Modulation Considerations for the Transmission of Real-Time Space Television

31 MAY 1963

Prepared by JEAN A. DEVELET, JR.
Electronics Research Laboratory

Prepared for COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

LABORATORIES DIVISION • AEROSPACE CORPORATION
CONTRACT NO. AF 04(695)-169
MODULATION CONSIDERATIONS FOR THE
TRANSMISSION OF REAL-TIME
SPACE TELEVISION

Prepared by
Jean A. Develet, Jr.
Electronics Research Laboratory

AEROSPACE CORPORATION
El Segundo, California

31 May 1963

Prepared for
COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California
MODULATION CONSIDERATIONS FOR THE
TRANSMISSION OF REAL-TIME
SPACE TELEVISION

30 May 1963

Prepared
Jean A. Develet, Jr.

Approved
M. T. Weiss
M. T. Weiss, Director
Electronics Research Laboratory

AEROSPACE CORPORATION
El Segundo, California
ABSTRACT

In recent years, the field of space communications and telemetry has seen channel information capacity grow from a few kilobits to megabits per second. A principal factor for the interest in megabit channels is the increasing requirement for real-time, high-definition, television transmission. This requirement is a natural result of the existence of communication satellites which will soon continuously link the continents with a high capacity communication channel. The modulation techniques for the Telstar and Relay communication satellites were determined by considerations identical to those presented in this report. In addition, the soft landing of instruments and men on the moon makes a real-time television link with the earth during critical maneuvers highly desirable.

The question now arises as to the best method of constructing such a communication link. Recently, there has been much discussion about the type of modulation, quality, power levels, and necessary receiver sensitivities required to realize such a channel. This report briefly reviews some of the fundamentals requiring consideration before a reasonable solution at any point in the state of the art can be determined.
CONTENTS

I. INTRODUCTION ................................................. 1
II. DISCUSSION ..................................................... 1
   A. General ................................................... 1
   B. Baseband Signal .......................................... 3
   C. Digital Communication System ............................ 4
   D. Analogue Communication System .......................... 7
III. CONCLUSIONS .................................................. 10
REFERENCES ...................................................... 13
FIGURES

1 Typical Television Waveforms ...................... 3
2 CCIR Video Weighting ............................ 3
3 Simplified Digital Communications System .......... 4
4 Digital Television Contouring ...................... 5
5 Simplified Analogue Communications System ........... 7
6 Closed-Loop Baseband Transfer Function Requirement 10

TABLES

1 Characteristics of Monochrome Television Signal .... 2
2 Digital Television Moon Link ....................... 6
3 Analogue Television Moon Link ..................... 9
I. INTRODUCTION

In recent years, the field of space communications and telemetry has seen channel information capacity grow from a few kilobits to megabits per second. A principal factor for the interest in megabit channels is the increasing requirement for real-time, high-definition, television transmission. This requirement is a natural result of the existence of communication satellites which will soon continuously link the continents with a high capacity communication channel. The modulation techniques for the Telstar and Relay communication satellites were determined by considerations identical to those presented in this report. In addition, the soft landing of instruments and men on the moon makes a real-time television link with the earth during critical maneuvers highly desirable.

The question now arises as to the best method of constructing such a communication link. Recently, there has been much discussion about the type of modulation, quality, power levels, and necessary receiver sensitivities required to realize such a channel. This report briefly reviews some of the fundamentals requiring consideration before a reasonable solution at any point in the state of the art can be determined.

Implementation of the receiver, a key component for a wideband-band frequency modulation (WBFM) communication system, is the subject of Ref. 1.

II. DISCUSSION

A. GENERAL

To better define the problem, a 525-line video baseband signal, typical of a high-definition television system, is selected for analysis. To illustrate two extremes of transmission possibility, the baseband signal is assumed (1) digitally encoded and modulated on the carrier as binary PCM/PM -- an efficient and yet simple digital modulation -- and (2) directly analogue modulated as wideband FM. The performance and complexity of these two systems is then reviewed with parameters typical of a moon mission. Brief mention is also made of the improvement to be expected by a more exotic orthogonal coding scheme for the digital implementation.
Table 1. Characteristics of Monochrome Television Signal (from Ref. 2, Courtesy of International Telecommunication Union)

<table>
<thead>
<tr>
<th>Item</th>
<th>Description of Item</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>405</td>
</tr>
</tbody>
</table>

**Video characteristics**

<table>
<thead>
<tr>
<th>1.</th>
<th>Number of lines per picture (frame)</th>
<th>405</th>
<th>525</th>
<th>625</th>
<th>625</th>
<th>819</th>
<th>819</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Field frequency (fields/second)</td>
<td>50</td>
<td>60</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>4.</td>
<td>Picture (frame) frequency (pictures/second)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>5.</td>
<td>Line frequency and tolerance when operated non-synchronously (lines/second)</td>
<td>10,125</td>
<td>15,750</td>
<td>15,625 ± 0.1 confidence</td>
<td>15,625 ± 0.1 confidence</td>
<td>15,625 ± 0.1 confidence</td>
<td>20,475 ± 0.1 confidence</td>
</tr>
<tr>
<td>6.</td>
<td>Aspect ratio (width:height) (fields)</td>
<td>4:3 *</td>
<td>4:3 *</td>
<td>4:3 *</td>
<td>4:3 *</td>
<td>4:3 *</td>
<td>4:3 *</td>
</tr>
<tr>
<td>7.</td>
<td>Scanning sequence (lines) Top to bottom</td>
<td>Left to right *</td>
<td>Left to right *</td>
<td>Left to right *</td>
<td>Left to right *</td>
<td>Left to right *</td>
<td>Left to right *</td>
</tr>
<tr>
<td>8.</td>
<td>System capable of operating independently of power supply frequency *</td>
<td>Yes *</td>
<td>Yes *</td>
<td>Yes *</td>
<td>Yes *</td>
<td>Yes *</td>
<td>Yes *</td>
</tr>
<tr>
<td>9.</td>
<td>Approximate gamma of picture signal</td>
<td>0.4-0.5</td>
<td>0.45</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>10.</td>
<td>Nominal video bandwidth (Mc/s)</td>
<td>3</td>
<td>4.2 (4.0)</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>10</td>
</tr>
</tbody>
</table>

**Radio frequency characteristics**

<table>
<thead>
<tr>
<th>a.</th>
<th>Nominal radio-frequency bandwidth (Mc/s)</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>7</th>
<th>8</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>b.</td>
<td>Sound carrier relative to vision carrier Mc/s</td>
<td>-3.5 *</td>
<td>+4.5 *</td>
<td>+5.5 *</td>
<td>+5.5 *</td>
<td>+6.5 *</td>
<td>+6.5 *</td>
</tr>
<tr>
<td>c.</td>
<td>Sound carrier relative to nearest edge of channel</td>
<td>+0.25 *</td>
<td>-0.25 *</td>
<td>-0.25 *</td>
<td>-0.25 *</td>
<td>-0.25 *</td>
<td>-0.25 *</td>
</tr>
<tr>
<td>d.</td>
<td>Nominal width of main sideband (Mc/s)</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>e.</td>
<td>Nominal width of vestigial sideband (Mc/s)</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>f.</td>
<td>Type of polarity of vision modulation</td>
<td>A5 * positive</td>
<td>A5 * negative</td>
<td>A5 * negative</td>
<td>A5 * positive</td>
<td>A5 * negative</td>
<td>A5 * positive</td>
</tr>
<tr>
<td>g.</td>
<td>Type of sound modulation</td>
<td>Asymmetric sideband</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>h.</td>
<td>Synchronizing level for percentage peak carrier</td>
<td>3</td>
<td>100</td>
<td>72.5-77.5 (75)</td>
<td>22.5-27.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>Difference between blanking level and blanking level for percentage peak carrier</td>
<td>3</td>
<td>75</td>
<td>72.5-77.5 (75)</td>
<td>22.5-27.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>j.</td>
<td>Peak white level as percentage peak carrier</td>
<td>5</td>
<td>4.0-4.5</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>k.</td>
<td>Type of sound modulation</td>
<td>A3</td>
<td>F3 = 7.5 kHz</td>
<td>F3 = 10 kHz</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

* These characteristics are in accordance with Recommendation No. 212.

1. The values to be considered are respectively the r.m.s. value of the carrier at the peak of the modulation envelope for the vision signal and the r.m.s. value of the unmodulated carrier for amplitude-modulated and frequency-modulated sound transmitters.

2. Figures in brackets refer to Japanese 525-line system.

3. Figures in brackets refer to Australian 625-line system.

4. Tentative data.
B. BASEBAND SIGNAL

The exact definition of the standard 525-line television signal is in documentation issued by the International Radio Consultative Committee (CCIR), Ref. 2. In Table 1, certain physical parameters of the signal are displayed. A typical time waveform is shown in Fig. 1.

![Typical Television Waveforms](image)

**Fig. 1. Typical Television Waveforms**

For purposes of communication system design, two significant parameters of this signal are the baseband width, 4.0 Mc in this instance, and the allowable noise, which may corrupt the picture. The CCIR's desired objective is a weighted signal-to-continuous-noise power ratio of 50 db. Weighting takes into account the subjective effect of noise at different frequencies. The CCIR recommended weighting to be applied to the interference prior to power measurement is shown in Fig. 2.

![CCIR Video Weighting](image)

**Fig. 2. CCIR Video Weighting**
C. DIGITAL COMMUNICATION SYSTEM

A typical realization of television transmission by digital means appears in Fig. 3.

The analogue video from a vidicon or other information source is converted to a binary stream at the rate of one sample every \( 1/2 \) \( F_{\text{max}} \) or \( 1/8 \) μsec. This stream is then encoded on a carrier wave in the form of phase reversals.

An object of considerable previous study has been the required number of quantum steps or levels per sample for good subjective picture quality. Bell Telephone Laboratories (Ref. 3) has concluded that 7 bits or 128 grey levels are adequate for the majority of viewers. For space television, to economize on transmitter power, a smaller number of grey levels, perhaps half as many, might be selected. For purposes of this report, 6 bits will be considered an adequate quantization. It should be noted that the subjective effect of quantization noise is not similar to that of continuous random noise; i.e., a weighting filter, similar to that described for continuous random noise, is not usually applied in treating this effect.
A qualitative picture of quantization noise, or contouring, which is characteristic of a digital picture, is shown in Fig. 4.

Since quantization has been briefly discussed, it is appropriate to examine another significant parameter in a digital communication system, viz., error rate. Assuming that out of the 6 bits per sample only the 2 significant bits can cause subjectively important errors, the tolerable error rate may be approximated as follows:

\[
\text{sec/frame} = \frac{1}{30} \\
\text{samples/sec} = 8 \times 10^6 \\
\text{samples/frame} = \frac{(8 \times 10^6)}{30} \\
\text{allowable errors/frame} = 100 \\
\text{sample error rate} = \frac{(3 \times 10^3)}{(8 \times 10^6)} \\
\text{significant bits/sample} = 2 \\
\text{bit error rate} \geq \left( \frac{(3 \times 10^3)}{(2 \times 8 \times 10^6)} \right) = 1.9 \times 10^{-4}
\]
For simple binary PCM/PM, an error rate of $1.9 \times 10^{-4}$ requires an energy per bit/noise density ratio of about 6.0. The energy per bit required by a more complex bi-orthogonal system (Ref. 4) having a similar sample error rate as the binary system but an alphabet of 64 letters is about 3.0 or 3 db less.

The results can be combined with the standard radar equation to yield a typical moon-to-earth, real-time, high-definition digital television link (Table 2).

Table 2. Digital Television Moon Link

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODULATION</td>
<td>PCM/PM (2L) PCM/PM (64L)</td>
</tr>
<tr>
<td>FREQUENCY, Mc</td>
<td>2300 2300</td>
</tr>
<tr>
<td>TRANSMITTER POWER*, W</td>
<td>30 15</td>
</tr>
<tr>
<td>CABLE LOSS, dB</td>
<td>1 1</td>
</tr>
<tr>
<td>TRANSMITTER ANTENNA GAIN (10 FT DIAM), dB</td>
<td>34.5 34.5</td>
</tr>
<tr>
<td>SPACE LOSS (4.07 x 10^5 km), dB</td>
<td>211.9 211.9</td>
</tr>
<tr>
<td>ELLIPTICITY LOSS, dB</td>
<td>1 1</td>
</tr>
<tr>
<td>RECEIVER ANTENNA GAIN, db</td>
<td>52 52</td>
</tr>
<tr>
<td>RECEIVER SIGNAL POWER, dbm</td>
<td>-83 -86</td>
</tr>
<tr>
<td>RECEIVER NOISE DENSITY (300°K), dbm/Mc</td>
<td>-113.8 -113.8</td>
</tr>
<tr>
<td>RECEIVER NOISE BANDWIDTH, Mc</td>
<td>48 48</td>
</tr>
<tr>
<td>RECEIVER NOISE POWER, dbm</td>
<td>-97 -97</td>
</tr>
<tr>
<td>PREDETECTION (S/N), db</td>
<td>14 11</td>
</tr>
<tr>
<td>THRESHOLD, db</td>
<td>6 5</td>
</tr>
<tr>
<td>MARGIN, db</td>
<td>6 6</td>
</tr>
</tbody>
</table>

*EXOTIC PREMODULATION REDUNDANCY REMOVAL MAY SAVE 3 dB

It should be noted that rather sophisticated redundancy removal, prior to modulation, will only buy about another 3 db of necessary transmitter power for a quality transmission (Ref. 5).
D. ANALOGUE COMMUNICATION SYSTEM

Realization of an analogue television link may be accomplished by the system shown in Fig. 5. The block diagram representation of the analogue system indicates it to be simpler than the digital approach, which is in fact true; the actual analogue system hardware realization is not only simpler, but it is more reliable.

Fig. 5. Simplified Analogue Communications System

The one remaining question is how the raw power requirement of the spacecraft, which uses an analogue system, compares with the power used by a digital system.

This is best answered by using very simple relationships governing the performance of modulation tracking phase-lock receivers (Refs. 6, 7). This more optimum type of receiver is essential in a space communications link, because a standard FM discriminator would require significantly more received power at threshold.
For an analogue FM system, using phase-lock reception, key relationships for quality and sensitivity are given below:

\[
\frac{S_{pp}}{N_o} = 3 \frac{S_{if}}{\Phi_{if} B_N} \cdot \left(\frac{f_{pp}}{f_m}\right)^2 \cdot \frac{B_N}{f_m} \cdot W
\]  

(1)

\[
B_N = 4.03 \left(\frac{f_{pp}}{\tau_{t_m} f_m}\right)^{1/2}
\]  

(2)

\[
BW_{rf} = 2f_m + f_{pp}
\]  

(3)

\[
\frac{S_{if}}{\Phi_{if} B_N} \geq 4(6 \text{ db})
\]  

(4)

where

- \(S_{pp}/N_o\) = peak-peak television output signal to noise power ratio
- \(S_{if}\) = received signal power, w
- \(\Phi_{if}\) = receiver noise density, w/cps
- \(B_N\) = receiver noise bandwidth, cps
- \(f_{pp}\) = peak-peak frequency deviation, cps
- \(f_m\) = highest baseband frequency, cps
- \(W\) = improvement factor due to weighting (CCIR wtg, \(W = 12.3 \text{ db}\))
- \(\tau_{t_r}\) = 10-90 percent rise time of video waveform, sec
- \(e_m\) = maximum allowable phase-lock loop modulation error, rad
- \(BW_{rf}\) = radio frequency bandwidth occupancy of the FM signal, cps
These relationships are valid only for a second-order receiving system with a damping of 0.707. Yovits and Jackson results, in a very significant paper in 1955, indicate that for pulse-type waveforms, such as television signals, a second-order receiver will yield minimum mean-square phase error between the received signal and the local replica. Minimizing this error yields a receiver of maximum sensitivity.

By means of parameter juggling in the undetermined set of relations shown in Eqs. (1-4), a reasonable communication link design can be achieved (Table 3).

### Table 3. Analogue Television Moon Link

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUALITY (WEIGHTED)</td>
<td>40 db</td>
</tr>
<tr>
<td>MODULATION</td>
<td>WBFM</td>
</tr>
<tr>
<td>FREQUENCY</td>
<td>2300 Mc</td>
</tr>
<tr>
<td>TRANSMITTER POWER</td>
<td>10 W</td>
</tr>
<tr>
<td>CABLE LOSS</td>
<td>1 db</td>
</tr>
<tr>
<td>TRANSMITTER ANTENNA GAIN (10 FT DIAM)</td>
<td>34.8 db</td>
</tr>
<tr>
<td>SPACE LOSS (4.07 x 10^5 km)</td>
<td>211.9 db</td>
</tr>
<tr>
<td>ELLIPTICITY LOSS</td>
<td>1 db</td>
</tr>
<tr>
<td>RECEIVER ANTENNA GAIN</td>
<td>52 db</td>
</tr>
<tr>
<td>RECEIVER SIGNAL POWER</td>
<td>-87.9 db</td>
</tr>
<tr>
<td>RECEIVER NOISE DENSITY (300°K)</td>
<td>-113.8 db/Me</td>
</tr>
<tr>
<td>RECEIVER NOISE BANDWIDTH</td>
<td>24.3 Mc</td>
</tr>
<tr>
<td>RECEIVER NOISE POWER</td>
<td>-99.9 db</td>
</tr>
<tr>
<td>PREDETECTION (S/N)</td>
<td>12 db</td>
</tr>
<tr>
<td>THRESHOLD</td>
<td>6 db</td>
</tr>
<tr>
<td>MARGIN</td>
<td>6 db</td>
</tr>
</tbody>
</table>

DEVIATIONS = 10 Mc, PICTURE ONLY
- 4 Mc, SYNCH
RF BW = 25 Mc
LOOP 3 db BW = 7.5 Mc
DAMPING = 0.707
Figure 6 shows the resulting closed-loop receiver transfer function and illustrates the wide bandwidth required for transmission of high-definition television; it should be noted that the requirements derived here have resulted in a phase-lock receiver whose bandwidth is the widest ever achieved to date. The construction of such a receiver has been accomplished but not without design problems (Ref. 1).

![Graph of closed-loop receiver transfer function]

**III. CONCLUSIONS**

Modulation considerations for the design of a real-time space/earth television link have been treated.

To illustrate two extremes of transmission possibility, the baseband signal was assumed: (1) digitally encoded and modulated on a carrier as binary PCM/PM, and (2) analogue modulated as wideband FM. Standards of quality established for the design of each system were then used to estimate receiver power requirements (Ref. 2-3). The performance and
complexity of these two approaches were then reviewed with parameters typical of a moon mission. In comparing the digital to the analogue approach, it was found that the analogue system was superior in all respects, e.g., simplicity, reliability, and spacecraft power.

Identical comparisons as the foregoing were necessary to establish the modulation techniques for Telstar and Relay, the world's first wideband communication satellites. It is not surprising, therefore, that these satellites utilize analogue wideband FM with frequency-following receivers.
REFERENCES


Aerospace Corporation, El Segundo, California.
MODULATION CONSIDERATIONS FOR THE
TRANSMISSION OF REAL-TIME SPACE
TELEVISION, prepared by Jean A. Develet, Jr.
(Report TDR-169(3250-43)TN-3; SSD-TDR-63-117)
(Contract AF 04(695)-169) Unclassified report

In recent years, the field of space communications
and telemetry has seen channel information
capacity grow from a few kilobits to megabits per
second. A principal factor for the interest in
megabit channels is the increasing requirement for
real-time, high definition, television transmission.
This requirement is a natural result of the exist-
ence of communication satellites which will soon
continuously link the continents with a high
capacity communication channel. The modulation
techniques for the Telstar and Relay communi-
cation satellites were determined by considerations
(over)

Aerospace Corporation, El Segundo, California.
MODULATION CONSIDERATIONS FOR THE
TRANSMISSION OF REAL-TIME SPACE
TELEVISION, prepared by Jean A. Develet, Jr.
(Report TDR-169(3250-43)TN-3; SSD-TDR-63-117)
(Contract AF 04(695)-169) Unclassified report

In recent years, the field of space communications
and telemetry has seen channel information
capacity grow from a few kilobits to megabits per
second. A principal factor for the interest in
megabit channels is the increasing requirement for
real-time, high definition, television transmission.
This requirement is a natural result of the exist-
ence of communication satellites which will soon
continuously link the continents with a high
capacity communication channel. The modulation
techniques for the Telstar and Relay communi-
cation satellites were determined by considerations
(over)

Aerospace Corporation, El Segundo, California.
MODULATION CONSIDERATIONS FOR THE
TRANSMISSION OF REAL-TIME SPACE
TELEVISION, prepared by Jean A. Develet, Jr.
(Report TDR-169(3250-43)TN-3; SSD-TDR-63-117)
(Contract AF 04(695)-169) Unclassified report

In recent years, the field of space communications
and telemetry has seen channel information
capacity grow from a few kilobits to megabits per
second. A principal factor for the interest in
megabit channels is the increasing requirement for
real-time, high definition, television transmission.
This requirement is a natural result of the exist-
ence of communication satellites which will soon
continuously link the continents with a high
capacity communication channel. The modulation
techniques for the Telstar and Relay communi-
cation satellites were determined by considerations
(over)
identical to those presented in this report. In addition, the soft landing of instruments and men on the moon makes a real-time television link with the earth during critical maneuvers highly desirable. The question now arises as to the best method of constructing such a communication link. Recently, there has been much discussion about the type of modulation, quality, power levels, and necessary receiver sensitivities required to realize such a channel. This report briefly reviews some of the fundamentals requiring consideration before a reasonable solution at any point in the state of the art can be determined.