RANGE SAFETY RECEIVER-DECODER FOR SPACE SHUTTLE LAUNCH VEHICLE

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ABSTRACT

Flight Termination Sub-Systems for range safety purposes are a part of all spacecraft launch vehicles. The Command Receiver and Decoder portion of this sub-system receives the rf up-link signal and initiates the flight termination action. For launch vehicles for unmanned spacecraft, the range safety up-link command signal is composed of selected IRIG audio tones, in a specified sequence, frequency modulated on an rf carrier. For the Space Shuttle launches, a more sophisticated high-alphabet modulation technique is used. This provides for a better probability against an undesired output caused by interfering signals.

The Shuttle system uses a complex command modulation format composed of various audio tones frequency modulated on the standard UHF carrier. The characters in the command word are made up of two simultaneously transmitted tones selected from seven possible frequencies. These seven tones, taken two at a time, provide an alphabet of twenty-one different characters from which a command word is formed. The transmitted sequence of characters is selectable from mission to mission. Approximately 10^{12} possible code combinations exist for any one mission.

For the Space Shuttle launches, the range safety Command Receiver-Decoders will be used on the Solid Rocket Boosters and the External Tank portions of the complex launch vehicle. The receiver section of these units is a single superheterodyne design fixed tuned to the proper rf center frequency at the time of manufacture. The decoder section utilizes a microprocessor to effect the decoding function. The decoder is “programmed” prior to flight to recognize only the code of the mission. In addition, the microprocessor is used to accomplish the audio tone demodulation using a Fast Fourier Transform (FFT) algorithm. Solid state output switches provide the decoder output voltages to the flight termination destruct mechanism.

INTRODUCTION

For the purpose of safety, of both property and personnel, all spacecraft launch vehicles are required to contain a flight termination subsystem. This is used when an abnormal flight profile occurs during launch and the vehicle's path would take it outside the safe limits of the range. When necessary as indicated by the various monitoring and display equipment available to him, the Range Safety Officer will initiate the flight termination command. In most vehicle subsystems, this will cause rocket engine shut-down, disruption of the vehicle air-foil, disperse the fuel, or some combination of action that will terminate the flight and control the location of the impact area of the resulting debris.

Through the efforts of various organizations such as the Range Commanders Council, the Range Safety ad hoc Committee, and others, a degree of range safety standardization has been obtained through the years. The command up-link for space launch vehicles uses an rf carrier in the UHF Band of 400 to 500 MHz. Typically, IRIG standard audio tone frequencies are frequency modulated on the rf carrier. In most cases, three tones are transmitted in a selected sequence to initiate the flight termination.

For manned space flight launches, a variation in this technique is utilized. The standard UHF/FM link is used, but a high-alphabet modulation technique, as developed for the Saturn/Apollo Program, is used. This modulation technique provides at least ten orders of magnitude better probability against an undesired output caused by interfering signals than the standard range safety modulation method.

In the early 1960's, when manned space flight was becoming a reality, NASA became particularly concerned with the flight termination system used for range safety. They felt that with the normal range safety system, the possibility of an unwanted destruct event was sufficiently great - and the results of an unwanted destruct would be sufficiently devastating to the manned space flight program - that a different approach to range safety was warranted for manned flight. NASA desired a system which would provide a means of protection or a "secureness" against unwanted destruction caused by either intentional or unintentional interfering signals. In general, if a range safety system can be devised that would reduce the probability of an unwanted output caused by some intelligent source who is purposely trying to destroy a good launch, then the probability of an unwanted output caused accidentally is even far less likely to occur. Therefore, any method that would make it more difficult for an "unfriendly" source to effect a destruct would increase the security of the system.

After much study, the Digital Range Safety Command System was implemented for the Saturn/Apollo Program. And, this system, with more modern state-of-the-art hardware, will be used for the Space Shuttle Program.

The System uses a complex command format made up of various audio tones that frequency modulate the standard UHF carrier. The characters in the command word are made up of two simultaneously transmitted audio tones selected from seven possible tones. The tones are in the lower portion of the IRIG frequencies, and all are harmonically related to 1050 Hz. All seven tones are contained within an octave to prevent harmonic interference. Figure 1 illustrates the linearly-spaced high-alphabet tone frequencies compared to the logarithmically-spaced IRIG range safety channels. These seven tones--taken two at a time--provide an alphabet of 21 different characters from which to form a command word.

Illustrated in Figure 2 is a typical message waveform and format. The first character is made up to tones 1 and 2; the second character is tones 1 and 3; and so on. Looking at the modulation waveform, it is evident that each character is separated by a period of dead-time. The character duration is 6-2/3 milliseconds with a 1.9 millisecond dead time between characters.

The message consists of two words: an address word and a command word. The address is the first nine characters. This address word uses 9 of the 21 possible characters available, and selection of these nine characters is changed for each mission. The use of 9 characters out of the possible 21 provides 1.067×10^{11} possible code combinations for any one mission.

The command word consists of the last two characters in the message. Since there are 21 character-coding arrangements available for the 10th position and 20 available for the 11th position, that gives the possibility of a total of 420 command words.

Figure 3 illustrates five commands and tone frequencies used for the Saturn/Apollo. All missions used the same command code. However, the address word was changed for each mission. Address selection or programming the flight hardware to recognize the correct code was accomplished by hardware--a code plug.

SPACE SHUTTLE HARDWARE

For Space Shuttle launches, range safety flight termination devices are used on the Solid Rocket Boosters and on the External Tank portion of the complex launch vehicle. If the destruct command were to be issued, the Orbiter is set free from the other elements of the launch vehicle and manully flown back to earth by the astronauts. When the Orbiter is clear, the Solid Rocket Boosters and the External Tank are destroyed.

The Command Receiver-Decoder portion of the Space Shuttle flight termination system is shown in Figure 4. Each of the two Solid Rocket Boosters will have two of these units mounted in a redundant configuration. A single receiver-decoder unit will be used on the External Tank. As you know, it is planned to recover the Solid Rocket Boosters after each launch. The four range safety receiver-decoders on these boosters will be refurbished and used again. The External Tank and its unit are not recovered and are lost after each launch.

	IRIG	HIGH ALPHABET
1.	7.50 kHz	7.35 kHz
2.	8.46 kHz	8.40 kHz
3.	9.54 kHz	9.45 kHz
4.	10.76 kHz	10.50 kHz
5.	12.14 kHz	11.55 kHz
6.	13.70 kHz	12.60 kHz
7.	15.45 kHz	13.65 kHz

Figure 1. Baseband Tone Frequencies

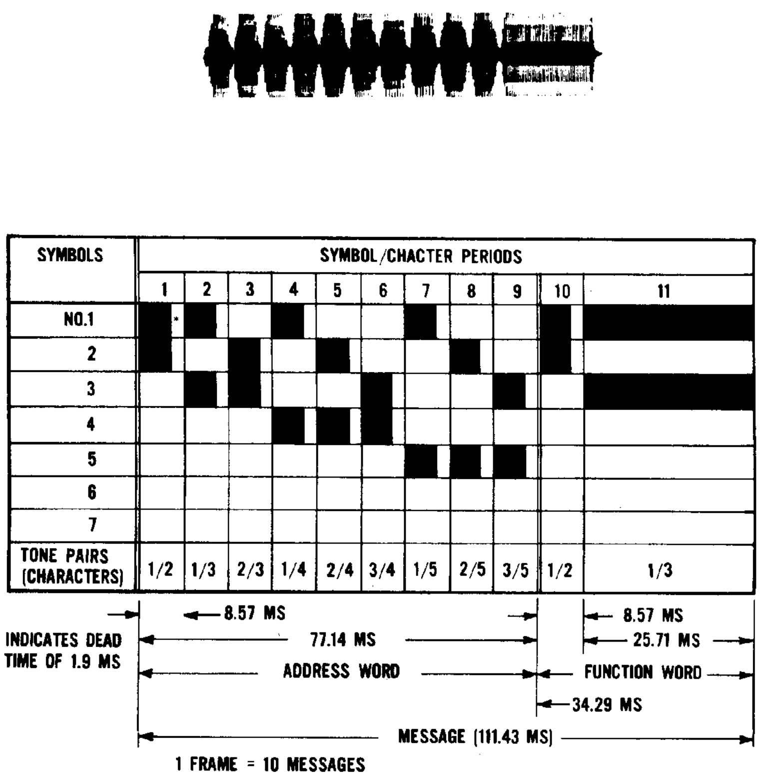

Figure 2. Typical Message Waveform and Foremat

COMMAND	10th. CHARACTER TONES	11th. CHARACTER TONES
1. DESTRUCT (PROPELLANT DISPERSION)	1 AND 2	1 AND 3
2. ARM/FUEL CUTOFF (CHARGING OF THE EBW FIRING UNIT AND THRUST TERMINATION)	2 AND 3	2 AND 4
3. MSCO/ASCO (SATURN SPARE NO. 1)	4 AND 5	4 AND 6
4. SPARE (NO.2)	3 AND 4)	3 AND 5
5. SAFE	5 AND 6	5 AND 7

Figure 3. Command Encoding Scheme

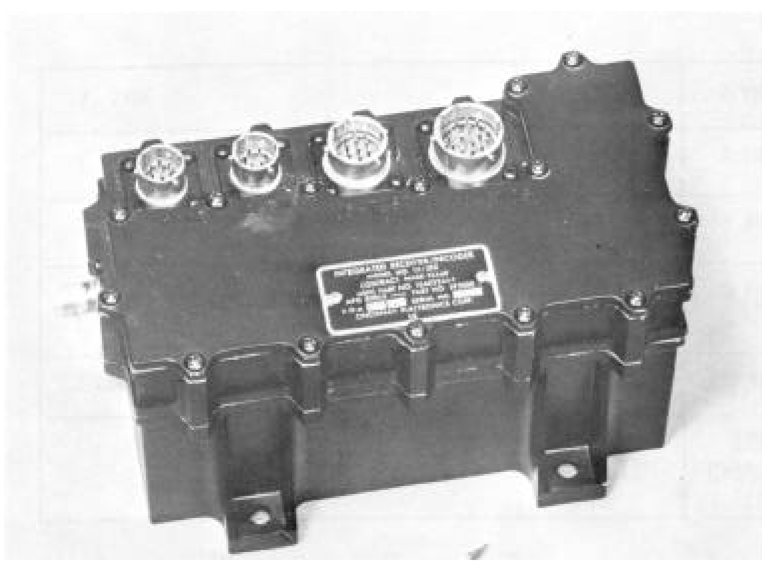

Figure 4. Command Receiver-Decoder

The range safety receiver-decoder for the Space Shuttle vehicle is now in production at Cincinnati Electronics Corporation under contract with NASA, Marshall Space Flight Center, Huntsville, Alabama. The equipment design utilizes "Hi-Rel" piece parts, and is designed such that no single point failure can cause an unwanted output. In addition, this failsafe concept is implemented in the software/fimware realm of the design.

The qualification tests conducted on the unit consisted of the various qual level environments anticipated during a typical flight profile of the Solid Rocket Booster. One cycle of environmental tests consisted of those environments simulating lift-off, boost phase, separation, re-entry, and water impact. This cycle of tests was repeated several times to establish confidence in the re-use concept.

Receiver Section

The receiver section is located in the cover assembly of the unit, and the decoder section is located within the main body of the unit. The receiver is a single superheterodyne design with a 10.7 MHz IF. The input signal is routed through the rf connector into a tuneable preselector which consists of four high Q coaxial resonators. Three stages of amplification using Field Effect Transistors are designed in the preselector. These provide about 20 dB net gain with a 4 MHz passband. Referring to Figure 5, the selected carrier frequency is coupled into a balanced hot-carrier diode mixer, where it is mixed with a local oscillator signal at a frequency of 10.7 MHz above the carrier frequency. After a stage of amplification, the signal is routed through a nine-pole crystal filter which sets the specified 180 kHz receiver selectivity. From the crystal filter, the signal is amplified and processed through FM limiting into a quadrature FM detector. The IF subsystem provides detected audio at 5 millivolts per kHz deviation. The audio signal is amplified and presented to the decoder section.

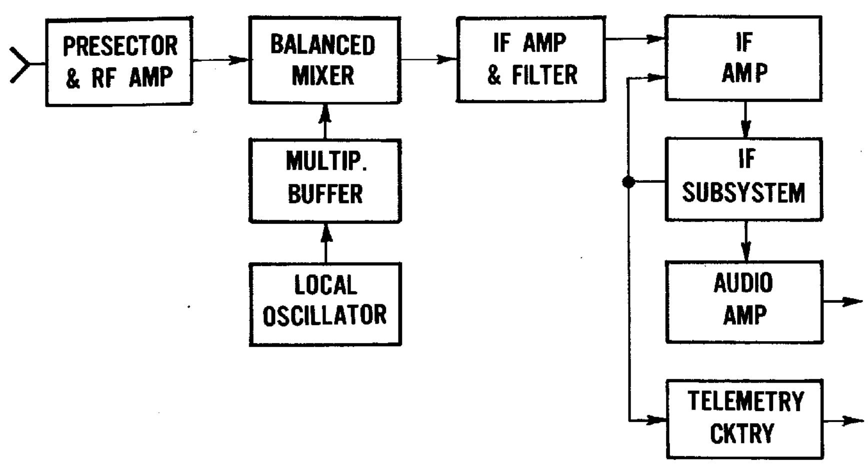

Figure 5. Block Diagram Receiver Section

Decoder Section

Until recently, it has been impractical to implement a digital filter or sampling technique as an audio frequency detector in a space launch environment. With the advent of microprocessor devices, however, digital filters for space launch vehicles and missile application are not only practical, but even desirable in some cases.

A microprocessor can be used as part of the tone detection function by sampling the composite waveform. Of the various microprocessor "digital filtering" techniques, a Fast Fourier Transform algorithm is most appropriate due to the complex waveform. and time duration of the intelligence. Mathematically, a Fourier Analysis can be used on any complex periodic function to determine the magnitudes and frequencies of the constituent parts of the function.

In the Space Shuttle Range Safety Receiver-Decoder design, the Fast Fourier Transform (FFT) tone detection is implemented using a Microprocessor device (µP) as the Central Processing Unit (CPU); a Read Only Memory Device (ROM); Random Access Memory elements (RAM); Direct Memory Access circuits (DMA); Analog-to-Digital Converter (A/D); appropriate Input/Output devices (I/O); and control circuits. Figure 6 is a block diagram of the decoder section.

The high-alphabet range-safety audio signal as recovered by the receiver is presented to an A/D Converter where the signal is sampled. Each sample results in a 6-bit binary word which represents the magnitude of the input signal at that time. This binary word is put into Random Access Memory (RAM) via the DMA. The binary samples are initially processed in groups of 32. For convenience, we define this 32 sample period as a "sub-character" time period. On close inspection of this sub-character time period, it is evident that each of the audio tone frequencies used in the high-alphabet go through an integral number of cycles in this 32 sample period. The 7.35 kHz tone goes through 7 cycles, the 8.40 kHz tone has 8 cycles, the 9.45 kHz tone has 9 cycles, and so on. In addition, there are seven sub-character time periods in the full character time of 6-2/3 milliseconds.

Like samples in each of the seven sub-characters are algebraically summed. Samples 1 in each of the seven sub-characters are summed together, samples 2 in each subcharacter are summed together, and so on through to samples 32 which are summed together. Note that for any of the seven tones, like samples in each sub-character will occur at the same point on the sine-wave signal. At the end of the full character period, when 32 samples have been taken in each of the seven sub-characters and summed, the data is then processed through the FET.

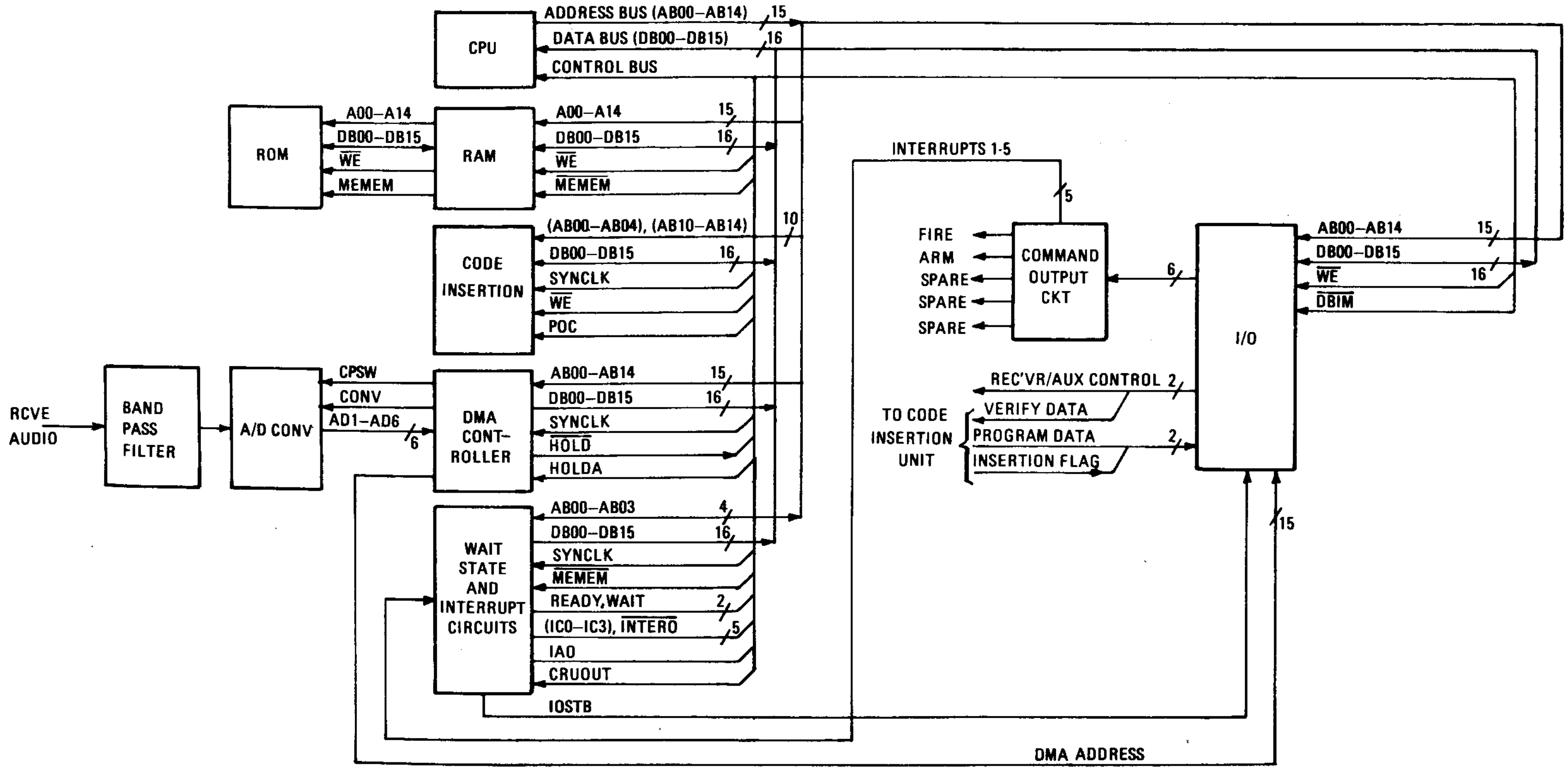

Figure 6. Decoder Block Diagram

The summed values of the 32 samples of data are processed using a Fast Fourier Transform algorithm. The sampled data is manipulated by adding and subtracting values of the various samples in such a way that results in determination of the relative magnitudes of each of 7 tones present in that character. In-phase, and quadrature components of each of the seven tones are determined, and the square root of the sum of the squares of these components are calculated. This results in the absolute values of each of the tones that are present in that character.

Figure 7 illustrates the FFT characteristics. The numbers on the left side of the figure represnet the 32 summed data samples. Solid lines represent an addition function, dashed lines represent subtraction, and the circled numbers represent a multiplication function. The numbers on the right represent the resulting in-phase and quadrature values of the seven tones. This figure illustrates the calculations required to arrive at the values of the tones in that character period. For example, the in-phase component of tone 8 (8I) is determined by manipulating the data of the sample points as below:

[(1 + 17) + (9 + 25)] + [(5 + 21) + (13 + 29)]

- [(3 + 19) + (11 + 27)] + [(7 + 23) + (15 + 31)]

The quadrature component (8Q) is:

[(2 + 18) + (10 + 26)] + [(6 + 22) + (14 + 30)]

- [(4 + 20) + (12 + 28)] + [(8 + 24) + (16 + 32)]

The calculation of the square root of the sum of the square of these terms represents the value of the tone 8 frequency that is present in this character. In similar manner, the magnitudes of each of the seven tones are calculated and stored in memory.

The microprocessor goes through perhaps some 300 calculations to determine the magnitude of each tone in each character. It takes approximately 600 microseconds to perform these calculations.

The data representing the magnitudes of the seven tones are then examined to determine if a valid character was present. A fixed threshold is used to reject signals too small to be valid; that is, the magnitude data for two of the tones must be greater than some fixed minimum value. A variable threshold is used to reject results that were likely the result of noise; that is, magnitude of two of the tones must be greater than some percentage of the magnitude of the other five tones.

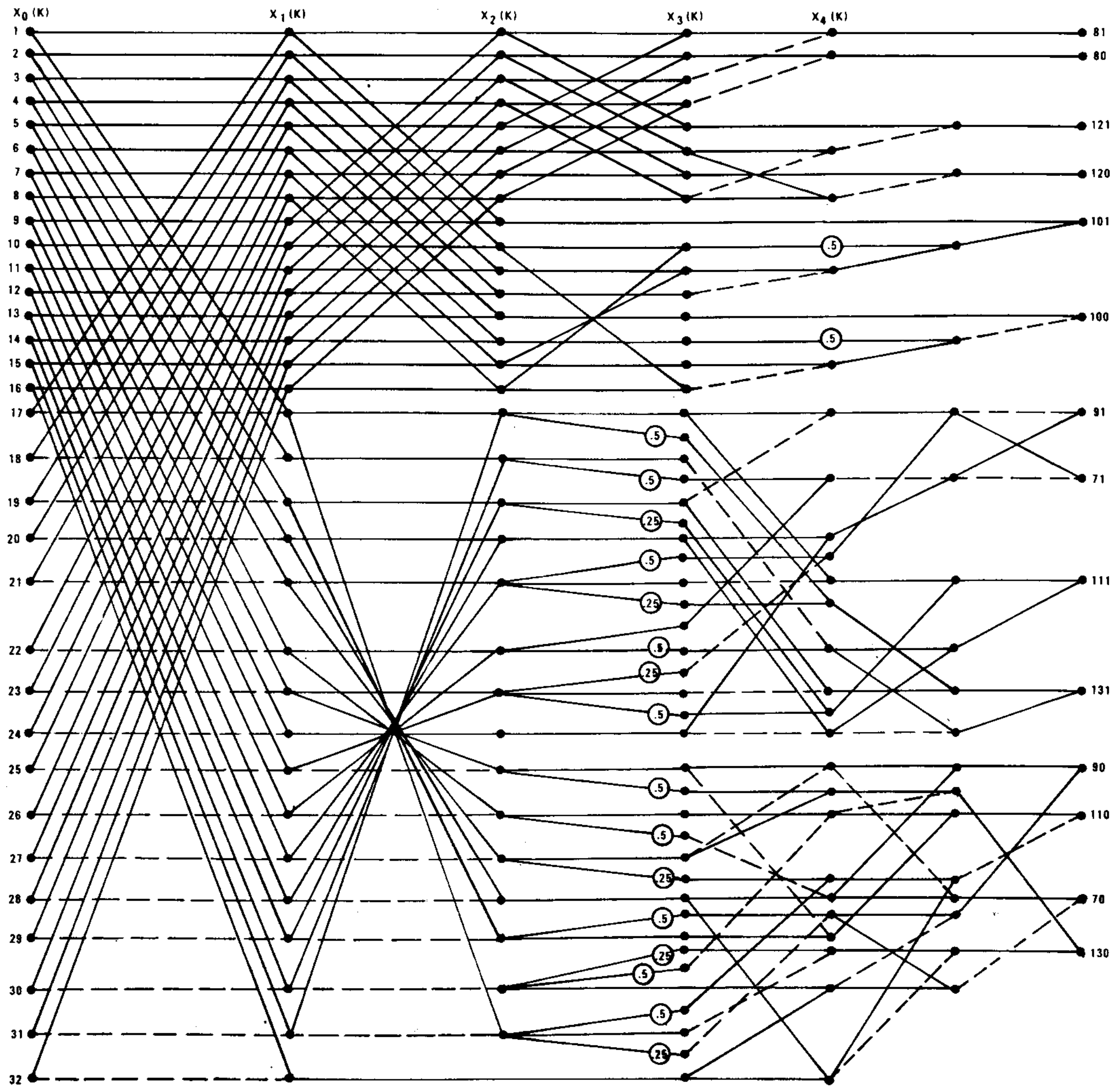

Figure 7. FFT Characteristics

After deciding that a character is valid (not necessarily correct according to the stored address), it is stored into memory. After all 11 characters have been detected, they are compared with the pre-stored commands for validation. The 11th character is detected twice to determine end of message (the transmitted 11th character is three character periods in duration).

The initial decoder function (prior to the Command Signal FFT mode of operation) is to conduct a “Signal Search” to determine when a command message begins. When a proper signal is present, the summing of the data samples produce some magnitude representation of the signal. On the other hand, noise is random, and the summing of noise samples produces a zero in essence. The Signal Search algorithm then samples and sums the data of five sub-characters in overlapped groups.

The summation results of the four most recent groups are saved in memory. Each time a new sum occurs, it is moved into the memory register containing the oldest sum. The new sum is compared to a calculated threshold value related to the running average. The new value must be greater than the average of the previous three groups by a particular ratio. This in essence provides an automatic variable threshold.

Code Entry

To program the receiver-decoder to recognize the one valid code for the mission, a data entry device which is presently in the government inventory is used. This data entry unit is a hand-held electronic transfer device.

Prior to launch, the selected code of the mission is loaded into the memory of the data entry unit. Subsequently, the unit is taken to the launch site, the pig-tail is connected into the flight receiver-decoders, and the code is transferred to the memory of the flight units. Also, the ground transmitter is programmed with the code of the mission with this same hand-held unit.

SUMMARY AND CONCLUSIONS

The range safety receiver-decoder for the Space Shuttle launch vehicle is presently in production at Cincinnati Electronics Corporation under contract with NASA, Marshall Space Flight Center. The unit consists of a single superheterodyne receiver design tuned to 416.5 MHz and a microprocessor controlled tone demodulator and decoder. The microprocessor uses a Fast Fourier Transform (FFT) algorithm to effect the audio tone detection. The design uses “Hi-Rel” piece parts that meet the requirements of MIL-STD-975B, Quality Level Grade 1. These requirements are similar to level S or equivalent screening on active parts. In addition, a fail-safe concept is implemented in the design of the software and hardware.

The unit is compatible with the “high-alphabet” range safety modulation technique that is used for manned space flight launches. This approach is superior to the normal range safety system in that it offers far better probability against an undesired output caused by interfering signals. The decoder is programmed just prior to launch to recognize only the selected code of the mission.