SATELLITE COMMUNICATIONS PAYLOAD AND SYSTEM
SATELLITE COMMUNICATIONS PAYLOAD AND SYSTEM

TERESA M. BRAUN
To Walter and Amy

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This book is about the payload of communications satellites. Several books have been written about the satellite bus or platform, particular satellites, general satellite communications, and applications of satellite communications, but the payload has been covered only briefly in these books. Detailed books on how to design the various payload units, for example, antennas and filters, exist, but no book focuses on unit performance at a level appropriate for payload systems engineering.

This book is a unique combination of practical payload systems engineering and applied communications theory. As the payload is desired to have higher and higher capability, it becomes larger and more complex. More complicated analyses are required. The payload systems engineer is called upon to deal with things he never had to before or deal with the old things in a more exact way, to squeeze out higher performance. The engineer about to model the end-to-end communications system needs to fully understand the payload subtleties, new or old. The writer of the payload part of the proposal needs to realize that the formulations or values of some requirements may have to be rethought out. A satellite customer new to the business may be mystified by discussions with the payload manufacturer and need more knowledge to be able to get what he wants. Today it takes on the order of 10 years to “know” the payload. This book can accelerate learning.

The intended audience of this book is the following people who work with communications satellites:

- Payload systems engineers, at all stages in their careers
- Satellite-communications system designers and analysts
- Satellite proposal-writers
- Satellite customers
• Payload unit engineers
• Satellite control-center engineers, electrical and software
• Satellite bus engineers who need a payload reference now and then.

Prerequisite for full understanding of most of the chapters is knowledge of the Fourier transform and the duality of the time and frequency domains. However, without that almost of the book can still be understood.

My “love” for the satellite payload started from a rather early work experience. As a beginning engineer, armed with mathematical and some theoretical engineering knowledge, I attended a technical Space Shuttle meeting. One of the topics discussed was the screws on a unit. I felt disdain. Ten or 15 years later, for the first time being a systems engineer on a payload subsystem development, I learned that screws are fascinating—I saw the results of the unit’s mechanical analysis. From then on I knew that things only seem boring when I do not know anything about them. Every bit of the satellite payload has to meet such stringent electrical and mechanical requirements that it has an intricate story behind it.

TERESA M. BRAUN
I would like to express my deepest thanks to my husband, Walter Braun, who taught me communications theory on the job at LinCom Corp. in Los Angeles in the 1970s and 1980s and who has lovingly supported me and encouraged me in the writing of this book. Walter has a Ph.D. in Electrical Engineering with specialty in communications theory. I would also like to especially thank my Ph.D. advisor, Dr. Ezio Biglieri, for being so helpful and kind in the late 1980s when I was his graduate student and, a few years ago now, for his wonderful suggestion to write a book. I will always be grateful to all the wonderful engineers I have worked with over the years, especially Richard Hoffmeister and Dr. Charles Hendrix, who were instrumental in my career development. Almost all of the engineers I have worked with have been passionate about their work and willing to help others learn, and they have made mine such an interesting career. Of all the companies I have worked at, two stand out for having provided me limitless opportunities to do good work: Space Systems/Loral and William Lindsey’s LinCom Corp. of 30 years ago. My career has spanned the time since the American equal-opportunity laws were being implemented at federal contractors, and I have gone from being an oddity in the engineering workplace to feeling at home among many women colleagues, in California, anyway. I wish to thank the colleagues who reviewed the book and provided corrections, suggestions, and explanations: my husband, who has read all of it and performed simulations; Richard Hoffmeister and Dr. Charles Hendrix, for reading most of it; Eddy Yee for Chapter 2; Gary Schennum for Chapter 3; Stephen Holme for the filter section of Chapter 4; James Sowers for Chapter 5; Dr. Messiah Khilla and Reinwald Gerhard for Chapter 6; Dr. Chak Chie for Chapters 8, 9, 11, and 13; and Dr. Ezio Biglieri for Chapter 10.

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ABOUT THE AUTHOR

Dr. Teresa M. Braun received the B.A. in Mathematics from the University of California, San Diego, in 1970; and from the University of California, Los Angeles, the M.A. in Mathematics in 1973, the M.S. in Systems Science in 1977, and the Ph.D. in Electrical Engineering in 1989 with dissertation on modulation and coding. She has also taken short courses on computer networks. She has been employed for 23 years in satellite communications and 3 years in satellite navigation. In California, from 1973 to 1976 she worked on GPS development at The Aerospace Corp.; from 1977 to 1986 on analysis and simulation of end-to-end satellite communications at LinCom Corp. (now LinQuest Corp.); from 1989 to 1997 in development of new payload technology in communications and navigation at Hughes Space & Communications (now Boeing Satellite Development Center); from 1997 to 1999 in development of new payload and ground-receiver technology and on a satellite constellation at Lockheed Martin’s Western Development Laboratory (now part of LM’s Management & Data Systems); and from 1999 to 2003 as a payload manager and department manager of payload systems analysis at Space Systems/Loral. After moving to Switzerland in 2003, she has worked in project management, supplier management, modem algorithm development, and payload analysis. She is still often in the US. She was née Thesken and also formerly named McKenzie. She has worked on NASA, defense, commercial, and ESA programs.
ABBREVIATIONS

- Convolution
- * Complex conjugation
- ≈ Is approximately equal to
- △ Is defined as
- ≪ Is much less than
- ≫ Is much greater than
- ∝ Is proportional to

\( \varphi(f) \) Phase of transfer function in radians, a function of frequency \( f \); also called “phase response”

\( \phi \) Azimuth angle in spherical coordinates

\( \sigma \) Standard deviation

\( \theta \) Polar angle in spherical coordinates

\( \theta(t) \) Signal phase in radians as a function of time \( t \)

8PSK 8-ary phase-shift-keying

16QAM 16-ary quadrature amplitude modulation

AC Alternating current

ADC Analog-to-digital converter

A/D Analog-to-digital converter

\( A(f) \) Signal-amplitude multiplication function of a filter as a function of frequency \( f \); called for shorthand the “amplitude function” of the filter

AIAA American Institute of Aeronautics and Astronautics, Inc.

ALC Automatic level control

A-to-D Analog-to-digital (converter)

AWGN Additive white Gaussian noise

\( B \) Bandwidth in Hz
ABBREVIATIONS

BER Bit error rate
BFN Beam-forming network
\( B_L \) Loop bandwidth (one-sided baseband) of phase-locked loop
BOL Beginning of life
BPF Bandpass filter
BPSK Binary phase-shift-keying
\( C \) Carrier or signal power in a given bandwidth
CAMP Channel amplifier
CC Conduction-cooled
coax Coaxial cable
CONUS Continental US
CP Circularly polarized
CRO Coaxial-resonator oscillator
CW Continuous wave, that is, a sinewave
C/3IM Ratio of carrier power to 3rd-order IMP power when nonlinearity’s input is two equal-power carriers
\( D \) Directivity; antenna aperture diameter
DAC Digital-to-analog converter
D/A Digital-to-analog converter
dB Decibels
dBm 10 times log of milliwatts
DC Direct current
D/C Downconverter
DEMUX Demultiplexer
DRC Direct-radiation-cooled
DRO Dielectric-resonator oscillator
D-to-A Digital-to-analog (converter)
DUT Device under test
DVB Digital Video Broadcast
DVB-RCS DVB–Return Channel Satellite
DVB-S DVB–Satellite
\( E \) Electrical field vector
\( E_b \) Energy per bit
EHF Extremely high frequency (between 30 and 300 GHz)
\( E_s \) Energy per modulation symbol
EIRP Equivalent isotropically radiated power
EOC Edge of coverage
EOL End of life
EPC Electronic power conditioner
\( E_s \) Energy per modulation symbol
ESA European Space Agency
ETSI European Telecommunications Standards Institute
E–W East-west; east and west
F Flight
\( F \) Noise figure
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>Frequency in Hz; focal length</td>
</tr>
<tr>
<td>$f/D$</td>
<td>Ratio of focal length to aperture diameter, for a paraboloidal reflector antenna</td>
</tr>
<tr>
<td>FDM</td>
<td>Frequency-dimension multiplexing</td>
</tr>
<tr>
<td>FGM</td>
<td>Fixed-gain mode</td>
</tr>
<tr>
<td>FIR</td>
<td>Finite-impulse response</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of view</td>
</tr>
<tr>
<td>$G$</td>
<td>Gain</td>
</tr>
<tr>
<td>GaAs</td>
<td>Gallium arsenide</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary orbit</td>
</tr>
<tr>
<td>$G(f)$</td>
<td>Filter gain, a function of frequency $f$; also called “gain response”</td>
</tr>
<tr>
<td>$G/T_s$</td>
<td>Antenna gain divided by system noise temperature</td>
</tr>
<tr>
<td>$H$</td>
<td>Horizontal linear polarization; hybrid coupler</td>
</tr>
<tr>
<td>$H$</td>
<td>Magnetic field vector</td>
</tr>
<tr>
<td>HEO</td>
<td>Highly elliptical orbit</td>
</tr>
<tr>
<td>HF</td>
<td>Harmonic filter</td>
</tr>
<tr>
<td>$H(f)$</td>
<td>Filter transfer function, a function of $f$</td>
</tr>
<tr>
<td>HPA</td>
<td>High-power amplifier</td>
</tr>
<tr>
<td>HPF</td>
<td>High-pass filter</td>
</tr>
<tr>
<td>$h(t)$</td>
<td>Filter impulse response, a function of $t$</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz, unit of frequency</td>
</tr>
<tr>
<td>$I$</td>
<td>Interference power in a given bandwidth; in-phase component of baseband signal</td>
</tr>
<tr>
<td>IBO</td>
<td>Input backoff</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers, Inc.</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate frequency</td>
</tr>
<tr>
<td>Im</td>
<td>Function that takes the imaginary part of a complex number</td>
</tr>
<tr>
<td>IMP</td>
<td>Intermodulation product</td>
</tr>
<tr>
<td>IMUX</td>
<td>Input multiplexer</td>
</tr>
<tr>
<td>InP</td>
<td>Indium phosphide</td>
</tr>
<tr>
<td>ISI</td>
<td>Intersymbol interference</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>$j$</td>
<td>$\sqrt{-1}$</td>
</tr>
<tr>
<td>LCAMP</td>
<td>Linearizer-CAMP unit</td>
</tr>
<tr>
<td>LEO</td>
<td>Low earth orbit</td>
</tr>
<tr>
<td>LHCP</td>
<td>Left-hand circularly polarized</td>
</tr>
<tr>
<td>ln</td>
<td>Natural logarithm</td>
</tr>
<tr>
<td>LNA</td>
<td>Low-noise amplifier</td>
</tr>
<tr>
<td>LO</td>
<td>Local oscillator</td>
</tr>
<tr>
<td>log</td>
<td>Logarithm base 10</td>
</tr>
<tr>
<td>LP</td>
<td>Linearly polarized</td>
</tr>
<tr>
<td>LPF</td>
<td>Low-pass filter</td>
</tr>
<tr>
<td>LTWTA</td>
<td>Linearized TWTA</td>
</tr>
<tr>
<td>(L)CAMP</td>
<td>CAMP that may or may not contain the linearizer function</td>
</tr>
<tr>
<td>(L)TWTA</td>
<td>TWTA that may or may not be linearized</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
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</tr>
<tr>
<td>MAC</td>
<td>Medium-access control</td>
</tr>
<tr>
<td>MBA</td>
<td>Multibeam antenna</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium earth orbit</td>
</tr>
<tr>
<td>MF</td>
<td>Matched filter</td>
</tr>
<tr>
<td>MLO</td>
<td>Master local oscillator</td>
</tr>
<tr>
<td>MPA</td>
<td>Multiport amplifier</td>
</tr>
<tr>
<td>MPEG</td>
<td>Moving Picture Experts Group</td>
</tr>
<tr>
<td>MPM</td>
<td>Microwave power module</td>
</tr>
<tr>
<td>MRO</td>
<td>Master reference oscillator</td>
</tr>
<tr>
<td>MUX</td>
<td>Multiplexer</td>
</tr>
<tr>
<td>N</td>
<td>Noise power in a given bandwidth</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>$N_0$</td>
<td>One-sided RF or IF power-spectral-density of noise</td>
</tr>
<tr>
<td>NF</td>
<td>Noise figure</td>
</tr>
<tr>
<td>NPR</td>
<td>Noise-[to]-power ratio. Ratio of IMP power in one slot to carrier power in a slot, when input to HPA is a large number of equal-power, equally spaced carriers with one missing in center slot</td>
</tr>
<tr>
<td>N–S</td>
<td>North-south; north and south</td>
</tr>
<tr>
<td>OBO</td>
<td>Output backoff</td>
</tr>
<tr>
<td>OBP</td>
<td>Onboard processor</td>
</tr>
<tr>
<td>OCXO</td>
<td>Oven-controlled crystal oscillator</td>
</tr>
<tr>
<td>OMUX</td>
<td>Output multiplexer</td>
</tr>
<tr>
<td>OQPSK</td>
<td>Offset QPSK</td>
</tr>
<tr>
<td>$P$</td>
<td>Long-term average of signal power. Average is over a time much, much longer than inverse of signal’s noise bandwidth</td>
</tr>
<tr>
<td>P2dB</td>
<td>Amplifier’s 2-dB compression point</td>
</tr>
<tr>
<td>$p(x)$</td>
<td>Probability density function of a random variable, a function of its values $x$</td>
</tr>
<tr>
<td>pdf</td>
<td>Probability density function</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>Power input to amplifier</td>
</tr>
<tr>
<td>$P_{in \text{ sat}}$</td>
<td>Power input to amplifier that saturates amplifier</td>
</tr>
<tr>
<td>pk-pk</td>
<td>Peak-to-peak</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase-locked loop</td>
</tr>
<tr>
<td>PM</td>
<td>Phase modulation</td>
</tr>
<tr>
<td>PN</td>
<td>Pseudo-noise</td>
</tr>
<tr>
<td>$P_{op}$</td>
<td>Amplifier’s operating point</td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>Power output by amplifier</td>
</tr>
<tr>
<td>$P_{out \text{ sat}}$</td>
<td>Power output by amplifier when saturated</td>
</tr>
<tr>
<td>Pr</td>
<td>Probability</td>
</tr>
<tr>
<td>Preamp</td>
<td>Preamplifier</td>
</tr>
<tr>
<td>PS</td>
<td>Power supply</td>
</tr>
<tr>
<td>psd</td>
<td>Power spectral density</td>
</tr>
<tr>
<td>PSK</td>
<td>Phase-shift-keyed</td>
</tr>
<tr>
<td>$P(t)$</td>
<td>Instantaneous power of signal as a function of time $t$. Equal to signal’s square magnitude averaged over carrier cycle</td>
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