G
G	19, 21, F and H
H	20 and G

*** Recommended for use in UHF transmission systems only.

If a 100 KC tape speed compensation tone is mixed with these bands, the 93 KC band must be omitted and the 124 KC band must not be deviated ±15%.

TABLE 6.0 CONSTANT BANDWIDTH SUBCARRIER CHANNELS (Now IRIG Standards)

Deviation = ±2kc/s Nominal frequency response = .4kc/s Maximum frequency response = 2kc/s**		Deviation = ±4kc/s Nominal frequency response = 0.8kc/s Maximum frequency response = 4kc/s**		Deviation = ±8kc/s Nominal frequency response = 1.6kc/s Maximum frequency response = 8kc/s**	
Channel	**Center Frequency kc/s**	**Channel**	**Center Frequency kc/s**	**Channel**	**Center Frequency kc/s**
1A	16				
2A	24				
3A	32	3B	32		
4A	40				
5A	48	5B	48		
6A	56				
7A	64	7B	64	7C	64
8A	72				
9A	80	9B	80		
10A	88				
11A	96	11B	96	11C	96
12A	104				
13A	112	13B	112		
14A	120				
15A	128	15B	128	15C	128
16A*	136				
17A*	144	17B*	144		
18A*	152				
19A*	160	19B*	160	19C	160
20A*	168				
21A*	176	21B*	176		

* Recommended for use in UHF transmission systems only.

** The indicated maximum frequency response is based upon the maximum theoretical response that can be obtained in a bandwidth between deviation limits specified for the channel. (See discussion in Appendix II for determining practical accuracy vs response tradeoffs.)

numbers and the SCO center frequency. The deviation, nominal frequency response, and maximum frequency response are constant within a given A, B, or C grouping. (See Table 6.0).

The standards are adhered to very stringently and SCO's with these specifications are readily available off the shelf. Other systems are also available such as shown in the bottom of Table 7.0. These are constant bandwidth systems running from a deviation of ± 62.5 Hz to ± 64 KHz. This obviously is an expansion of the IRIG standards as shown in Table 6.0. The top of Table 7.0 also shows an expansion of the standards.

6.0 Frequency Allocations

One of the first decisions which must be made when designing a telemetering system, or any other transmission link, is the transmission frequency. There are many things that affect the choice of a transmission frequency. Among these are:

(a). transmission path parameters.

(b). power budget considerations.

(c). data rate and necessary bandwidth.

(d). compatability with support equipments.

(e). antenna configurations.

(f). legal and available frequency allocations.

The FCC has established a system of frequency allocation for Meteorological telemetering use. Table 8.0 shows these allocations, and must be adhered to when making transmission frequency decisions. It must be pointed out that this table, gives frequency allocations for meteorological data links.

7.0 and 8.0 Identification and Determination of Important Parameters

The proper design of any system requires an initial identification and determination of the important parameters. Each parameter has been mentioned during previous discussions, and each will be considered in detail in Section 9.0.

AIA PROPOSED CONSTANT-BANDWIDTH STANDARDS

Table 7.0

Band	Center Frequency (kc)	Deviation (kc)	Frequency Response (kc)		Band	Center Frequency (kc)	Deviation (kc)	Frequency Response (kc)	
			m=2	m=5				m=2	m=5
1C	12.5	±2	1	0.4	18C	154.2	±2	1	0.4
2C	20.8	±2	1	0.4	19C	162.5	±2	1	0.4
3C	29.2	±2	1	0.4	20C	170.8	±2	1	0.4
4C	37.5	±2	1	0.4	21C	179.2	±2	1	0.4
5C	45.8	±2	1	0.4	22C	187.5	±2	1	0.4
6C	54.2	±2	1	0.4					
7C	62.5	±2	1	0.4	2CW	20.8	±4	2	0.8
8C	70.8	±2	1	0.4	4CW	37.5	±4	2	0.8
9C	79.2	±2	1	0.4	6CW	54.2	±4	2	0.8
10C	87.5	±2	1	0.4	8CW	70.8	±4	2	0.8
11C	95.8	±2	1	0.4	10CW	87.5	±4	2	0.8
12C	104.2	±2	1	0.4	12CW	104.2	±4	2	0.8
13C	112.5	±2	1	0.4	14CW	120.8	±4	2	0.8
14C	120.8	±2	1	0.4	16CW	137.5	±4	2	0.8
15C	129.2	±2	1	0.4	18CW	154.2	±4	2	0.8
16C	137.5	±2	1	0.4	20CW	170.8	±4	2	0.8
17C	145.8	±2	1	0.4	22CW	187.5	±4	2	0.8

Note 1. The number of these channels that may be transmitted over an RF link simultaneously will be limited by the available transmitter deviation.

Note 2. The bands with ±4-kc deviation will be designated with the suffix W.

Note 3. The even numbered wide deviation bands, 2CW through 22-CW, are optional and may be used by omitting the adjacent odd numbered narrow bands.

DCS CONSTANT-BANDWIDTH SYSTEMS

Deviation	±62.5 cps	±125 cps	±250 cps	±500 cps	±1 kc	±2 kc	±4 kc	±8 kc	±16 kc	±32 kc	±64 kc
Center Frequencies	391 cps	781 cps	1.56 kc	3.13 kc	6.25 kc	12.5 kc	25 kc	50 kc	100 kc	200 kc	400 kc
	625 cps	1.25 kc	2.50 kc	5.00 kc	10.00 kc	20.0 kc	40 kc	80 kc	160 kc	320 kc	640 kc
	859 cps	1.72 kc	3.44 kc	6.88 kc	13.8 kc	27.5 kc	55 kc	110 kc	220 kc	440 kc	880 kc
	1.09 kc	2.19 kc	4.38 kc	8.75 kc	17.50 kc	35.0 kc	70 kc	140 kc	280 kc	560 kc	1.12 mc
	1.33 kc	2.66 kc	5.31 kc	10.60 kc	21.3 kc	42.5 kc	85 kc	170 kc	340 kc	680 kc	1.36 mc

Table 8.0

METEOROLOGICAL FREQUENCY ALLOCATIONS

4-6 Mcs	Buoy, Marine Meteorological (SMT-I)
4-16 Mcs	Land and Buoy, Fixed stations (WMT-I)
7-10 Mcs	Buoy, Oceanographic
28 Mcs	Meteorological Aids
137 Mcs	Meteorological Satellite
162-174 Mcs	Buoy Bathythermographs and Sonobuoys
225-235 Mcs	Buoy Telemetry
225-260 Mcs	Buoy Droppable Electronic Marker Beacon
400-406 Mcs	Radiosonde

However, for convenience, they are listed below.

(a). Frequency and Bandwidth

(b). Modulation modes

(c). Signal to noise ratio

(d). Power requirements

(e). Error introduction and accuracy

(f). Antennas and propagation

(g). Cost, size and compatability

9.0 Actual Design (Follow Through)

Introduction

This section will describe an actual system design study performed by the U.S. Naval Avionics Facility, Indianapolis, Indiana (Ref. 6). This NAFI publication (TR 987, dated January 1967), entitled, "Design Requirements for a Tactical Automatic Weather Station System", considers the design requirements for an air dropped expendable meteorological buoy, which will be readout by a P3 Orion aircraft. Only part of the study is reproduced here to show the telemetering system. The important parameters are discussed below.

Aircraft as Data Link

The transfer of information from the tactical AWS to usable data for analysis involves the interrogation of the buoy, transmission to the aircraft, the link between aircraft and evaluation center, and processing the data.

The aircraft, having received the data, has three possible telemetry roles, i.e., retransmit, or record and store, or record and then retransmit. The selected role of the aircraft is determined by data delay time, overall accuracy, and reliability. Data delay time refers to the time lapse between reception of data from the buoy and delivery of data for analysis. The aircraft used as a relay transmitter will give almost instant access to the data at the evaluation station. The delay involved in recording and storing the signal is determined by the duration of a flight mission. Average mission duration in fleet service has been about six hours per flight.

In the relay mode, the increased noise added by retransmission will decrease the accuracy of the data. Recording the signal at the aircraft will eliminate this noise; however, the tape recorder will add some inaccuracies.

Reliability, in this context, refers to how reliable is the data link between aircraft and evaluation center. The retransmit mode is relatively unreliable since the retransmission may be missed or too weak due to propagation conditions. If the data is monitored while it is recorded, the reliability is good.

The most versatile method from these considerations is to record the data with retransmission at a later time. The simplest method and recommended approach is to record the data on magnetic tape (AN/AQH-1 Recorder) with the possibility of adding a retransmit function if preliminary use and other applications make it justified.

Range and Power

The range, % data recovery, frequency, and modulation system basically determine the amount of RF pwer required for a data link. The range should be as far as possible. There are, however, certain limitations. Line of sight propagation is limited by the curvature of the earth, how high the aircraft can fly, multipath reflections, and atmospheric conditions. Table 9 is a listing of distance to the horizon for many altitudes. It is useful when figuring line of sight ranges. The range is also limited by the amount of available r-f power. This power limit is due to the state-of-the-art of solid-state transmitters and the size of the buoy power supply. All of these above factors will be considerations in determining the range.

The % of data recovery refers to the amount of data recovered on one readout of the data. This data recovery should be close to 100%. The cost involved in making a flight to the buoy is large enough that a return for missed data should be minimized.

Distance to the Horizon

Height feet	Nautical miles	Statute miles	Height feet	Nautical miles	Statute miles	Height feet	Nautical miles	Statute miles
1	1. 1	1. 3	120	12. 5	14. 4	940	35. 1	40. 4
2	1. 6	1. 9	125	12. 8	14. 7	960	35. 4	40. 8
3	2. 0	2. 3	130	13. 0	15. 0	980	35. 8	41. 2
4	2. 3	2. 6	135	13. 3	15. 3	1, 000	36. 2	41. 6
5	2. 6	2. 9	140	13. 5	15. 6	1, 100	37. 9	43. 7
6	2. 8	3. 2	145	13. 8	15. 9	1, 200	39. 6	45. 6
7	3. 0	3. 5	150	14. 0	16. 1	1, 300	41. 2	47. 5
8	3. 2	3. 7	160	14. 5	16. 7	1, 400	42. 8	49. 3
9	3. 4	4. 0	170	14. 9	17. 2	1, 500	44. 3	51. 0
10	3. 6	4. 2	180	15. 3	17. 7	1, 600	45. 8	52. 7
11	3. 8	4. 4	190	15. 8	18. 2	1, 700	47. 2	54. 3
12	4. 0	4. 6	200	16. 2	18. 6	1, 800	48. 5	55. 9
13	4. 1	4. 7	210	16. 6	19. 1	1, 900	49. 9	57. 4
14	4. 3	4. 9	220	17. 0	19. 5	2, 000	51. 2	58. 9
15	4. 4	5. 1	230	17. 3	20. 0	2, 100	52. 4	60. 4
16	4. 6	5. 3	240	17. 7	20. 4	2, 200	53. 7	61. 8
17	4. 7	5. 4	250	18. 1	20. 8	2, 300	54. 9	63. 2
18	4. 9	5. 6	260	18. 4	21. 2	2, 400	56. 0	64. 5
19	5. 0	5. 7	270	18. 8	21. 6	2, 500	57. 2	65. 8
20	5. 1	5. 9	280	19. 1	22. 0	2, 600	58. 3	67. 2
21	5. 2	6. 0	290	19. 5	22. 4	2, 700	59. 4	68. 4
22	5. 4	6. 2	300	19. 8	22. 8	2, 800	60. 5	69. 7
23	5. 5	6. 3	310	20. 1	23. 2	2, 900	61. 6	70. 9
24	5. 6	6. 5	320	20. 5	23. 6	3, 000	62. 7	72. 1
25	5. 7	6. 6	330	20. 8	23. 9	3, 100	63. 7	73. 3
26	5. 8	6. 7	340	21. 1	24. 3	3, 200	64. 7	74. 5
27	5. 9	6. 8	350	21. 4	24. 6	3, 300	65. 7	75. 7
28	6. 1	7. 0	360	21. 7	25. 0	3, 400	66. 7	76. 8
29	6. 2	7. 1	370	22. 0	25. 3	3, 500	67. 7	77. 9
30	6. 3	7. 2	380	22. 3	25. 7	3, 600	68. 6	79. 0
31	6. 4	7. 3	390	22. 6	26. 0	3, 700	69. 6	80. 1
32	6. 5	7. 5	400	22. 9	26. 3	3, 800	70. 5	81. 2
33	6. 6	7. 6	410	23. 2	26. 7	3, 900	71. 4	82. 2
34	6. 7	7. 7	420	23. 4	27. 0	4, 000	72. 4	83. 3
35	6. 8	7. 8	430	23. 7	27. 3	4, 100	73. 3	84. 3
36	6. 9	7. 9	440	24. 0	27. 6	4, 200	74. 1	85. 4
37	7. 0	8. 0	450	24. 3	27. 9	4, 300	75. 0	86. 4
38	7. 1	8. 1	460	24. 5	28. 2	4, 400	75. 9	87. 4
39	7. 1	8. 2	470	24. 8	28. 6	4, 500	76. 7	88. 3
40	7. 2	8. 3	480	25. 1	28. 9	4, 600	77. 6	89. 3
41	7. 3	8. 4	490	25. 3	29. 2	4, 700	78. 4	90. 3
42	7. 4	8. 5	500	25. 6	29. 4	4, 800	79. 3	91. 2
43	7. 5	8. 6	520	26. 1	30. 0	4, 900	80. 1	92. 2
44	7. 6	8. 7	540	26. 6	30. 6	5, 000	80. 9	93. 1
45	7. 7	8. 8	560	27. 1	31. 2	6, 000	88. 6	102. 0
46	7. 8	8. 9	580	27. 6	31. 7	7, 000	95. 7	110. 2
47	7. 8	9. 0	600	28. 0	32. 3	8, 000	102. 3	117. 8
48	7. 9	9. 1	620	28. 5	32. 8	9, 000	108. 5	124. 9
49	8. 0	9. 2	640	28. 9	33. 3	10, 000	114. 4	131. 7
50	8. 1	9. 3	660	29. 4	33. 8	15, 000	140. 1	161. 3
55	8. 5	9. 8	680	29. 8	34. 3	20, 000	161. 8	186. 3
60	8. 9	10. 2	700	30. 3	34. 8	25, 000	180. 9	208. 2
65	9. 2	10. 6	720	30. 7	35. 3	30, 000	198. 1	228. 1
70	9. 6	11. 0	740	31. 1	35. 8	35, 000	214. 0	246. 4
75	9. 9	11. 4	760	31. 5	36. 3	40, 000	228. 8	263. 4
80	10. 2	11. 8	780	31. 9	36. 8	45, 000	242. 7	279. 4
85	10. 5	12. 1	800	32. 4	37. 3	50, 000	255. 8	294. 5
90	10. 9	12. 5	820	32. 8	37. 7	60, 000	280. 2	322. 6
95	11. 2	12. 8	840	33. 2	38. 2	70, 000	302. 7	348. 4
100	11. 4	13. 2	860	33. 5	38. 6	80, 000	323. 6	372. 5
105	11. 7	13. 5	880	33. 9	39. 1	90, 000	343. 2	395. 1
110	12. 0	13. 8	900	34. 3	39. 5	100, 000	361. 8	416. 5
115	12. 3	14. 1	920	34. 7	39. 9	200, 000	511. 6	589. 0

Table 9.0

To get line-of-sight distance D from your eyes (or antenna) at height h above sealevel to a light or object seeming to be on the horizon but actually at distance d_1 beyond the horizon and at height h_1 above sealevel, add distance d from your eyes to horizon to the distance d_1 from object to its horizon, i.e., $D = d + d_1$. If you first add the two heights and then make a single conversion, the result will be in error. NOTE: Nautical charts give range to important lights based on mean high water and an eye-above sealevel height of 15 feet. Table above was computed thus: $D = 1.144\sqrt{h}$ nautical miles; $D = 1.317\sqrt{h}$ statute miles (h is in feet). The constants are based on the mean radius of the earth according to the Clarke spheroid of 1866.

Frequency Selection

The considerations for frequency selection are made by first looking at the legal allocations of frequencies for related projects. The frequencies as shown in Table 8.0 are used with meteorological systems.

A second factor in frequency determination is compatibility with the aircraft and its electronic systems. The addition of new antennas on the aircraft is costly and limits use to only modified aircraft. The frequencies which are available on the Orion are in the 2-30 Mcs, 118-151 Mcs, 160-174 Mcs and 225-400 Mcs range.

The third consideration is based on what frequency would be the optimum frequency for reliable data transmission with minimum power requirements. This frequency is determined by optimization of the propagation equation (Ref. 7). The composite transmission loss equation is shown in Figure 10.0 and reduces to:

$$\begin{aligned} P_{td} &= 20 \log d + 20 \log f + 36.6 - G_t - G_r + A + L_{td} \\ &\quad + 10 \log \ r(f_a - 1 + f_c \ f_t \ f_r) \ k \ t \ b + \sum_{u=1}^{m} r_u \ P_u \end{aligned}$$

The optimum frequency is basically determined by minimizing the losses, effective receiver noise factor, and interference from other signals. At ranges of extreme line of sight with low elevation angles, losses in excess of free space are frequency dependent and are due to multipath reflection, wave shadowing, cross polarization due to tilt of the buoy, and atmospheric effects such as ducting, absorption, and scattering. Effective noise factor is due to atmospheric noise, man-made noise, and galactic noise, with this noise being frequency dependent. The carrier frequency must then be high enough to avoid the noise and interference inherent in the HF band and low enough to limit propagation losses to reasonable values. These propagation losses cannot be appreciably recovered by increasing antenna gain because the buoy must radiate in all directions and the present aircraft antennas are also omnidirectional. The best frequency band is therefore VHF with the 162-174 Mcs segment especially advantageous because of the preponderance of receiving equipment aboard the P-3. Use of this band suggests that some

Table 10.0

Composite Transmission Loss Equation

Required Transmitter Power (in dbm).

Transmitter Circuit Losses Including Cable & Antenna Losses (in dB).

$$P_{td} = L_d + L_{td} + P_m$$

Transmission Loss of The Desired Signal (in dB).

Minimum Signal Power Required at Receiving Antenna Terminals that Provide Satisfactory reception (in dbm).

Where: $L_d = L_b - G_t - G_r + A$

L_b = Basic Transmission Loss for Isotropic Antennas in Free Space (in dB)

$$L_b = 10 \text{ Log}_{10} \left(\frac{4\pi d}{\lambda}\right)^2 = 20 \text{ Log}_{10}\left(\frac{4\pi}{C}\cdot f\cdot d\right)$$

$$L_b = 20 \text{ Log}_{10} d + 20 \text{Log}_{10} f + 36.6\text{dB}$$

Distance in Statute Miles

Frequency in Mcs

G_t = Transmitting Antenna Gain(in dB)

G_r = Receiving Antenna Gain (in dB)

A = Loss in Excess of Free Space(dB) Including Multipath, Wave Shading, Polarization, & Atmospheric.

Where: $P_m \cong 10 \text{ Log}(rfktb + \sum_{u=1}^{m} r_u P_u)$

r = Minimum Signal to Noise Ratio that provides satisfactory reception

f = Effective Noise Factor at Receiving Antenna Terminals

$f = f_a - 1 + f_c \; f_t \; f_r$

$f_a = \dfrac{\text{Average Available Noise Power}}{\text{Thermal Noise Power (ktb)}}$

f_c = Receiving Antenna Loss Factor

$= \dfrac{\text{Available Input Power}}{\text{Available Output Power}}$

f_t = Receiving Transmission Line Loss

f_r = Receiver Noise Factor

k = Boltzman's constant = 1.38×10^{-23} joule/°K

t = Absolute Temperature in °K.

b = Effective Noise Bandwidth (≅ 3 db B.W.)

r_u = Minimum Signal to Interference Ratio That Provides Satisfactory reception

P_u = Available Interfering Signal Power degree of coordination with the sonobuoy program is required.

Modulation Scheme

The approach taken for modulation considerations is to reduce the possibilities by preliminary study to two modulation techniques and study these in greater detail. First, PCM-PS and PCM-SSB were rejected on the basis of receiver and transmitter complexity and susceptibility to doppler shift. Modulation systems such as PDM, PAM, PPM, AM, etc., were eliminated for reasons such as input $\frac{S}{N}$ ratio required for satisfactory reception, power efficiency, noise susceptibility, lack of available technology and hardware, etc. The choice of a modulation technique is dependent on the carrier frequency. Since the VHF range looks most promising, the choice of a modulation system at this frequency is a decision between a digital PCM/FM or an analog FM/FM technique.

The basic factors in the selection of a modulation system are data accuracy, readout time, battery energy, compatibility with the aircraft, and available implementation hardware. With the carrier frequency selected at approximately 170 Mhz, the modulation system becomes a choice between PCM/FM and FM/FM. The comparison of these two techniques is shown in the Appendix. Another factor in determining the modulation system is the data format of the processed meteorological information. For example, if the tactical AWS is used to supplement a larger buoy network, such as in hurricane detection, and the meteorological data is to be computer analyzed, then a PCM/FM system would most efficiently be used. If the tactical AWS is used in limited situations where analog data is sufficient, then the FM/FM system would be used because of its lower cost.

The FM/FM system proposed would have a 30 Khz r-f bandwidth and use a receiver with a 200 Khz i-f bandwidth. This means that the Radio Receiving Set AN/ARR-52(V) aboard the aircraft will be used, and if needed, an r-f preselector filter may be added for increased range. Also the use of a 30 Khz r-f bandwidth will permit the use of inexpensive crystals in the buoy transmitter and eliminate the need for a crystal oven. The frequency response of the audio section within the receiver has an upper limit of 5 Khz at 2 db down. This response characteristic limits the use of subcarrier channels to IRIG channels 1-6. The selection of subcarrier channels, shown in the Appendix was made in terms of the frequency response of the measured parameters, and subcarrier channels 1-6 were chosen. The audio response of the receiver and the system selection of subcarrier channels are compatible. Due to 400 Hz power in the aircraft, channel 1 with a center frequency at 400 Hz may be replaced by another channel. The complex audio signal from the receiver will then be recorded on the AN/AQH-1 Recorder and visually displayed at a later time.

The proposed PCM/FM system would transmit each sensor data with an eight-digit word. Again, realizing the low pass characteristic of the audio section of the receiver, the modulating signal would consist of a 3-state VCO operating with a nominal frequency of 3.9 Khz. Allowing the FM detection threshold and the PCM detection threshold to occur at the same carrier signal strength gives the system a deviation ratio of D = 0.6. The r-f bandwidth can be calculated by knowing f_m = 4.0 Khz and D = 0.6.

$$B_{r-f} = \emptyset\ (D) \times f_m = \emptyset\ (0.6) \times 4.0 \text{ Khz} = 4 \times 4.0 \text{ Khz} = 16 \text{ Khz}$$

This calculated r-f bandwidth is optimum when the i-f bandwidth can be matched to the r-f bandwidth. In the case where the i-f bandwidth is predetermined and is larger, it might be advisable to increase the transmitted r-f bandwidth. This increased r-f bandwidth would increase the output $\frac{S}{N}$ ratio of the FM receiver. There is one other point of consideration and that is as the r-f bandwidth is increased, the threshold input $\frac{S}{N}$ ratio increases (Ref. 8). There is, then, a trade off between minimum input $\frac{S}{N}$ and the deviation ratio. This particular problem is one where experimentation is needed. The system will use the AN/ARR-52 Receiver with a 200 Khz i-f bandwidth. The digital audio signals can again be recorded on magnetic tape.

Transmitter Power Required

Referring to the transmission previously discussed, loss equation,

$$P_{td} = 20 \log d + 20 \log f + 36.6 - G_t - G_r + A + L_{td} + 10 \log \left[r(f_a - 1 + f_c\, f_t\, f_r)\, Ktb + \sum_{u=1}^{m} r_u\, P_u \right]$$

and assuming,

d = 200 statute miles

f = 170 Mhz

G_t = 2.5 dB

G_r = 1.5 dB

A = 12 dB (at 27,000 feet)

L_{td} = 1.5 dB

r = 10 (10 db)

f_a = 1 (thermal noise only)

f_c = 1 (0 db)

f_t = 1.28 (1 db)

f_r = 4 (6 db)

$Ktb = (1.380 \times 10^{-23})\ (290)\ (2 \times 10^5) = 8.00 \times 10^{-16}$ watts

$\sum_{u=1}^{m} r_u P_u = 0$ (no interfering signals)

20 log 200 = 46.0 db

20 log 170 = 44.6 db

$$10 \log \left[10(1 - 1 + (1)\ (1.28)\ (4))\ 8 \times 10^{-16} + 0 = -134 \text{ dbw} \right]$$

$\sum(+)$ = 140.7 db $\sum(-)$ = −138 dbw

P_{td} = 3 dbw or 2 watts (minimum)

Since the variability in the transmission loss is great at low grazing angles (near the radio horizon), the approach generally taken to achieve reliable communications is to increase the transmitter power considerably above the calculated minimum required value. Experimental measurements are usually made to determine the approximate mean and standard deviation of the path loss. With many measurements, it is possible to predict the probability that a given radio path loss will be less than a specified value. Since these measurements are expensive to make, a trade-off must be made based on measurements made by others and the power limitations of the buoy. A transmitter power of approximately 20 watts is recommended as the best compromise.

Additional study is recommended to determine the expected service probability of the tactical AWS. The best way of attaining a high communications reliability is to interrogate the weather station at distances less than 200 miles when possible.

Command Function

A basic concept of the tactical AWS is an "interrogate for data" operation instead of a clocked function. Interrogation of the buoy by the aircraft again involves a data link with a selection of frequency and "command on" code. The frequency recommended for interrogation is the 225 to 399.9 Mhz UHF range. This selection was made by considering aircraft equipment. The "command on" code such as an audio tone or digital word needs further investigation. Compatibility of the command code with Command Active Sonobuoy System (CASS) also needs further investigation.

Antenna Selection

The selection of an antenna for use on the tactical AWS was very heavily determined by the requirement of an omnidirectional pattern and a polarization the same as the antenna of the aircraft. The antenna system aboard the P-3 is vertically polarized. In general directional pattern in azimuth has low gain. An antenna with an artificial ground plane such as a 1/2 wave dipole is expected to be better than 1/4 wave whip since it is less susceptible to tilting and bobbing of the buoy. The recommended antenna, then, is a vertical center-fed 1/2 wave dipole. This antenna would be vertically polarized, have an omnidirectional pattern, and have a theoretical gain over isotropic of 2.54 dB. The antenna has certain mechanical features such as ease of erection and small length that make it attractive. There are, however, certain considerations that need further investigation such as cable loss, effect of tilt, and effect of wave shadowing.

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APPENDIX

APPENDIX

COMPARISON OF MODULATION TECHNIQUES

I. INTRODUCTION

The modulation technique used for the tactical AWS is very dependent on the choice of the carrier frequency. Since this application is for line of sight, a frequency in the VHF range is optimum. The selection of a modulation scheme at this frequency is made by first narrowing the field with preliminary study to an FM/FM or a PCM/FM system. These two systems will be compared on a basis of accuracy, bandwidth, signal to noise conversion, energy requirements, complexity, and cost.

First, a brief summary of how each system operates. In an FM/FM system, each quantity to be measured is converted by a transducer into an equivalent electrical signal. Each electrical signal, in turn, modulates a separate subcarrier oscillator. These signals modulate the subcarrier oscillator by varying the output frequency. The output voltages of all the subcarriers are combined and give in effect a complex or video signal. This complex signal is applied as a modulation signal to the FM transmitter, and the signal is transmitted. The r-f signal is recovered by the receiver which converts the r-f signal by detection back to the complex signal. Bandpass filters separate the complex signal into individual subcarrier signals. The filtered signals are applied to frequency discriminators which produce a data voltage output. All the data channels can be monitored simultaneously on strip charts or other data reduction equipment and then converted into terms of the original quantity for analysis. See Figure B1.

In the pulse code modulation (PCM) system, each measured quantity is converted by a transducer into an electrical signal. The input signal is converted to an n bit digital word. The digital word is processed and then stored. In the PCM/FM system, a transmitter is frequency modulated

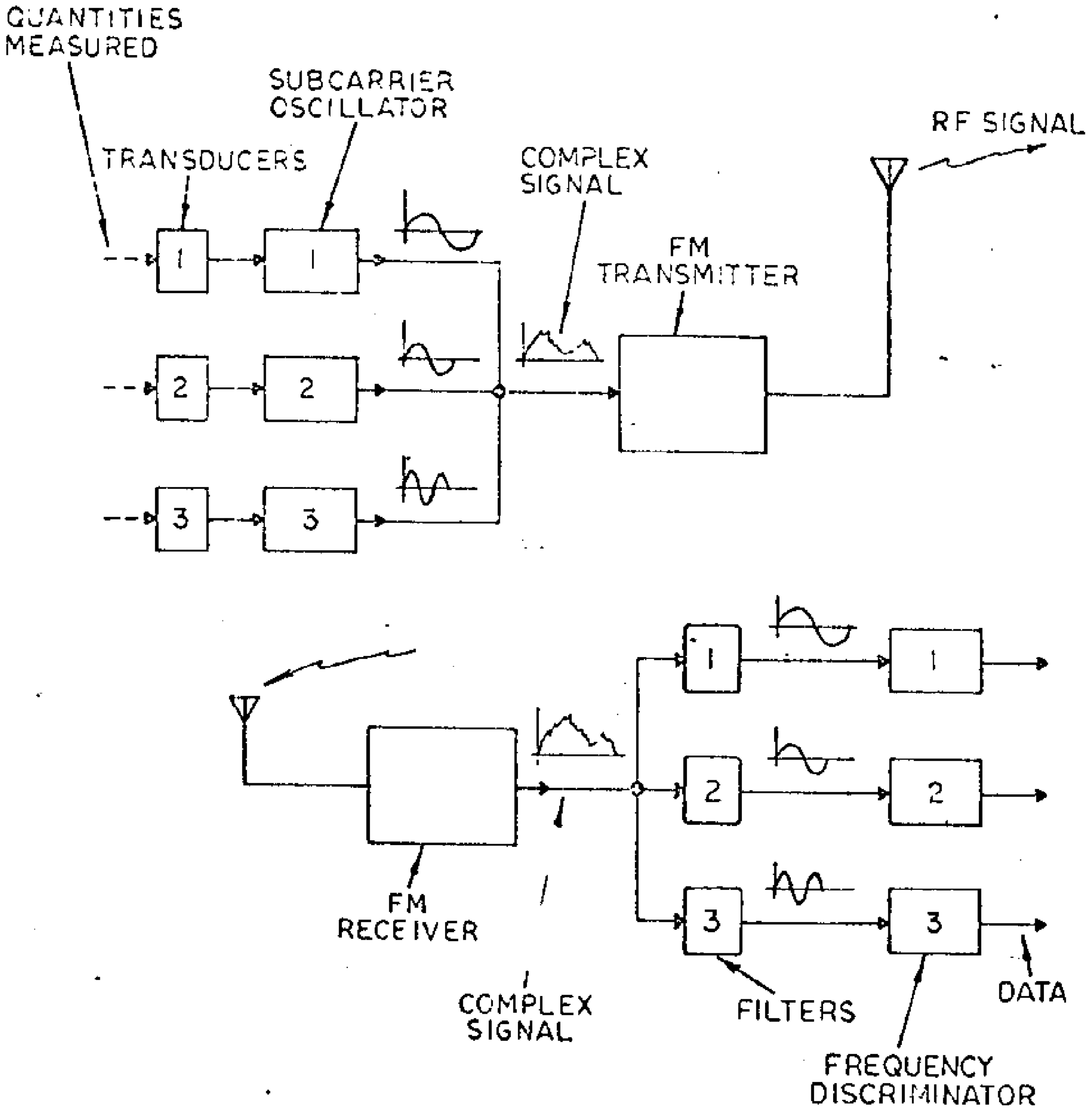

FIGURE B-1. FM/FM SYSTEM

by the n digit word as the data is serially shifted out of storage. This sequence is repeated for each measured quantity. The received r-f signal is detected by the receiver. The detected digital signal can be converted into data for analysis by use of conversion charts. See Figure B2.

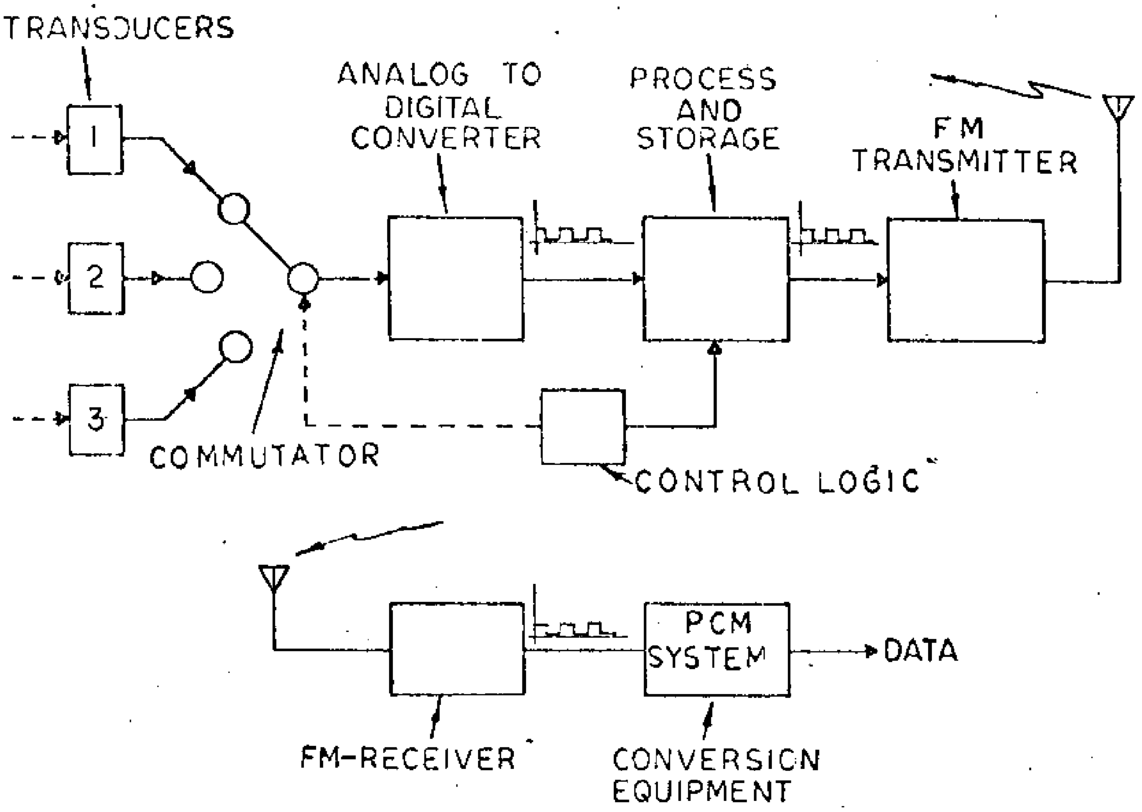

FIGURE B-2. PCM/FM SYSTEM

II. LIMITING ACCURACY

Considering the case where high signal levels and low noise levels are present in both an FM/FM and a PCM/FM system, a general evaluation and comparison of the limiting accuracy can be made. This accuracy involves only the modulation system and not the accuracy of the transducers.

The PCM/FM system will use an eight-digit word ($\varkappa = 8$) for the data value of each sensor. With low noise, the error in the output signal is due only to the quantization error. Quantization error, which is due to approximating an analog quantity with discrete levels, is equal to $1/2^{\varkappa}$ where $2^{\varkappa}$ is the number of discrete levels.

The quantized error $= \frac{1}{2^n} = \frac{1}{2^8} = \frac{1}{256} = 0.4\%$.

The limiting accuracy of the selected PCM system is due to quantized error and is 0.4% of the full scale input signal.

The accuracy of an FM/FM system is more indeterminate. Under the rigorous conditions of field service, system errors of less than 0.5% can be obtained[1]. However, with the use of modern solid state equipment, accuracies near 0.3% can be achieved. This comparison was made with little or no noise in the system and shows that both systems are limited to about the same accuracy. Further investigation will take into account noise in the system and its effect on performance.

III. EFFECT OF MODULATION TYPE ON TRANSMITTER POWER

Referring to the transmission loss equation of Section III.E and assuming a given range, frequency, lack of atmospheric and man-made noise, and non-interfering signals, the modulation system affects "b" the effective noise bandwidth, and "r" the minimum signal-to-noise ratio at the receiver that provides satisfactory reception.

The effective noise bandwidth is actually determined by the i-f bandwidth of the receiver. The r-f bandwidth needed by both systems depends on the input signal frequency response, the stability of the receiver and transmitter, the noise modulation of the transmitter, and the required accuracy of the data.

A. BASEBAND FREQUENCY

The input frequency response refers to the rate of change with respect to time of the quantity being measured. In the case of the weather

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[1] Report No. 9-638, Bendix Corporation, The Theory and Application of FM/FM Telemetry

station, the quantities being measured are water temperature, air temperature, barometric pressure, wind speed, and wind direction. With wind direction there is also an additional measurement for determining a heading reference such as with a compass. Actual data concerning maximum rates of change for all the parameters was not readily available, so in most cases estimates were made. The maximum rate of change of air and water temperature with respect to time is estimated at 2°C/min., or 0.033°C/sec. For barometric pressure a, a maximum rate of change of 10mb/hr. or 0.0278mb/sec. seems reasonable. The rate of change for wind speed is in the order of 4 knots/sec. Wind direction is expected to have the greatest rate of change; this maximum rate might be 30°/sec. The compass might change at a rate of 15°/sec. In general, all data will have low intelligence frequencies and will require small bandwidths. Each of the transducer analog signals must be low pass filtered to insure that frequency components much higher than those assumed here are not present.

In an FM/FM system, the maximum frequency response for each parameter determines the subcarrier channel used and, hence, the r-f bandwidth. Since all the measured parameters are low in frequency response, subcarrier channels 1-6 were selected. In Table B1, the estimated frequency response of each measured parameter, the selection of subcarrier channels and the subcarrier frequency response is shown. The calculated data frequency response is the highest frequency component that produces a 1% change in the data.

In the PCM/FM system, the frequency response determines the allowable sample aperture and required sampling rate. The rate at which the word is transmitted is controlled by how fast the word is shifted out of storage. This transmitted bit rate will determine the required r-f bandwidth.

B. DRIFT

The receiver and transmitter stability are determined by a crystal oscillator in the unit. Crystal oscillators, in general, have frequency stabilities in the order of ± 0.002%. With a carrier frequency of 170 Mcs, an additional bandwidth due to drift of the carrier of ± 3,400 cps is present ($2 \times 10^{-5} \times 1.70 \times 10^{8} = 3,400$ cps).

TABLE B-1

SUBCARRIER SELECTION

Measured Data		Subcarrier			
Parameter	Frequency Response	Channel	Frequency Range	Frequency Response	
				Nominal	Maximum
Water Temperature	0.05 cps	1	370 - 430 cps	6 cps	30 cps
Air Temperature	0.05 cps	2	518 - 602 cps	8 cps	42 cps
Barometric Pressure	0.02 cps	3	675 - 785 cps	11 cps	55 cps
Compass	4.2 cps	4	888 - 1,032 cps	14 cps	72 cps
Wind Speed	3.3 cps	5	1,202 - 1,398 cps	20 cps	98 cps
Wind Direction	8.4 cps	6	1,572 - 1,828 cps	25 cps	128 cps

C. NOISE MODULATION

Due to noise modulation of the transmitter, some minimum deviation of the r-f carrier is required. Empirical results indicate that a minimum of 3 Kcs r-f deviation is sufficient[2]. The 3 Kcs minimum is a lower limit and need not be considered when r-f deviations greater than 3 Kcs are to be used.

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[2] The Theory and Application of FM/FM Telemetry (see p. B-4)

D. SIGNAL-TO-NOISE RATIO

The r-f bandwidth using FM modulation is determined by knowing the modulation signal and the deviation ratio. There is, however, a relationship between r-f bandwidth and "r" input signal-to-noise ratio. This interdependence will lead to a trade-off between these factors, so considerations will now turn toward "r".

A comparison will be made of the overall system accuracy and signal-to-noise conversion for the analog and digital system. A PCM system using an eight binary digit data word, from Figure B-3, requires a S/N ratio of 20 db or greater at the threshold detector for an output signal-to-noise ratio of 48 db.[3] The output signal-to-noise ratio in this case refers to the recovered data word and its relationship to the measured analog value, so that 48 db represents the quantized error (48 db = 20 log 256). It should be mentioned, also, that for detector signal-to-noise ratios less than 20 db for PCM, there is a possibility of misreceived digits in the eight digit word due to impulse noise. The error is more properly stated as the probability of a misreceived digit in the n number of digits. An output signal-to-noise ratio below 48 db is a statistical mean of many received words and does not hold true for predicting a one word case. There are two important facts to note. First, increasing the detector signal-to-noise above 20 db does not increase the output signal-to-noise. Second, with detector signal-to-noise ratios less than 20 db, the noise may reverse a binary digit with a certain probability; and, if the word is just sent once and a digit is in error, the data is invalid. The PCM/FM system is basically made up of two subsystems. An FM receiver is used to demodulate the r-f signal. This demodulated signal in a binary format is then applied to a PCM detection system. It is this PCM detection system that requires an input S/N ratio of 20 db. However, the FM receiver also provides signal improvement. An FM system with a deviation ratio of D = 0.6, and with an input S/N of 10 db will provide a S/N ratio of 20 db at the PCM system. In general, the PCM/FM system requires an input S/N ratio of 10 db for

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[3] Nichols, M. H. and Rauch, L. L., Radio Telemetry (New York, 1956)

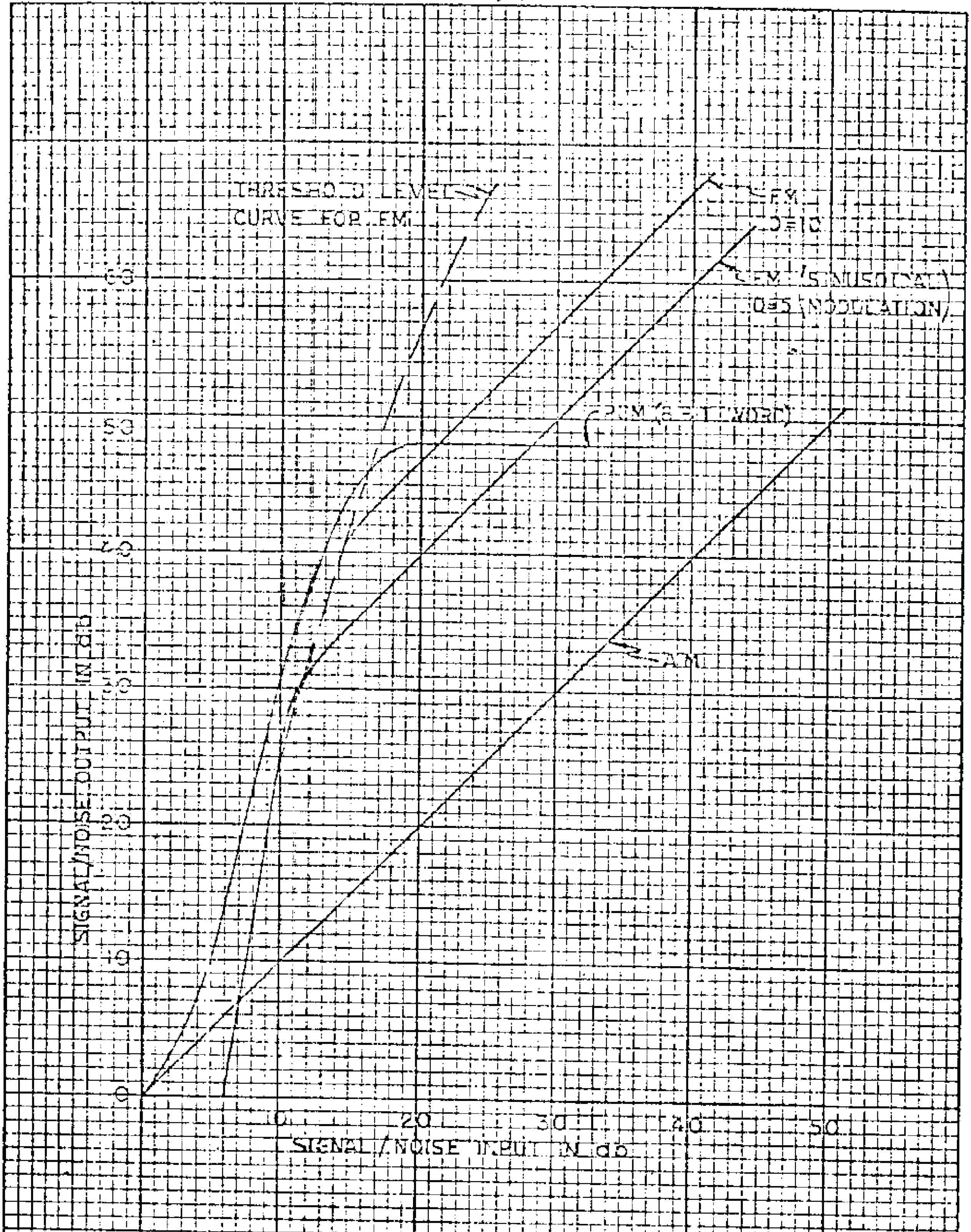

FIGURE B-3. $\left(\frac{S}{N}\right)$ CHARACTERISTICS satisfactory reception of the data. Since 10 db is also the threshold of the FM system, no additional improvement results from increasing the deviation ratio.

Since the S/N conversion in FM/FM is on a proportional basis and not a limited function, the needed input signal-to-noise ratio will be determined by the accuracy needed for the output data. This accuracy is shown in table B-2.

TABLE B-2

DATA AND ACCURACY

Parameter	Range	Accuracy	Accuracy % of Range
Water Temperature	-20°C to 50°C	± 1°C	± 1.4%
Air Temperature	-20°C to 50°C	± 1°C	± 1.4%
Barometric Pressure	900 - 1050 mb	± 1 mb	± 0.67%
Wind Speed	0 - 120 Knots	± 5 Knots	± 4.2%
Wind Direction	0 - 360°	± 10°	± 2.8%

The minimum input signal-to-noise ratio that provides satisfactory reception for an FM signal depends on the "detection threshold" and the required data accuracy. Fluctuation noise that has passed through a bandpass filter has the characteristics of a sine wave with amplitude and frequency modulation. When the filtered fluctuation noise exceeds that of the desired signal, the detector responds to noise. The "threshold" condition in FM detection refers to where there is just enough input signal voltage to overcome the noise, except for a certain occurrence of exceptionally high noise peaks.

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[4] Uglow, K., "Noise and Bandwidth in FM/FM Radio Telemetry," IRE Transaction on Telemetry and Remote Control, Vol TRC-3 pp 19-22, May 1957

Therefore, the FM/FM system should be operated above this threshold. This threshold will in effect be a lower limit on the minimum signal-to-noise input to the receiver. In Figure B-3 is shown the "threshold level curve."[5] An important factor to note concerning this curve is as the deviation ratio of the carrier signal is increased the threshold increases. The deviation ratio increases when a wider r-f bandwidth is used for the same modulation signal.

The output accuracy of the data in an FM/FM channel above threshold can be estimated by the following equation:[6]

$$\left(\frac{S}{N}\right)_d = \left(\frac{S}{N}\right)_c \left(\frac{3}{4}\right)^{\frac{1}{2}} \left[\frac{Bc}{Fud}\right]^{\frac{1}{2}} \frac{fdc}{fs} \times \frac{fds}{Fud} \qquad (1\text{-}1)$$

See Figure B-4 for explanation of system and symbols.

where

$\left(\frac{S}{N}\right)_d$ = discriminator output signal-to-noise voltage ratio

$\left(\frac{S}{N}\right)_c$ = receiver carrier-to-noise voltage ratio

B_c = carrier bandwidth (receiver i-f bandwidth)

Fud = subcarrier discriminator output filter

fs = subcarrier center frequency

fdc = carrier peak deviation due to the particular subcarrier of interest

fds = subcarrier peak deviation

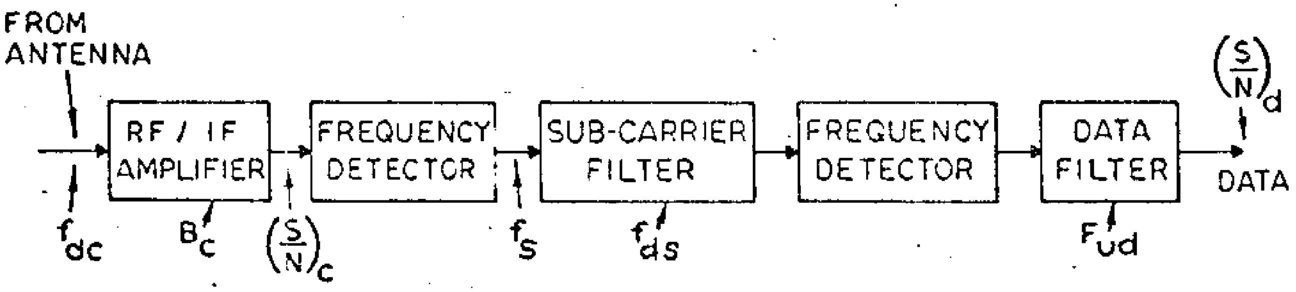

FIGURE B-4. ILLUSTRATION OF SYMBOLS

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[5] Floraman, E. F. and Tary, J. J., Required Signal-To-Noise Ratios, R.F. Signal Power, and Bandwidth for Multichannel Radio Communication System Technical Note 100, National Bureau of Standards

[6] Uglow

As mentioned previously, there is interdependency between r-f bandwidth and signal-to-noise ratio. For an analysis of this relationship, a $\left(\frac{S}{N}\right)_d$ in Equation (1-1) of 256 or 48 db (the same accuracy as an eight bit PCM system) was selected for subcarrier channel 6. The following equation parameters are determined by the subcarrier channels: let Fud = fds = 128 cps, fs = 1700 cps, and $fdc = \frac{Bc\ (1700)^{3/2}}{6{,}000}$. Substituting these values in Equation (1-1), we get:

$$\left(\frac{S}{N}\right)_c = \frac{1.51 \times 10^7}{B_c^{3/2}}$$

The transmitter power is determined by both 10 log Bc and 20 log $\left(\frac{S}{N}\right)_c$. In Figure B-5 is a plot of 10 log Bc, and 20 log $\left(\frac{S}{N}\right)_c$, and 10 log B_c + 20 log $\left(\frac{S}{N}\right)_c$. It is important to note that at $\left(\frac{S}{N}\right)_c$ = 10 db, the detection threshold is reached and $\left(\frac{S}{N}\right)_c$ should not be reduced below this point. The composite curve of 10 log B_c + $\left(\frac{S}{N}\right)_c$ shows a minimum at 30 Kcs. In general, minimum power would be required by having a 30 Kcs bandwidth with a $\left(\frac{S}{N}\right)_d$ of 256 and operation above the detection threshold. For satisfactory operation, an input signal-to-noise ratio of 10 db or more is required; however, a signal-to-noise ratio of 15 db or more is recommended.

E. BANDWIDTH

For PCM/FM, the modulating signal is a given frequency for a "zero" level and shifted in frequency for a "one" level. In PCM/FM, two detection thresholds exist, FM detection threshold and PCM threshold. Optimum performance is usually obtained by making the two thresholds occur at the same carrier signal strength. This occurs at a deviation ratio of D = 0.6. Assuming a 3.9 Kcs modulating frequency, Brf = ϕ (D) x fm, Brf = $\phi(0.6)$ x 3.9 Kcs $\cong$ 16 Kcs. The total bandwidth needed at the receiver, Bc, is the sum of Brf and B stability.

As determined before, B stability = ± 3,4000 cps, so

$$Bc = \pm\ 3{,}4000 \text{ cps} + 16{,}000 \text{ cps}$$

$$Bc = 22{,}800 \text{ cps}$$

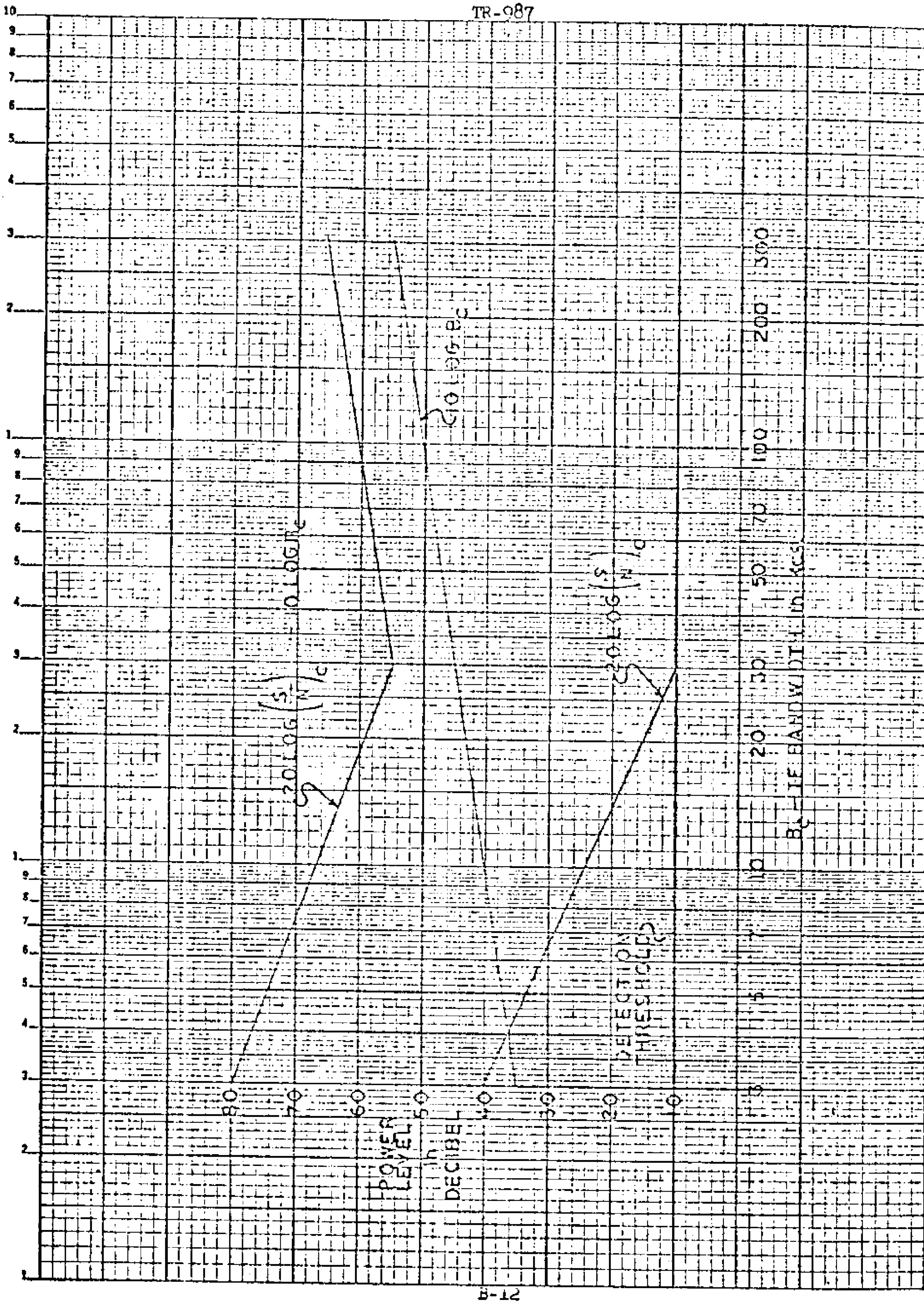

FIGURE B-5. OPTIMUM FREQUENCY SELECTION

This type of modulation is more correctly called PCM/FM/FM since a coded frequency modulated subcarrier is used to frequency-modulate the carrier.

In the FM/FM system with the predetermined subcarrier channels, a Brf = 30 Kcs seems near optimum so that now:

$$Bc = 30 \text{ Kcs} \pm 3.4 \text{ Kcs} = 36.8 \text{ Kcs}$$

With an r-f bandwidth of 30 Kcs and subcarrier channels 1-6, the fdc, carrier peak deviation due to the particular subcarrier of interest, can be calculated. The basic criterion used in this calculation is that equal subcarrier amplitude-to-noise ratios in all the channels at the detection threshold will be obtained by setting the r-f carrier deviation proportional to the 3/2 power of the subcarrier center frequency.

fdc = "conversion constant" x $(fs)^{3/2}$ and "conversion constant" = $\frac{Bc}{\Sigma\,(fs)^{3/2}}$.

This calculation is shown in Table B-4

TABLE B-4

R-F CARRIER DEVIATION

Sub-Carrier Frequency	$\left(\text{Sub-Carrier Frequency}\right)^{3/2}$	R-F Carrier Deviation $\left(\frac{30 \text{ Kcs}}{\Sigma\,(\;)^{3/2}}\right)\left(\frac{\text{Sub-Carrier}}{\text{Frequency}}\right)^{3/2}$
1 0.400 Kcs	0.2529×10^3	1.265 Kcs
2 0.560 Kcs	0.4190×10^3	2.09 Kcs
3 0.730 Kcs	0.6230×10^3	3.11 Kcs
4 0.960 Kcs	0.9406×10^3	4.72 Kcs
5 1.300 Kcs	1.482×10^3	7.31 Kcs
6 1.700 Kcs	2.268×10^3	11.31 Kcs
	$\Sigma\,(\;)^{3/2} = 5.855 \times 10^3$ $\approx 6 \times 10^3$	$\Sigma = 30$ Kcs

Due to noise modulation of the transmitter, a minimum deviation of the r-f carrier is needed. Empirical results indicate that a minimum of 3 Kcs per subcarrier of r-f deviation is required. For a practical 3/2 power taper, the deviation of the lower channels is raised to 3 Kcs and the r-f deviation of the higher frequencies is slightly reduced to make up for the change.[7] The revised carrier deviations are shown in Table B-5.

TABLE B-5

R-F CARRIER DEVIATION - CORRECTED

Channel	Sub-Carrier Frequency	R-F Carrier Deviation
1	0.400 Kcs	3 Kcs
2	0.560 Kcs	3 Kcs
3	0.730 Kcs	3.11 Kcs
4	0.960 Kcs	4.28 Kcs
5	1.300 Kcs	6.31 Kcs
6	1.700 Kcs	10.0 Kcs
		Σ = 30 Kcs

F. CONCLUSION

A general comparison on the basis of input signal-to-noise ratio required for satisfactory reception shows that for both the FM/FM and PCM/FM system, an input $\left(\frac{S}{N}\right)_e$ = 10 db will be needed. The minimum r-f bandwidth is considerably greater for the FM/FM case, however.

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[7] The Theory and Application of FM/FM Telemetry (see p. B-4)

IV. ENERGY CONSIDERATIONS

Since the tactical AWS is battery powered, the overall energy required to convey the sensor data is of importance. The overall energy conversion of the PCM/FM system and FM/FM system will be compared on the basis of one complete data transmission. The energy requirements are determined by the "time on" for readout, DC to r-f conversion efficiency, and the r-f power required for satisfactory reception of the data. There are five meteorological parameters to be measured; this means a readout of six sensors, including a compass for heading reference. If the transmitter and receiver are crystal-controlled, then minimum tuning, if any, will be needed. Readout time depends on the use of parallel or serial readout. In PCM the six sensors would be read out serially; i.e., one sensor data will be transmitted and then the next and so forth. However, FM/FM is parallel readout; i.e., all sensor data is transmitted at once. Because of parallel readout, the FM/FM could transmit all the required data in one burst in the time required to serially read one sensor. There is also the difference between sampled data (PCM) and continuous data (FM/FM) in long time readout. In some cases the continuous monitoring might be more advantageous.

The DC to r-f conversion efficiency of the two systems are approximately the same since both are frequency modulation.

The modulation technique as stated before affects r-f power in terms of bandwidth and $\left(\frac{S}{N}\right)_c$. For FM/FM a Bc of 36.8 Kcs and a $\left(\frac{S}{N}\right)_c$ of 10 db is needed. In PCM/FM a Bc of 22.8 Kcs and a $\left(\frac{S}{N}\right)_c$ of 10 db is needed.

r-f power $\propto$ Bc x $\left(\frac{S}{N}\right)_c$

so r-f power (FM/FM) $\propto 36.8 \times 10^3 \times 3.2 = 117.5 \times 10^3$

r-f power (PCM) $\propto 22.8 \times 10^3 \times 3.2 = 72.8 \times 10^3$

Energy is power x time

Energy (FM/FM) $\propto$ readout time x Pr-f

$$\frac{\text{Energy (FM/FM)}}{\text{Energy (PCM/FM)}} = \frac{1 \times 117.5 \times 10^3}{6 \times 72.8 \times 10^3} = 0.271$$

The PCM system will use about four times as much battery energy for a readout. This, however, is very dependent on the readout time of the FM/FM system. If the readout time is equal to PCM, then the PCM system uses less battery energy. It should also be noted that readout times of perhaps 20 seconds or more are desirable for direction finding purposes.

V. ADDITIONAL CONSIDERATIONS

It might be appropriate at this time to consider practical limitations. First, the tactical AWS by its very nature is air-droppable and will undergo large shock stress upon opening of the descent device and water entry. Any "moving part" components in the system will be extremely vulnerable to this shock. Devices such as stepping switches, relays, or vacuum tubes used in the system might result in failure. In the PCM system, a commutator is required to sequentially sample the different sensors. A solid state type of commutator such as a MOS-FET commutator should be used.

Another factor involved is a cost factor or cost effectiveness. The subcarrier oscillators, composite amplifier, voltage regulator, etc., for use in the FM/FM system are standardized equipment which reduces cost. The PCM system involves additional logic and operations for data readout which would involve a higher cost of development.

A third consideration is such effects as crosstalk and doppler shift. When more than one subcarrier channel is multiplexed into a single data link channel, another type of distortion or noise may be generated. This crosstalk noise might occur in the FM/FM system. If the data link is operated linearly, crosstalk will not occur[8]. If the link is nonlinear, then the effect of this nonlinearity is to generate other frequencies which are combinations of the subcarrier channels. In the case of six subcarriers, near linear operation is expected; however, testing of the system will be needed for exact determination and reduction of crosstalk to an acceptable level.

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[8] Nichols, M. H. and Rauch, L. L., Radio Telemetry (New York 1956)

When an emitting source is moving relative to an observer, the frequency observed is different for the emitting source. The magnitude and and direction of this change, doppler effect, depends on the relative velocity between the source and observer. In the case of the two considered modulation systems, doppler shift due to the velocity of the interrogating aircraft does not affect the accuracy but will require AFC or a slightly wider bandwidth. For an aircraft with a velocity of 400 knots toward the buoy and a carrier frequency of 170 Mcs, the doppler shift is only 120 cps. For this system, doppler shift is not seen as a problem.

One remaining problem area is worthy of mention. In an FM/FM system, the sensor outputs generally modulate the subcarrier oscillator during the time that the transmitter is on. Care must be exercised during the design to eliminate any induced RFI by shielding and low pass filtering. Another way to eliminate this problem is to record on tape the composite waveform of all the subcarriers and play it back into the transmitter. This method also allows storage of data, which would give a time history of the weather on each interrogation. This would reduce the number of interrogations required. However, the added cost of this technique may not be warranted.

VI. COMPATIBILITY WITH AN/ARR-52

The final and most important consideration is the compatibility of the modulation system with the equipment in the aircraft. In more specific terms, the Radio Receiver AN/ARR-52(V) will be investigated for compatibility. The approach for this investigation will be to consider the characteristics of the receiver, and then consider a narrow r-f bandwidth with the receiver i-f bandwidth. Last, a matched wide r-f bandwidth and receiver i-f bandwidth will be reviewed.

The Radio Receiving Set AN/ARR-52(V) is basically a wide band FM receiver with crystal controlled preset channels. The basic characteristics of the receiver are presented in Table B-6.

TABLE B-6

RECEIVER CHARACTERISTICS

Frequency Stability	± 30 Kcs
i-f Bandwidth	≈ 200 Kcs
Audio Response "Standard Audio Output"	200 to 5,000 cps @ 2 db
"High Audio Output"	10 to 3,000 cps @ 2 db

The audio output of the receiver can then be recorded by the AN/AQH-1 tape recorder system.

By using a receiver with a 200 Kcs i-f bandwidth, approximately 8 db more transmitted power is needed over a 30 Kcs system to maintain the same receiver input $\left(\frac{S}{N}\right)_c$. This 8 db increase is due to the increase of available thermal noise power in the wider bandwidth of the i-f amplifier.

Considerations might now be turned toward how the receiver output $\left(\frac{S}{N}\right)_d$ is affected by the ratio of i-f bandwidth to r-f bandwidth. As given previously, $\left(\frac{S}{N}\right)_d$ for an FM/FM system can be estimated by:

$$\left(\frac{S}{N}\right)_d = \left(\frac{S}{N}\right)_c \left(\frac{3}{4}\right)^{\frac{1}{2}} \left[\frac{Bc}{Fud}\right]^{\frac{1}{2}} \frac{fdc}{fs} \times \frac{fds}{Fud}$$

The first case of comparison of $\left(\frac{S}{N}\right)_d$ is a system with a transmitted r-f bandwidth of 30 Kcs and a receiver i-f bandwidth of 200 Kcs compared against a system where $B_{RF} = B_{IF} = 30$ Kcs.

CASE I

System A: $B_{RF} = 30$ Kcs, $Bc = 30$ Kcs

System B: $B_{RF} = 30$ Kcs, $Bc = 200$ Kcs

Since the RF bandwidth is the same in both systems, the same modulation parameters will be assumed. So that:

$$Fud_A = Fud_B$$

$$fds_A = fds_B$$

$$fs_A = fs_B$$

$$fdc_A = fdc_B$$

then:

$$\frac{\left(\frac{S}{N}\right)_{d_A}}{\left(\frac{S}{N}\right)_{d_B}} = \frac{\left(\frac{S}{N}\right)_{c_A}\left[30\ \text{Kcs}\right]^{\frac{1}{2}}}{\left(\frac{S}{N}\right)_{c_B}\left[200\ \text{Kcs}\right]^{\frac{1}{2}}}$$

Now by setting the receiver output $\left(\frac{S}{N}\right)_d$ equal for both systems, the above equation can be solved in terms of the required carrier $\left(\frac{S}{N}\right)_c$.

$$\frac{\left(\frac{S}{N}\right)_{c_A}}{\left(\frac{S}{N}\right)_{c_B}} = \frac{1}{\left(\frac{3}{20}\right)^{\frac{1}{2}}} = 2.58$$

This means that System A required 2.58 times the carrier $\frac{S}{N}$ voltage ratio of System B for the same receiver output $\frac{S}{N}$ voltage ratio. This is equal to 20 log 2.58 or 8.2 db higher $\frac{S}{N}$ ratio required for System A. But System A, having a narrow i-f bandwidth, also has 8.2 db less available noise power. The net result is that both systems will have approximately the same accuracy for the same transmitter power. The shortcoming of System B is that it reaches the detector threshold at a shorter range (equivalent to 8.2 db less allowable transmission loss) than System A.

The second comparison of $\left(\frac{S}{N}\right)_c$ is with a system with $B_{RF} = B_{IF} = 200$ Kcs against a system with $B_{RF} = B_{IF} = 30$ Kcs.

CASE II

System A - $B_{RF} = 30$ Kcs, $B_{IF} = 30$ Kcs

System C - $B_{RF} = 200$ Kcs. $B_{IF} = 200$ Kcs

In this comparison both systems will be assumed to have the same subcarrier channels so that now:

$$\begin{aligned} Fud_A &= Fud_C \\ fds_A &= fds_C \\ fs_A &= fs_C \\ fdc_C &\cong fdc_A \cdot \left(\frac{200 \text{ Kcs}}{30 \text{ Kcs}} \right) \\ \text{or } fdc_A &\cong \frac{1}{6.67} fdc_C \end{aligned}$$

then:

$$\frac{\left(\frac{S}{N}\right)_d \text{ for System A}}{\left(\frac{S}{N}\right)_d \text{ for System C}} = \frac{\left(\frac{S}{N}\right)_{c_A} \times \left[Bc\right]^{\frac{1}{2}} \times 1}{\left(\frac{S}{N}\right)_{c_C} \times \left[Bc\right]^{\frac{1}{2}} \times 6.67}$$

Also assume that $\left(\frac{S}{N}\right)_{d_A} = \left(\frac{S}{N}\right)_{d_C}$

$$1 = \frac{\left(\frac{S}{N}\right)_{c_A} \times \left[30 \text{ Kcs}\right]^{\frac{1}{2}} \times 1}{\left(\frac{S}{N}\right)_{c_C} \times \left[200 \text{ Kcs}\right]^{\frac{1}{2}} \times 6.67}$$

$$\left(\frac{S}{N}\right)_c \text{ for 200 Kcs} = .058 \left(\frac{S}{N}\right)_c \text{ for 30 Kcs}$$

$$\text{or } \left(\frac{S}{N}\right)_c \text{ for 30 Kcs} = 17.2 \left(\frac{S}{N}\right)_c \text{ for 200 Kcs}$$

$$\frac{\left(\frac{S}{N}\right)_c \text{ for 30 Kcs system}}{\left(\frac{S}{N}\right)_c \text{ for 200 Kcs system}} = 17.2$$

$$20 \log 17.2 = 24.7 \text{ db}$$

It has been shown that the matched wide band System (C) had 24.7 db $\frac{S}{N}$ improvement over the matched narrow band System (A). The shortcoming once again is that System C will have a shorter range (8.2 db less allowable transmission loss) due to the detector threshold affect. Also, for the same transmitter power, System C has in reality only 16.5 db improvement since 8.2 db more noise is present.

In both Case I and II, System B and System C require less carrier signal-to-noise at the receiver; however, there is a definite limitation as to how low this ratio can go. This lower limitation is the detection threshold, since at this threshold the detector is responding to peak noise signals. The effect then of the increased i-f bandwidth is to increase the $\left(\frac{S}{N}\right)_d$. This signal improvement increases the accuracy of the r-f data link. However, the accuracy of the output data is also limited by the transducers and subcarrier oscillators. The main point of interest is that the use of the wider band FM cannot reduce the required transmitter power. A total of 8.2 db more transmitted power is needed when using a 200 Kcs bandwidth instead of a 30 Kcs bandwidth for the same transmission range.

The receiver under consideration has the audio response shown in Table B-6. This audio response limits the use of certain subcarrier channels. The subcarrier channels above 5 Kcs should not be used.

If PCM/FM/FM were used instead of FM/FM, the preceding bandwidth comparisons are still valid, assuming that the digitized data frequency modulates a single subcarrier.

In conclusion, it has been shown that the AN/ARR-52 Receiver, while satisfactory, is not extremely well suited for receiving the weather station because of its wide bandwidth. Either the analog or digital FM system will function equally well with the receiver.