X-460-70-299
PREPRINT

NASA TM X-65304

SUPER-HIGH-FREQUENCY (SHF) COMMUNICATIONS SYSTEM PERFORMANCE ON ATS

VOLUME 1: SYSTEM SUMMARY

AUGUST 1970

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-460-70-299

SUPER-HIGH-FREQUENCY (SHF)

COMMUNICATIONS SYSTEM

PERFORMANCE ON ATS

VOLUME 1: SYSTEM SUMMARY

Prepared by:
Westinghouse Electric Corporation
and
The ATS Project Office

August 1970

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

This report consists of two volumes. Volume 1, System Summary (X-460-70-299), contains section 1 only (section 2 was deleted). Volume 2, Data and Analysis (X-460-70-300), contains sections 3, (4 deleted), 5, 6, and 7.

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COMMUNICATIONS PERFORMANCE SUPER HIGH FREQUENCY (SHF)

1. SHF SYSTEM PERFORMANCE

1.1 INTRODUCTION AND OVERALL PERFORMANCE SUMMARY

The purpose of the Applications Technology Satellite (ATS) - SHF communications experiment is to advance the state-of-the-art in satellite communications by evaluating new concepts, techniques and applications, and provide the information which will influence and improve the design of future satellite systems. These studies are among some twenty major experiments which are a part of NASA's Application Technology Satellite program necessitated by rapidly increasing requirements and advancements in techniques. Other areas of experimentation of the ATS program include satellite design, propulsion and stabilization; meterological concepts and techniques; and space environment and measurement studies.

The development of the synchronous altitude, spin stabilized spacecraft configuration on the SYNCOM program formed the basis for a new generation of satellites, wherein more sophisticated antenna systems could be developed to increase the capability of spaceborn communications transponders, to provide greater channel capacity and improved channel performance. The development of stabilization of satellites by gravity gradient techniques provided an additional, potentially competitive technique, wherein the increased system capability might be achieved with less sophisticated but equally high gain antenna systems. To promote continued advancement, NASA has implemented the study of an SHF communications system which encompasses a program of design, manufacture, operation and evaluation. This system provides two modes of operation, Multiple Access (SSB-FDMA/PhM) and Frequency Translation (FM/FM). The SSB-FDMA/PhM mode is designed to handle frequency division multiplex (FDM) signals while the FM/FM mode is designed to handle television signals as well as FDM.

Westinghouse is designated the "Communications Experimenter", responsible to evaluate these areas as they relate to future users and the state-of-the-art in satellite communications and summarize these findings. Theoretical and analytical studies are supported by a test program designed by NASA and Westinghouse to confirm design predictions, demonstrate feasibility and evaluate predicted and unpredicted problems. The test program was based on five satellites and three earth stations representing different capabilities and locations. The earth stations provide support to ATS operations for performance of communications experiments by the acquisition of data. Spacecraft maneuvers and experiments are controlled by directions from the ATS project Operations Control Center at Goddard Space Flight Center (GSFC), at Greenbelt, Maryland. All test data is forwarded from the earth stations to GSFC for processing and distribution to the experimenter, Westinghouse Electric Corporation.

Significant hardware characteristics of the satellites are listed in table 1.1. As shown, this new generation of satellites initially consisted of a family of five satellite configurations starting with a synchronous altitude, spin stabilized model, with a collinear array receiving antenna and an electronically despun transmitting antenna (ATS-1). The ATS program with its higher satellite EIRP's, provided the capability of 1200 channels and a sufficient bandwidth for a color television channel when using an 85' earth station antenna. The second successful spacecraft (ATS-3), contains a mechanically despun antenna which provides a 10 db increase in receiving antenna gain over the first model while increasing the satellite EIRP (approximately 3 db) to provide the same system capability when using a 40' earth station antenna.

The first gravity-gradient satellite (ATS-2) on the program was designed for a 6000-nautical mile orbit to be used to verify the mathematical model of the gravity gradient system. The desired orbit and proper stabilization, however, were not obtained due to a faulty launch vehicle. The second gravity gradient satellite, ATS-4 failed to attain synchronous orbit also due to launch vehicle problems. The third gravity gradient satellite (ATS-5) developed technical problems after launch, and as a result, could not be gravity gradient stabilized. ATS-5 is spin stabilized and is providing useful data, however, no particular effort was made to acquire SHF Communications data since data from ATS-1 and ATS-3 is more than adequate for SHF Communications system evaluation.

Future plans in the ATS program call for the development of another generation of satellites (ATS F&G) employing three axis stabilization and large erectable (in orbit) parabolic antennas which will not only improve the system capability for point-to-point voice and television communication, but will make possible direct TV broadcast from an earth station via satellite to small stations (G/T less than 20 db).

Flight models ATS-1 and ATS-3 contain two dual mode SHF communication transponders. All transponders are identical except for the antenna systems, transmitter power output, and an additional 10 db gain (on command) in transponder two of ATS-3. Two communications modes are employed in each transponder. The first, designated MA (Multiple Access), supports the unique SSB-FDMA/PhM (single sideband-frequency division multiple access/phase modulated) system to simultaneously relay a large number of voice transmissions between a combination of participating earth stations. This mode is considered a systems breakthrough in the state-of-the-art since it optimizes the trade-off between spectrum utilization and the available satellite EIRP in a truly multiple access mode employing up to a total of 1200 FDM voice channels.

The second mode designated FT (Frequency Translation) and suitable for FDM as well as TV, employs the more conventional frequency translation transponder similar to that used in many terrestrial line-of-sight microwave systems. The primary purpose of this transponder is the relaying of high quality television. The ATS program is advancing technology by producing higher quality audio and video than in previous satellite systems by means of increased spacecraft EIRP. The FM/FM mode when employed for FDM is of secondary interest and used primarily as a base of reference for SSB-FDMA/PhM.

Three ATS earth stations, located at Rosman, N.C.; Mojave (near Barstow), California; and Cooby Creek, Australia, characterized in table 1.2, are an integral part of the complete earth-satellite-earth system configuration being evaluated. Most significant are the availability of earth stations of representative G/T* values; one representative of a large station (the 85 foot antenna at Rosman with a G/T near 40 db) and the other two representative of medium size stations (the 40 foot antennas at Mojave and Cooby Creek with G/T values near 32 db). G/T values at the Rosman stations are seen to differ slightly between ATS-1 and ATS-3 because of the different elevation angles of the earth stations antenna which affect the values of system noise temperature. System combinations of spacecraft and earth stations which most nearly simulate operational conditions were selected for communications experiments and are described within each of the subsystem sections.

The three sections which follow this introduction discuss the Multiple Access Mode; Frequency Translation Mode-Television; and Frequency Translation Mode-FDM Multiplex. The overall results for these modes are contained in tables 1.3 through 1.11. A discussion and analysis of these results are located in subsequent paragraphs of this section and also in section 3. Each of the above sections describe the system configuration in detail and include measured performance data and curves on equipment where appropriate. Significant performance parameters are then evaluated individually followed by a discussion of subjective tests, where applicable. Performance calculations for each configuration of satellite, link, mode and transponder are also presented in tabular form.

The MULTIPLE ACCESS SECTION describes the performance of the SSB-FDMA/PhM mode for the transmission of voice, data and teletype signals between earth stations via a satellite link. The ability of the SSB-FDMA/PhM mode to pass up to 1200 simultaneous one way voice channels through the spacecraft is demonstrated. The adequacy of the mode in terms of idle system test tone-to-noise**, intermodulation distortion (especially

* G/T is used here as a measure of earth station capability calculated as receive system antenna gain (G) divided by system noise temperature (T).

** The idle system test tone-to-noise is based on the total noise measured in the multiplex channel in the absence of a signal. The major contributor to this total noise is thermal noise; thus the two terms, idle and thermal, are used interchangeably.

contributions of the SSB transmitter and spacecraft transponder); the ability of the frequency and level control loops to operate properly and the short term frequency stability of the system components are evaluated. These parameters are analyzed and compared to CCIR and CCITT recommendations where applicable. Frequency shift keyed digital transmission through a standard FDM voice channel is analyzed on the basis of the error rate produced for different system conditions.

To evaluate this mode which is in most cases idle noise limited, the system capability in terms of idle system test tone-to-noise is related to spacecraft EIRP for various values of earth station performance in terms of G/T. These curves graphically present the relation between the several combinations of satellite EIRP and earth station G/T available within the ATS Program.

The ability of the AFC loop to correct for long term frequency instability as might be caused by component drift and doppler effects resulting from spacecraft motion is analyzed, measured and compared to CCITT standards. Short term instabilities which are caused by oscillator phase noise, power line frequency modulation, thermal noise and the spacecraft spin modulation are outside the capability of the AFC system to correct. Their effect is analyzed in depth both theoretically and by actual test results. A digital fourier analysis presentation technique was developed and used as an analytical tool to graphically display the resulting frequency spectra. The capability of the automatic level control loop to correct for long and short term disturbances is described and compared to theoretically acceptable limits.

Noise characteristics of the MA mode are examined and four noise components are identified and analyzed. The results of special data error rates and multistation tests are presented.

The FREQUENCY TRANSLATION-TV SECTION describes the capability of the FM/FM mode to transmit TV, both monochrome and color video to meet user requirements, particularly CCIR recommendations where applicable. Continuous random noise, periodic noise, impulsive noise and crosstalk are analyzed under the general category of video channel performance. The capability of the higher spacecraft EIRP to produce higher continuous random (thermal) signal-to-noise ratios in a system which is thermal noise limited is displayed relative to earth station G/T and S/C EIRP. Examples of the resulting high quality TV pictures are also presented. Waveform distortion is compared to CCIR recommendations including such parameters as baseband frequency response, and baseband envelope delay. These parameters are evaluated with and without the use of standard CCIR pre/de-emphasis.

Audio channel performance is evaluated from the viewpoint of noise degradation and waveform distortion, with and without pre/de-emphasis.

The FREQUENCY TRANSLATION-FDM SECTION describes the capabilities of the FM/FM mode to handle up to 1200 one-way voice and data channels, in terms of idle system test tone-to-noise ratio, intermodulation distortion, data error rate, and multiplex channel frequency stability. Where applicable, CCIR recommendations are used as a standard. Test tone to noise ratio is evaluated with and without the use of pre/de-emphasis.

Curves of idle system test tone-to-noise versus EIRP for several earth station G/T values are presented to graphically show system capability and theoretical limitations. Intermodulation noise is treated in depth. Its characteristics over the baseband are determined from theory and from test results of multitone, NPR/TPR, and IF/RF group delay tests. Major sources of intermodulation are identified.

Multiplex channel frequency stability, produced by the multiplex equipment, master oscillator instability and satellite doppler are treated with emphasis on the doppler effect due to range rate of the spacecraft and to the satellite spin effect. The quality of frequency shift keyed digital transmission through a standard FDM voice channel is analyzed by means of a data error rate experiment.

The sections which follow (1.1.2 to 1.1.4) are intended to sufficiently describe, for the communications engineer, the mode analyzed and the performance which it produced. However, those interested in background and supporting data may refer to sections 3, 5, 6, and 7. The tests and test data which provided the basis for these mode analyses are described in section 3. For each test, standards for comparison are listed and the test results analyzed. Section 5 contains a report on significant special investigations required during the course of experimentation in the areas of short term frequency stability in the MA mode. The glossary, references, and appendices are included in sections 6 and 7, respectively.

TABLE 1.1 ATS SPACECRAFT (S/C)

SHF COMMUNICATIONS CHARACTERISTICS

SPACECRAFT	ATS-1	ATS-2	ATS-3	ATS-4	ATS-5
Description	Synchronous Altitude, Spin Stabilized	Medium Altitude Gravity Gradient Stabilized	Synchronous Altitude Spin Stabilized	Synchronous Altitude Gravity Gradient Stabilized	Synchronous Altitude Gravity Gradient Stabilized
Launch Date	Dec. 7, 1966	April 6, 1967	Nov. 5, 1967	Aug. 10, 1968	Aug. 12, 1969
Location	Over the Pacific	Reentered Sep. 2, 1969	Over South America	Reentered Atmosphere Oct. 17, 1968	Over the Pacific (Spin Stabilized)
No. Voice Channels	1200		1200		1200
Modulation Conversion FT Mode MA Mode	 FM/FM SSB-FDMA/ PhM		 FM/FM SSB-FDMA/ PhM		 FM/FM SSB-FDMA/ PhM
Receiver B. W. (Nominal) FT Mode MA Mode	 25 MHz 5.4 MHz		 25 MHz 5.4 MHz		 25 MHz 5.4 MHz
Transmitter BW (Nominal) FT Mode MA Mode	 25 MHz 25 MHz		 25 MHz 25 MHz		 25 MHz 25 MHz
Transmitter Power	Two transponders each containing two-4 watt TWT single/ parallel		Transponder one, two-4 watt TWT single parallel at Transponder two, two 12 watt TWT single/parallel		Two-4 watt TWT single/ parallel
Receive Carrier Frequencies	6212 MHz 6301 MHz		6212 MHz 6301 MHz		6212 MHz
Transmit Carrier Frequencies	4120 MHz 4179 MHz		4120 MHz 4179 MHz		4120 MHz

TABLE 1.1 ATS SPACECRAFT (S/C) (Continued)

SHF COMMUNICATIONS CHARACTERISTICS

SPACECRAFT	ATS-1	ATS-2	ATS-3	ATS-4	ATS-5
Satellite Antenna Characteristics					
Type: Receive	Collinear Array		Mechanically Despun		Planar Array Horn
Transmit	Electronically Phased Array		Cylindrical Parabolic Reflector Coaxially Rotating about linear coaxial feed		Planar Array Horn
Gain: Receive	6.2 db		16.2 db		16.3 db
Transmit	12.7 net db		16.2 db		16.7 db
S/C EIRP	Transponder one or two	ATS-2 not available for communications testing	Transponder one two	ATS-4 not available for communications testing	
1 TWT	49.4 dbm		52.2 dbm 56.5 dbm		51.4 dbm
2 TWT	52.2 dbm		54.6 dbm *		54.4 dbm

* Second TWT failed in orbit

TABLE 1.2. ATS EARTH STATION SYSTEMS

ITEM DESCRIPTION		ROSMAN	MOJAVE	COOBY CREEK
ANTENNA	TYPE	Parabolic Reflector with Subreflector Cassegrain Feed	Parabolic reflector with Subreflector Cassegrain Feed.	Parabolic Reflector with Subreflector Cassegrain Feed.
	Diameter/Mount	85 Ft/X-Y	40 Ft/X-Y	40 Ft/AZ-EL
	Receive Gain (4 GHz) (nom.)	58.4 db	51 db	51 db
	Transmit Gain (6 GHz) (nom.)	61.5 db	54.6 db	54.6 db
	Receive System Noise Temperature (at Zenith)	63°K (Paramp)	63°K (Paramp)	55°/65°K (Paramps)
	Tracking Accuracy	±0.05 deg.	±0.015 deg.	±0.057 deg.
	Receive Beamwidth (P/2)	0.2 deg.	0.47 deg.	0.42 deg.
	Transmit Beamwidth (P/2)	0.13 deg.	0.28 deg.	0.28 deg.
SHF Transmitter	Maximum SHF Transmit Power	Two Redundant 10 kw SHF Transmitters	10 kw	10 kw
SHF Receiver	Simultaneous Capability	Capable of Transmitting Two Channels and Receiving Two Channels Simultaneously (SSB or FT)	Capable of Transmitting One Channel & receiving Two Channels Simultaneously	Capable of Transmitting One Channel & receiving Two Channels Simultaneously

TABLE 1.2. ATS EARTH STATION SYSTEMS (Continued)

ITEM DESCRIPTION		ROSMAN	MOJAVE	COOBY CREEK
	Number of Channels SSB Multiplex	Basic 1200 Channel Capability (One Way) 24 Channels Equipped with 12 ECHO Suppressors and Compandors	Basic 240 Channel Capability (One Way) 24 Channels Equipped with 6 ECHO Suppressors and Compandors	Basic 240 Channel Capability (One Way) 24 Channels Equipped with 6 ECHO Suppressors and Compandors
	TV Tape Recorders	Color and Monochrome Record and Playback	Monochrome-Record and Playback Color-Record Only	Monochrome-Record and Playback Color-Record Only
Overall Capability	G/T ATS-1	38.2 db	32.2 db	32.2 db
	G/T ATS-3	39.6 db	32.2 db	Not visible
Location	Area	near Ashville North Carolina	Goldstone Dry Lake, Mojave Desert, near Barstow, California	Near Toowoomba, Queensland, Australia
	Latitude	35° 11' 35.4" North Lat.	35° 17' 48" North Lat.	27° 23' South Lat.
	Longitude	82° 52' 22" West Long.	116° 53' 57" West Long.	151° 57' East Long.

TABLE 1.3. MULTIPLEX CHANNEL TEST TONE-TO-NOISE RATIOS MULTIPLE ACCESS (SSB-FDMA/PhM) MODE, SINGLE STATION OPERATION

System / Satellite	Measured ATS-1	Measured ATS-3			Predicted ATS-1	Predicted ATS-3			EIA	CCIR/ CCITT
EIRP (dbm) Nominal	52.2	52.2	54.6	56.5	52.2	52.2	54.6	56.5		
85 Foot Antenna - 1200 Channel Loading										
Idle System										
FDM Channel (F1A Weighted)										
342 KHz (db)	43.8	43.7	45.6	46.3	45.4	45.6	46.6	47.5	N/A	N/A
5340 KHz (db)	44.0	43.3	45.4	46.3	45.4	45.6	46.6	47.5	N/A	N/A
Loaded System										
FDM Channel (F1A Weighted)										
342 KHz (db)	40.2	42.2	43.0	43.3	40.3	42.9	43.3	43.7	45.0	50.0
5340 KHz (db)	41.1	42.1	43.0	43.3	40.3	42.9	43.3	43.7	45.0	50.0
40 Foot Antenna - 240 Channel Loading										
Idle System										
FDM Channel (F1A Weighted)										
342 KHz (db)	38.1	38.5	40.7	-	40.5	40.5	42.5	44.0	N/A	N/A
1248 KHz (db)	39.8	39.5	41.2	-	40.5	40.5	42.5	44.0	N/A	N/A
Loaded System										
FDM Channel (F1A Weighted)										
342 KHz (db)	37.4	37.9	39.9	-	39.5	40.5	42.3	43.7	45.0	50.0
1248 KHz (db)	38.7	38.2	40.9	-	39.5	40.5	42.3	43.7	45.0	50.0

TABLE 1.4. MULTIPLEX CHANNEL TEST TONE-TO-NOISE RATIOS FREQUENCY TRANSLATION (FM/FM) MODE, WITHOUT PRE/DE-EMPHASIS

System	Measured				Predicted				EIA	CCIR/ CCITT
Satellite	ATS-1	ATS-3			ATS-1	ATS-3				
EIRP (dbm) Nominal	52.2	52.2	54.6	56.5	52.2	52.2	54.6	56.5		
85 Foot Antenna - 1200 Channel Loading										
Idle System										
FDM Channel (F1A Weighted)										
342 KHz (db)	56.4	58.6	60.2	62.3	60.7	61.7	63.0	64.1	N/A	N/A
5340 KHz (db)	34.6	36.7	38.1	39.9	36.9	37.9	39.2	40.3	N/A	N/A
Loaded System										
FDM Channel (F1A Weighted)										
342 KHz (db)	56.4	56.8	57.6	58.4	58.1	60.1	61.0	61.6	45.0	50.0
5340 KHz (db)	34.2	36.4	37.8	38.1	35.5	36.9	37.9	38.8	45.0	50.0
40 Foot Antenna - 240 Channel Loading										
Idle System										
FDM Channel (F1A Weighted)										
342 KHz (db)	60.6	59.6	62.5		61.0	61.1	63.1	64.5	N/A	N/A
1248 KHz (db)	49.1	49.4	51.3		49.8	49.9	51.9	53.3	N/A	N/A
Loaded System										
FDM Channel (F1A Weighted)										
342 KHz (db)	56.8	56.1	57.7		58.2	59.7	61.0	61.8	45.0	50.0
1248 KHz (db)	47.3	47.7	49.6		47.6	48.7	50.1	51.1	45.0	50.0

TABLE 1.5. MULTIPLEX CHANNEL TEST TONE-TO-NOISE RATIOS FREQUENCY TRANSLATION (FM/FM) MODE, WITH PRE/DE-EMPHASIS

System / Satellite	Measured				Predicted				EIA	CCIR/ CCITT
	ATS-1	ATS-3			ATS-1	ATS-3				
EIRP (dbm) Nominal	52.2	52.2	54.6	56.5	52.2	52.2	54.6	56.5		
85 Foot Antenna - 1200 Channel Loading										
Idle System										
FDM Channel (F1A Weighted)										
342 KHz (db)	53.2	55.2	56.5	58.5	56.7	57.7	59.0	60.1	N/A	N/A
5340 KHz (db)	39.6	41.6	41.9	43.5	40.9	41.9	43.2	44.3	N/A	N/A
Loaded System										
FDM Channel (F1A Weighted)										
342 KHz (db)	52.8	54.2	55.3	55.6	54.1	56.1	57.0	57.8	45.0	50.0
5340 KHz (db)	38.7	40.5	41.5	42.5	39.5	40.9	41.9	42.8	45.0	50.0
40 Foot Antenna - 240 Channel Loading										
Idle System										
FDM Channel (F1A Weighted)										
342 KHz (db)	56.6	57.5	59.6	-	58.0	58.1	60.1	61.5	N/A	N/A
1248 KHz (db)	51.6	52.0	55.6	-	53.8	53.9	55.9	57.3	N/A	N/A
Loaded System										
FDM Channel (F1A Weighted)										
342 KHz (db)	50.3	50.2	51.6	-	55.2	56.7	58.0	58.8	45.0	50.0
1248 KHz (db)	51.5	50.7	53.7	-	51.6	52.7	54.1	55.0	45.0	50.0

TABLE 1.6. TELEVISION VIDEO AND AUDIO SIGNAL-TO-NOISE RATIOS
FREQUENCY TRANSLATION (FM/FM) MODE

System	Measured				Predicted				EIA	CCIR/ CCITT
Satellite	ATS-1	ATS-3			ATS-1	ATS-3				
EIRP (dbm) Nominal	52.2	52.2	54.6	56.5	52.2	52.2	54.6	56.5		
85 Foot Antenna - Idle System										
Without Pre/De-emphasis										
Video (CCIR Weighted) (db)	48.5	-	50.6	51.1	48.8	48.8	50.1	51.2	55.0	56.0
Audio Channel (db)	54.7	56.3	57.6	57.6	54.8	55.8	57.1	58.2	55.0	61.0
*With Pre/De-emphasis										
Video (CCIR Weighted) (db)	50.3	-	53.2	-	50.4	51.4	52.7	53.8	55.0	56.0
Audio Channel (db)	-	-	-	-	66.8	67.8	69.1	70.2	55.0	61.0
40 Foot Antenna - Idle System										
Without Pre/De-emphasis										
Video (CCIR Weighted) (db)	42.5	-	45.5	46.9	43.1	43.2	45.4	46.9	55.0	56.0
Audio Channel (db)	52.8	-	50.0	-	50.1	50.2	52.5	53.9	55.0	61.0
*With Pre/De-emphasis										
Video (CCIR Weighted) (db)	-	-	48.3	-	45.7	45.8	48.0	49.5	55.0	56.0
Audio Channel (db)	-	-	58.5	-	62.1	62.2	64.5	65.9	55.0	61.0

* S/N Ratios Measured with Pre/De-emphasis Applied Separately to Video and Audio Channels

TABLE 1.7. MULTIPLEX CHANNEL NOISE POWER RATIO

System	Measured								Predicted			
Satellite	ATS-1		ATS-3						ATS-1	ATS-3		
EIRP (dbm) Nominal	52.2		52.2		54.6		56.5		52.2	52.2	54.6	56.5
	NPR	TPR	NPR	TPR	NPR	TPR	NPR	TPR	TPR	TPR	TPR	TPR
85 Foot Antenna - 1200 Channel Loading SSB-FDMA/PhM Mode												
342 KHz	20	22	23	24	24	26	24	26	26	26	27	27
768 KHz	20	23	23	24	24	26	24	26	26	26	27	27
1248 KHz	20	23	23	24	24	26	24	26	26	26	27	27
2438 KHz	20	23	23	24	24	26	24	26	26	26	27	27
5340 KHz	20	23	23	24	24	26	24	26	26	26	27	27
85 Foot Antenna - 1200 Channel Loading FM/FM Mode Without Pre/De-emphasis												
342 KHz	38	38	38	40	40	40	40	43	42	42	44	45
768 KHz	32	32	32	33	33	33	33	36	35	35	37	38
1248 KHz	27	27	28	29	29	29	28	31	31	31	33	34
2438 KHz	21	21	22	23	23	23	23	26	25	25	27	28
5340 KHz	13	13	14	15	16	16	16	18	18	18	20	21
85 Foot Antenna - 1200 Channel Loading FM/FM Mode With Pre/De-emphasis												
342 KHz	34	34	37	38	37	37	37	39	38	38	40	41
768 KHz	28	28	31	32	30	31	30	33	32	32	34	35
1248 KHz	23	23	27	28	26	27	25	28	29	29	31	32
2438 KHz	19	19	22	23	22	23	22	24	25	25	27	28
5340 KHz	17	17	20	21	20	21	20	21	22	22	24	25

Note: Multiplex Channel Test Tone/Noise Ratio ≈ NPR + 19.5 db.

TABLE 1.7. MULTIPLEX CHANNEL NOISE POWER RATIO (Continued)

System	Measured								Predicted			
Satellite	ATS-1		ATS-3						ATS-1	ATS-3		
EIRP (dbm) Nominal	52.2		52.2		54.6		56.5		52.2	52.2	54.6	56.5
	NPR	TPR	NPR	TPR	NPR	TPR	NPR	TPR	TPR	TPR	TPR	TPR
40 Foot Antenna - 240 Channel Loading SSB-FDMA/PhM Mode												
342 KHz	19	19	18	18	20	21	20	20	22	22	23	23
768 KHz	20	20	19	19	20	21	21	21	22	22	23	23
1248 KHz	20	20	19	19	18	20	21	21	22	22	23	23
40 Foot Antenna - 240 Channel Loading FM/FM Mode Without Pre/De-emphasis												
342 KHz	37	41	31	39	39	42	-	-	42	42	44	-
768 KHz	32	33	30	34	34	35	-	-	35	35	37	-
1248 KHz	27	28	27	29	30	31	-	-	31	31	33	-
40 Foot Antenna - 240 Channel Loading FM/FM Mode With Pre/De-emphasis												
342 KHz	31	36	23	36	31	39	-	-	39	39	41	-
768 KHz	30	32	25	33	32	35	-	-	35	35	37	-
1248 KHz	31	31	30	32	33	34	-	-	34	34	36	-

Note: Multiplex Channel Test Tone/Noise Ratio = NPR + 17.7 db.

TABLE 1.7. MULTIPLEX CHANNEL NOISE POWER RATIO (Continued)

System	Measured				Predicted	
Satellite	ATS-1		ATS-3		ATS-1	ATS-3
EIRP (dbm) Nominal	52.2		54.6		52.2	54.6
	NPR	TPR	NPR	TPR	TPR	TPR
40 Foot Antenna - 1200 Channel Loading SSB-FDMA/PhM Mode						
342 KHz	*	*	19	20	-	23
768 KHz	*	*	19	20	-	23
1248 KHz	*	*	19	20	-	23
2438 KHz	*	*	19	20	-	23
5340 KHz	*	*	19	20	-	23
40 Foot Antenna - 1200 Channel Loading FM/FM Mode Without Pre/De-emphasis						
342 KHz	31	32	34	35	35	37
768 KHz	27	28	30	30	28	30
1248 KHz	23	24	25	25	24	26
2438 KHz	18	18	20	20	18	21
5340 KHz	10	10	11	11	11	13
40 Foot Antenna - 1200 Channel Loading FM/FM Mode with Pre/De-emphasis						
342 KHz	28	29	31	31	31	33
768 KHz	24	25	26	26	25	27
1248 KHz	21	22	22	22	22	24
2438 KHz	17	18	19	19	18	20
5340 KHz	13	13	15	15	15	17

Note: Multiplex Channel Test Tone/Noise Ratio = NPR + 19.5 db.

* No Data for 1200 Channel Loading Due to Limitation in SSB Power.

TABLE 1.8. MULTIPLEX CHANNEL TEST TONE-TO-NOISE RATIO, MULTIPLE ACCESS (SSB-FDMA/PhM) MODE. MULTISTATION OPERATION

STATION AND SATELLITE LOADING	ATS-1 SATELLITE EIRP 52.2 dbm								ATS-3 SATELLITE EIRP 54.6 dbm							
	LOADED SYSTEM MEASURED CHANNEL TT/N RATIO - db				IDLE SYSTEM MEASURED CHANNEL TT/N RATIO - db				LOADED SYSTEM MEASURED CHANNEL TT/N RATIO - db				IDLE SYSTEM MEASURED CHANNEL TT/N RATIO - db			
	342 kHz	1248 kHz	2438 kHz	5340 kHz	342 kHz	1248 kHz	2438 kHz	5340 kHz	342 kHz	1248 kHz	2438 kHz	5340 kHz	342 kHz	1248 kHz	2438 kHz	5340 kHz
COOBY CREEK																
(G/T = 32.2 db)																
240 Channels	37.5	37.7			38.0	37.8			Not visible							
640 Channels	36.4	37.9	37.4		37.7	38.4	37.8									
940 Channels	32.6	35.7	36.7		36.8	37.9	37.7									
1200 Channels	24.5	33.2	35.5	36.5	36.7	37.8	37.5	37.5								
MOJAVE																
(G/T = 32.2 db)																
240 Channel	33.9	35.1			34.1	35.3			39.0	40.7			40.1	41.0		
640 Channel	31.2	36.1	36.9		34.0	37.4	36.9		39.4	40.4	40.9		40.2	41.3	40.9	
940 Channel	28.9	34.7	35.7		35.2	37.3	37.2		38.6	40.7	40.2		40.6	42.0	41.2	
1200 Channel	23.7	32.6	35.0	36.5	37.7	38.3	37.5	37.5	34.1	39.4	39.0	37.5	42.6	43.6	41.0	40.5
ROSMAN																
(G/T = 39.6 db)																
240 Channel	39.5	40.1			40.1	40.5			42.7	44.7			44.7	45.9		
640 Channel	39.2	40.2	41.1		40.6	41.2	42.1		43.5	44.9	46.4		44.5	45.9	47.2	
940 Channel	39.3	39.6	39.7		40.7	40.9	40.8		43.6	44.3	45.5		45.2	46.8	47.0	
1200 Channel	34.8	38.4	38.9	40.0	41.9	41.9	43.2	43.5	41.8	43.1	43.4	43.9	47.0	48.2	47.2	47.0

Note: Satellite channel loading shown in divided among the three earth stations except Cooby Creek and Mojave load up to 120 channels each with Rosman making up the remainder.

TABLE 1.9. FREQUENCY DIVISION MULTIPLEX CHANNEL PERFORMANCE

Parameter	Mode	Measured	CCIR/CCITT	EIA
Frequency Stability	SSB-FDMA/PhM	Representative RMS frequency error varies from 3.5 Hz to 4 Hz (short term stability) can be reduced to 2.3 Hz utilizing the reference carrier stabilization technique. Long term frequency instability overall percent of secondly average frequency errors < 2 Hz, 95% of test time.	CCITT - G.225 Freq. error shall not exceed 2 Hz in MUX voice channel	Spec not applicable
Test Tone Level Stability		≤ 2 db (based on variation of test tone level for 80% of the secondly samples measured).	CCITT - G.121 Standard deviation of overall loss with time <1.0 db	Spec not applicable
Frequency Response		Within ±0.5 db from 300 to 3500 Hz	±1.3 db from 600 to 2400 Hz. +1.3, -2.6 db at 400 and 3000 Hz +1.3, -4.4 db at 300 and 3400 Hz	+1, -3 db from 300 Hz to 2500 Hz
Envelope Delay		0.7 millisec at 500 Hz 0.5 millisec at 3.2 kHz 1.2 millisec at 3.4 kHz (Referenced to 0 at about 1200 Hz)	≤20 millisec at 300 Hz ≤10 millisec at 3400 Hz	Not specified
Harmonic Distortion (Total Distortion)		< 1% at 500 Hz < 0.5% at 1000 Hz (2.4%)	≤5% at 800 Hz	≤5% at 1 kHz
Test Tone Level Stability	FM/FM (FT)	No fluctuations measurable.	CCITT - G.121 Standard deviation of overall loss with time <1.0 db	Spec not applicable
Frequency Response		Same as above	See above	See above
Envelope Delay		Same as above	See above	See above
Harmonic Distortion		Same as above	See above	See above

TABLE 1.10. TELEVISION VIDEO CHANNEL PERFORMANCE

Test		Measured		CCIR, CCITT	EIA
VIDEO CHANNEL		w/o Pre-Emphasis	With Pre-Emphasis		
Signal to Noise		See Table 3.1 & 3.2		-	-
Power Supply Hum		43 to 50db down	33 to 40db down	35 db down	37 db down
Linear Waveform Distortion	Field Rate	3%	<1%	10% (5% in U.S. and Canda)	-
	Line Rate	1%	≈1%	5% (1% in U.S. and Canda)	-
Short-time Linear Waveform Distortion		5.8%	≈7.4%	20% (13% in U.S. and Canda)	-
Insertion Gain Variations		Negligible	Negligible	±0.3 db (±0.2 db in US & Canada)	
Line-time Non-linearity Distortion		APL 10% 50% 90%	Mean 6.5% 7.0% 4.5%	(13% in US & Canada) 20% (International)	APL MAX 10% 11% 50% 7% 90% 11%
Color Vector Error					
- Amplitude		7%	< 2.5%	20%	20% FCC Limits
- Phase		3.5 degrees	<1.5 degrees	10°	10 degrees FCC Limits

TABLE 1.10. TELEVISION VIDEO CHANNEL PERFORMANCE (Continued)

Test	Measured	CCIR, CCITT	EIA
VIDEO CHANNEL (Continued)			
Frequence Response (Baseband)	The non-emphasized baseband frequency response is within -1db up to 2.7 MHz and is down 2.5db at 4 MHz. The pre-emphasized baseband frequency response is down 1db at 2 MHz and 3db at 4 MHz.	CCIR (US & Canadian) ±0.16 db between 10 kHz and 300 kHz, increasing linearly to ±0.63 db at 4 MHz.	CCIR (INTERNATIONAL) ±1 db from 160 to 800 kHz. Linear increase to ±2 db at 3.2 MHz. Linear increase to +2.5, -4 db at 4 MHz.
Baseband Envelope Delay	Variations less than ±25 nsecs to over 4 MHz for both non-emphasized and pre-emphasized basebands	CCIR (US & Canadian) ±32 nsec between 10 kHz and 3 MHz, thence increasing linearly to ±63 nsec at 4 MHz.	CCIR (INTERNATIONAL) ±100 nsec from 160 to 800 kHz. Linear increase to ±500 nsec at 4 MHz.

TABLE 1.11. TELEVISION AUDIO CHANNEL PERFORMANCE

Test	Measured		CCIR, CCITT	EIA
	w/o Emphasis	With Pre-Emphasis		
AUDIO CHANNEL				
Idle Noise	See Tables 3.1 and 3.2		-	-
Power Supply Hum	> 60db down	> 60db down	-	-
Video Crosstalk				
- Field Rate (60 Hz)	> 40 to > 55db down	> 60db down	-	-
- Line Rate (15.75 kHz)	> 65db down	> 70db down	-	-
- Picture Signal (other)	None		-	-
Frequency Response	+ 0, -1db between 100 and 10,000 Hz, -3db points at approx. 40 Hz and 13 kHz.	-3db points at approx. 40 Hz and 8 kHz	±0.9 db between 50 Hz, and 10 kHz, + 0.9, -4.3db at 30 Hz and 15 kHz	+ 0, -1db between 100 and 7500 Hz. + 0, -1.5db at 50 Hz + 0, -2.5db at 15 kHz
Harmonic Distortion	3.3% at 100 Hz 3.1% at 1 kHz 2.3% at 5 kHz	>1.5% >1% >1%	3% at fundamental frequencies below 100 Hz 1% at fundamental frequencies above 100 Hz to 7.5 kHz 3% at fundamental frequencies above 7.5 kHz	1.5% 50-100Hz 1.0% 100-7500 Hz 1.25% 7500-15000 Hz

1.2 MULTIPLE ACCESS MODE (SSB-FDMA/PhM)

1.2.1 INTRODUCTION

In a satellite communications system it is possible to operate with either single or multiple earth station access to the satellite. In the former case, a signal from one earth station enters the satellite transponder, and after amplification and other processing, it is retransmitted to another station (or possibly to a multiplicity of other stations). A second path in the return (or any other) direction is provided by an additional transponder. The use of the SHF frequency translation transponder in the ATS spacecrafts for sending a television picture from one earth station to another is an example of single access operation.

In the multiple access mode of operation, signals may pass through the S/C transponder between various pairs of earth stations. There are many different methods by which multiple access to a transponder may be achieved; they include the three main classes of frequency division, time division, and spread spectrum. Each of these three main classes includes a number of variations. The optimum method in any particular case depends upon considerations of S/C power, frequency allocations, the number of earth stations, the channel capacity, the possible need for mixing earth stations of different sensitivities, the possible need for security or privacy, the possible need for a priority override system, the possible need to mix different kinds of channels, and the requirement for access on a pre-assigned or on a demand basis. There is therefore no single optimum method of achieving multiple access, since each system configuration will have different requirements which will dictate a different optimum solution.

Some of the more popular methods of achieving multiple access have been reviewed by the CCIR Study Groups. CCIR Working Group IV-A (Doc IV/181 - E. 3rd. Oct. 1958) has issued a draft revision of report 211-1 on active Communication-Satellite Systems in which some of the more important modulation and multiple access methods are discussed. The ATS multiple access mode is similar to example B in the CCIR report. CCIR example B uses SSB signals from earth to the satellite, and FM signals from the satellite to earth. In the ATS system, PhM signals are used for the downlink.

The advantages of the ATS multiple access mode are:

1) The SSB uplink makes optimum use of the available spectrum, since it requires the least bandwidth for a given information bandwidth.
2) The use of a single PhM downlink to send information to all the earth stations requires less S/C transmitter power handling capability in comparison to that required with multiple carrier methods.
3) No time synchronization is required.

4) As indicated above, this mode can be used for any form of channel assignment from totally preassigned to totally demand assigned. Changes in assignment require no changes in hardware, except that all the multiplex channels involved must be available at each earth station.

5) The system is fully compatible with standard FDM multiplex used on terrestrial systems without the need for demultiplexing and remultiplexing.

6) Stations may come on and off without interference to those already in use provided pilot frequencies do not interfere with each other.

7) Hard limiting by the spacecraft transponder does not degrade performance since only one carrier is present.

Some of the more important limitations of the mode are:

1) The transponder can be used only for this type of signal; although command controlled switching would make it possible to use the spacecraft transmitter for other modes of operation, for example television.

2) In an operational system, all the earth stations require essentially the same receiver performance (same G/T).

3) Due to the system transport lag, the AFC cannot compensate for factors that cause short term frequency instability of the received signals.

4) The earth station SSB transmitter must be linear over the dynamic range of the input signal.

5) The spacecraft received signal level from each transmitting station must be controlled accurately.

A very important part of the experiment is evaluation of the effects of the satellite orbit and stabilization method on system performance. For example, the effects of modulation (both PhM and AM) due to spin in the case of the spin-stabilized satellites are evaluated. The effects of eclipse of the satellite on the antenna pointing system and the increase in noise due to solar conjunction are also evaluated.

In evaluating the overall usefulness of the multiple access mode to possible future users, the performance results obtained are compared to various accepted user standards. Where applicable and available, CCIR recommendations for the performance of multichannel signals on satellite links are employed. The comparison (See section 3) with user standards in the multiple access mode center around the performance of the individual voice channels. Comparisons are made on the basis of test tone-to-noise ratios (noise levels) under various system loading conditions, channel level stability, channel amplitude and phase responses, total channel distortion, and, most importantly, channel frequency stability and unwanted modulation of the signals by hum and noise. In addition, digital data transmission over voice channels is evaluated in terms of data error rate.

In evaluating the SSB-FDMA/PhM mode, the following subjects are discussed in the subsequent paragraphs:

1.2.2 Mode Description
1.2.3 Summary of Results
1.2.4 Frequency Stability
1.2.5 Level Stability
1.2.6 Test Tone-to-Noise
1.2.7 Noise Characteristics of the SSB/PhM Mode
1.2.8 Data Error Rate
1.2.9 Multistation Performance

The first two subsections contain a complete functional description of the SSB-FDMA/PhM mode. This is followed by a discussion of the overall performance of the mode based on the ATS test data. Next the frequency and level stability factors are discussed and test measurements given to show the effects of these parameters on the operation of the SSB/PhM Mode. The SSB uplink can be readily affected by these parameters. Interference to stations using the satellite from stations attempting access to the satellite is also discussed. Both idle system test tone-to-noise ratios (TT/R) and loaded system test tone-to-noise (TT/N) ratios are presented for the various ATS earth station-satellite system configurations. The TT/R ratio is a direct measure of the test tone power relative to the thermal noise power. Hence, this is the ratio that would be obtained in an ideal system. In any operating system, the noise power due to intermodulation can be much higher than the thermal noise power; hence, the operational test tone power to noise power ratio can be lower than the TT/R. The merit in computing TT/R is the fact that it is the maximum ratio possible with a given system. Also shown in this section are the system configurations which are uplink and downlink limited. This fact can be used to define which system parameter to improve to obtain a higher test tone to-noise ratio if it is desired.

The two basic noise types (thermal noise and intermodulation noise) as modified by threshold operation and which determine the actual system noise level, are discussed in the subsection entitled, "Noise Characteristics of the SSB/PhM mode." These noise types are defined and their magnitude and spectral characteristics shown, as well as their relationship to system parameters such as carrier-to-noise ratio.

The next subsection discusses multiplex channel performance in terms of digital data transmission. Bit error rate, as a function of multiplex channel TT/N ratio, is presented for single station operation and is compared to theoretical curves for non-coherent FSK and applicable baud rates. Next multiplex channel TT/N ratio is presented for multi-station operation (three stations participating) as a function of satellite loading, baseband frequency and carrier-to-noise ratio and is compared to single station performance.

1.2.2 MODE DESCRIPTION

1.2.2.1 Basic Operation

In the ATS multiple access mode, voice channels in standard FDM multiplex are translated by the earth terminal transmitter to SSB signals at 6 GHz and are transmitted to the S/C transponder. Each of the earth stations utilize different channels which arrive at the satellite as a composite (1200 channel maximum) SSB spectrum at 6 GHz. The S/C transponder then uses this composite signal to phase modulate (PhM) a 4-GHz carrier. This PhM signal is received by all the earth stations and demodulated to recover the full baseband spectrum. Each earth station then demultiplexes those channels which it desires to utilize. Channel assignments are completely flexible; they can be totally preassigned, in which case each pair of stations uses only a certain group or set of groups of channels in the baseband; they can be totally demand assigned, in which case each earth station would monitor all the channels to determine which is vacant and thus available for use; or, more realistically, channels can be preassigned, but the assignments would change with demand as influenced by station traffic.

To compensate for unavoidable frequency errors in the earth station and S/C oscillators, and for doppler shifts on the transmission paths, it is necessary for each station to transmit a unique pilot tone through the S/C. This tone is then received by the same station and used to offset the transmitter frequency so that the signals arriving from it and all other earth stations at the satellite have the proper frequency relationship. The same tones are also used for level control to compensate for changes of path loss on the SSB uplink. Additional tones are available for compensating for "doppler spread" across the FDM baseband which can occur if the velocity of the satellite relative to the earth station is appreciable. Earth station "lock" to this pilot tone constitutes earth station acquisition of the satellite.

The ATS has demonstrated the ability to pass simultaneously up to 1200 simulated FDM voice channels and up to 480 simulated TDM voice channels. In comparison to other systems in use, their TDM capability is yet to be demonstrated and their FDM capabilities are about one-half that of the ATS. Consequently, the ATS represents an advance in the state-of-the-art by demonstrating the use of up to 1200 channels in a multiple access mode. In addition, it has provided quantitative operational data on a candidate system for an operational multiple access mode.

As already indicated, the success of a multiple access system of the type tested in the ATS program depends primarily on the ability of the frequency and level control loops to operate properly, and upon adequate short term frequency stability in the oscillators. Also of great importance is the ability of the earth station SSB transmitters and the S/C SSB/PhM translator to operate with sufficiently low intermodulation noise. The requirements for adequate signal to overcome the receiver noise are similar to those for an FDM-FM/FM system.

Earth station parameters are summarized in table 1.12 and are presented in detail in tables 1.14 through 1.19 which present system path calculations for all mode configurations. In these calculations, the values for the system factors used to compute the test tone-to-thermal noise ratios were obtained from theoretical calculations. The overall link test tone to noise ratios were obtained by using these calculated test tone to thermal noise ratios and measured values of test tone to intermodulation noise ratios. Table 1.13 summarizes the calculated values of multiplex channel performance for system loaded and idle conditions for each mode configuration.

The calculations are presented for both the 85-foot and 40-foot diameter earth station antennas. Antenna gains and free space losses are calculated for an earth-to-satellite carrier frequency of 6.3 GHz and a satellite-to-earth carrier frequency of 4.17 GHz and a nominal slant range of 22,000 nmi. The actual slant range is dependent upon the relative positions of the satellite and the tracking station and may differ as much as 2000 nmi between an earth station operating with two synchronous satellites (causing up to 0.8 db difference in path loss).

1.2.2.2 Basic Mode Configuration

The SSB-FDMA/PhM mode configuration shown in figure 1.1 basically consists of multiplex send and receive terminals, an SSB transmitter, an antenna, the spacecraft repeater, and a PhM receiver. The input signal consists of one or more voice channels (300 Hz to 3400 Hz BW each), any one of which can be used to transmit digital or facsimile data. These channels are combined by using a frequency division type of multiplexing to expand the number of channels to either 240 or 1200 channels (depending on station capability).

The baseband information is applied to the transmitter where it amplitude modulates a 15-MHz first IF carrier; the lower sideband of this carrier is then selected and mixed with 85 MHz to develop the second IF at 70 MHz. The second IF is upconverted to the desired 6 GHz RF frequency by synthesizing several frequencies derived from an ultra-stable oscillator.

The output of the power amplifier is first applied to a linearly polarized RF feed, then to a duplexer and finally to the parabolic antenna. The Rosman station uses a fully steerable, X-Y mount, cassegrain type antenna that has the ability to transmit and receive simultaneously. The main reflector has a diameter of 85 feet and develops an antenna gain of 61.5 db at 6.3 GHz and 58.4 db at 4.17 GHz. Transmit and receive antenna patterns are shown in figure 1.2.

The Mojave and Cooby Creek stations use similar antennas except the main reflector has a diameter of 40 feet and the Cooby Creek antenna uses an Az-El mount. These 40-foot antennas develop a gain of 54.6 db at 6.3 GHz and 51.0 db at 4.17 GHz. Transmit and receive antenna patterns are shown in figure 1.3.

The spacecraft contains two repeaters (transponders), each capable of operation in two modes. In the multiple access mode, the repeater accepts the simultaneous transmissions from a number of earth stations and converts this composite signal into phase modulation of a carrier (4-GHz band) for transmission to earth stations.

In the case of ATS-1, the receiving antenna consists of a 6-element collinear array spinning with the spacecraft. This array provides omnidirectional coverage in the East-West plane about the satellite with an average gain around the spin axis of 6.2 db. The transmitting antenna is an electronically phased array with 16 elements (each consists of four collinear dipoles) arranged around a circle of one wavelength radius. A phased array control electronics (PACE) system provides phasing control to rotate the beam in such a manner that it remains stationary with respect to the earth. Beamwidth of this phased array is approximately 20 degrees (see figure 1.4) with a net gain of 12.7 db. The PACE control uses reference pulses provided by a sun sensor except during periods of eclipse, when reference pulses are provided from an earth station.

ATS-3 employs a mechanically despun antenna consisting of a cylindrical parabolic collimator. Beamwidth of this antenna is approximately 20 degrees with a transmitting and receiving gain of 16.2 db. A mechanical array control electronics (MACE) system provides beam control in a manner similar to the ATS-1 PACE system. Transmit and receive antenna patterns are shown in polar form in figures 1.5 and 1.6 respectively.

Each repeater contains two TWTs which may be operated singly or in parallel, thereby providing a choice of two power output levels. Each of the TWT's in ATS-1 has a nominal power output of 4 watts. In ATS-3, TWT No. 1 and No. 2 each have 4-watt power outputs; TWT No. 3 and No. 4 each have 12-watt power outputs. However, TWT No. 3 is inoperative, thus limiting the maximum S/C power output to 12 watts. The S/C diplexer routes the 4-GHz outputs of the TWT amplifiers to the antenna for transmission to the earth station. The S/C transmit and receive parameters are summarized in table 1.13 and are also presented in detail in tables 1.14 through 1.19.

The PhM receiver in the earth station contains a low noise parametric amplifier followed by a TWT amplifier (or tunnel diode amplifier). The paramp preamplifier is cooled to a cryogenic temperature of 25°K. After passing through the TWT (or TDA) amplifier, the RF signal is filtered, down-converted to 70 MHz and then amplified and demodulated in a PhM detector consisting of an FM discriminator and a de-emphasis filter. The baseband output from the detector is sent to the multiplex receive equipment where each multiplexed channel is translated to the audio frequency spectrum. A typical baseband frequency characteristic is shown in figure 1.7 for both RF and S/C loops (back-to back and through the spacecraft, respectively).

Conversion from 6 GHz to 4 GHz and conversion from SSB to phase modulation is provided for loop testing of the earth terminal units by use of an RF loop. Figure 1.8 shows a block diagram of this loop. The RF signal may be sampled either before or after the power amplifier, which is terminated into a dummy load during RF loop tests. The monitor receiver detects the SSB baseband signal which in turn phase modulates a 70-MHz IF. This IF is converted to 4 GHz for injection into the receiver RF preamplifier.

1.2.2.3 Automatic Frequency Control (AFC)

Doppler shifts occur because of the time rate of change of the line-of-sight range between the earth station transmitter and the spacecraft transponder. Therefore, to efficiently operate a multiple access FDM communications system, when a relatively large doppler shift is present, each earth station must independently shift the transmitted frequency in a direction required to compensate for the doppler shift plus any long term frequency drift of the spacecraft oscillator. This precorrection permits every multiplex signal to fall within its assigned 4-kHz frequency band in the overall spacecraft receive spectrum.

The overall AFC consists of a primary (closed) AFC loop and secondary open loop defined as an error correction loop. These loops are shown in figures 1.9 and 1.10, respectively. The primary AFC loop is type zero with an open loop gain of 60 db and a 3-db closed loop bandwidth of 0.32 Hz. This low bandwidth is required for loop stability because of the abnormally high transport lag value (T) of 0.27 seconds. Because of the low loop bandwidth, the system can only correct for long term frequency drifts and/or doppler shifts (δ).

The open loop AFC or error correction loop operating by itself applies an inverse δ correction to only the FDM signal in the SSB transmitter. The station pilot frequency F_p is transmitted in an uncorrected state. Because of this fact, this type of loop will only operate if the resulting frequency shift to F_p, in traveling to the spacecraft, and through the spacecraft receiver does not exceed 20 kHz. This value is the maximum offset (measured) that can be impressed on the pilot tone and still realize an open loop frequency correction of the FDM signal. However, in operating with the geostationary satellites it was found that the frequency offset of the S/C oscillator was generally 28 kHz or higher; hence, the error correction loop could not be employed by itself.

For actual operation, both the primary AFC and error correction loops are employed. This operation is explained in conjunction with figure 1.11 and is based on a geostationary satellite; thus the differential doppler correction shown in figure 1.9 is not considered. The δ frequency error is reduced by a factor of 1001 $(1 + K)$ by the primary AFC loop. The resulting residual frequency error, ϵ , is transmitted with the desired FDM and F_p signals. As shown, the ϵ factor is delayed by the transport lag T and any additional delay, T_f, within the baseband unit. This time displaced error is denoted by ϵ'. The error correction loop, (E Loop) in effect, subtracts the error produced by the primary AFC loop (ϵ) from the time displaced value ϵ'. As shown this difference factor is applied to the FDM signal but not the F_p signal. Ideally, the overall AFC operates in this manner: (1) The large frequency offset, δ , is reduced by the $(1 + K)$ factor to a value of ϵ . (2) If no time displacement is present, then $\epsilon = \epsilon'$ and the error correction unit cancels the remaining residual error. However, due to the $(T+T_f)$ factor the resulting residual error in the multiplex channel is modified by the factor of $2 \sin \pi f (T+T_f)$. Hence, the multiplex frequency error spectrum has a sinusoidal character. Assuming $T+T_f$ is approximately 0.27 seconds, the higher frequency errors are cancelled if they fall at multiples of 3.7 Hz. Also, the frequency components at 1.85 Hz, and multiples thereof, are increased by a factor of 6 db.

1.2.2.4 Automatic Level Control (ALC)

The primary purpose of the ALC is to maintain a constant received signal level at the spacecraft transponder.

Initially the spacecraft transponder receives the F_p pilot which is shifted by the frequency δ and retransmits the signal to the earth station. The pilot tone $(F_p + \delta)$ is recovered by the earth station receiver and applied to a bandpass filter in the pilot alarm and monitor unit. (See figure 1.20.) The output is rectified to develop a DC voltage proportional to the amplitude of the received pilot tone. This DC voltage is applied to a differential amplifier assembly and compared with a reference voltage. If the DC voltage is not within 0.1 db of the reference voltage, an increase or decrease level command is transmitted to the exciter unit. There a relay is energized, either manually or automatically which in turn controls a motor driven attenuator located in the intermediate power amplifier. This attenuator adjusts the drive level to the klystron in the power amplifier section.

Thus, any variation in the received pilot tone $(F_p + \delta)$ will in turn cause a change in the drive level applied to the klystron which controls the transmitter power output, thereby maintaining a constant received signal level at the S/C transponder.

The bandwidth of the ALC loop is limited by the 0.27 transport lag of the S/C loop and the finite speed limitation of the motor driven attenuator. These factors limit the response rate to 0.1 db per second.

1.2.2.5 Multiplex Equipment

The FDM equipment utilizes single sideband, suppressed carrier techniques to "stack" the voice channels in groups of twelve channels each. Referring to figures 1.12 and 1.13, the audio signal for channel 1 is used to amplitude modulate a 108-kHz subcarrier. The lower modulation sideband is filtered to provide a signal spectrum from 104.6 kHz to 107.7 kHz. In a similar manner, the channel 2 signal spectrum is limited to frequencies from 100.6 kHz to 103.7 kHz. The process is continued until all twelve channels are spaced in frequency from 60 kHz to 108 kHz (this spectrum constitutes a group). The various group signals are then used to modulate a group carrier. The process is extended to build up super-groups, mastergroups, and supermaster groups until all of the voice channels are placed in their proper frequency location. In the MUX equipment block diagrams, a triangle is used to symbolize the filter which separates the desired sideband energy from the carrier and unwanted sideband (a triangle with a positive slope indicates that the upper sideband is selected; conversely, a downward or negative slope indicates that the lower sideband is used). It should be noted that the Rosman station (figure 1.12) uses two identical mastergroups (designated MG3) which carry information at 11156 kHz to 12388 kHz. The mastergroups form part of two separate supermaster groups which are combined to provide the total baseband. Each of the supermaster groups is a standard 900-channel system (although in the ATS system one of the supermaster groups carries only the upper frequency spectrum).

Since the ATS system is not intended to be an operational system, there is no requirement to use all 1200 channels (240 at Mojave and Cooby Creek); consequently, only two twelve channel groups are provided at each terminal. Each group may be placed anywhere within the baseband as shown in figures 1.12 and 1.13.

It should be pointed out that the channel subcarrier frequencies are derived from separate master oscillators for the transmit and receive terminals. This allows shifting of each unit if desired for frequency corrections when operating with other stations.

1.2.3 SUMMARY OF PERFORMANCE

Considering the various combinations of the two synchronous orbit, spin stabilized satellites (EIRP from 49.4 dbm to 56.5 dbm) and three earth stations (theoretical G/T of 32.2 db and 39.6 db) presently available in the ATS experimental SSB-FDMA/PhM mode, no one combination (satellite and single earth station) achieves the CCIR recommended multiplex channel TT/N ratio of 50 db (psophometrically weighted). The closest approach (without compandors) at full 1200-channel system capacity is 43.3 db (F1A weighted) utilizing ATS-3

(EIRP of 56.5 dbm) and an 85-foot antenna (G/T of 39.6 db). By way of comparison, a TT/N ratio of 37.4 db is obtained by utilizing ATS-1 (EIRP of 52.2 db) and a 40-foot antenna (G/T of 32.2 db), and also by limiting system capacity to a 240-channel spectrum.

In the case of ATS-1, it has been determined that the uplink limitation is intermodulation noise for all combinations of the satellite and earth stations. In the downlink, intermodulation noise is the limiting factor for the large earth station (G/T of 39.6 db) while thermal noise is the limitation for the medium earth stations (G/T of 32.2 db). These results are based on a 1200-channel spectrum (nominal 30-MHz receiver IF filter) at the large earth station and a 240-channel spectrum (nominal 12-MHz receiver IF filter) at the medium earth stations. A 240-channel spectrum is used at the medium earth stations to realize above threshold operation.

For ATS-3 operation, the uplink limitation is thermal noise for all combinations of the satellite and earth stations. The downlink limitation follows the same pattern described for ATS-1. These results are based on the same channel spectra described for ATS-1. Using ATS-3 at full 1200-channel system capacity, medium station operation is at or near threshold.

On a systems basis, the ATS-1 uplink intermodulation noise limitation is attributed to intermodulation noise generated in the earth station transmitter. The ATS-3 to large earth station downlink limitation is attributed to intermodulation noise generated in the spacecraft and the earth station receiver.

Multiplex channel performance for the multistation combinations (either satellite and at least two earth stations) is limited, in the case of ATS-1, by the lower C/N ratios. The threshold noise effect, which is emphasized in multiplex channels at the low end of the baseband spectrum, results in TT/N ratios around 25 db in the 342-kHz channel. A lesser effect is noticed in the higher frequency channels evidenced by TT/N ratios around 36 db at 2438 kHz and above. At high C/N ratios, performance is essentially the same as that described for the single earth station. With a mix of large and medium earth stations improved performance at the medium earth stations is best achieved by assigning channels at the high end of the baseband to these stations. In addition, improved performance is achieved by limiting system channel capacity and by over deviating a limited channel spectrum (60 channels) at the low end of the baseband for reception by the medium earth stations.

Multiplex channel TT/N ratios (37.4 db and 43.7 db) were found more than adequate for the transmission of FSK digital data. The bit error rate has been better than 6.3×10^{-7} based on no errors received in 1.58×10^{6} bits transmitted.

TT/N performance in a multiplex channel during periods of solar conjunction (earth station, S/C and sun in line) cannot be evaluated due to the masking of the signal by the noise. However, approximately two minutes of degraded performance exists between the start of the conjunction period and the time that threshold is reached. An equivalent time interval of degraded performance occurs near the end of the period, resulting in a net system outage of five minutes out of a typical 9-minute conjunction period.

Frequency stability has been evaluated for two control techniques, open loop and closed loop AFC. Long term stability presents no problem if the closed loop AFC is used. In this case, long term drift, including both earth station and S/C oscillators, as well as doppler, need not be better than one part in 10^7. Open loop AFC generally cannot be used due to the large S/C frequency offset, which causes the system pilot frequencies to fall within the multiplex band of frequencies.

Due to the large system propagation delay (0.27 second) of the synchronous orbit satellite, short term frequency errors cannot be corrected by the closed loop AFC. In particular, discrete power line frequency components on the 6-GHz signal are a problem. Individual components have been suppressed to levels greater than 40 db below test tone.

Oscillator 1/f phase noise has been examined in detail. Based on certain qualifying assumptions regarding the subjective intelligibility of voice communication, short term frequency stability of some 3 parts in 10^{11} for a 1-second averaging time appears justified. The present SSB-FDMA/PhM mode achieves a stability of some 5 parts in 10^{10} for a 1-second averaging time.

One measure of the short-term tone-frequency instability is the standard deviation σ of the frequency-of-occurrence histogram described in the ATS SHF Special Communications Experiments document. For operation with ATS-1, a σ of 4 Hz is obtained; with ATS-3, a σ of 9 Hz is obtained. The σ for the latter case is greater because of large spurious frequency components that are present in the 130-Hz to 200-Hz region of the test-tone-error spectrum. These components are generated in the ATS-3 spacecraft; however, their specific source is not known.

A reference carrier stabilization technique utilizing supergroup correction reduces the components caused by incidental angle modulation, by a factor of approximately 40 db. A reduction of approximately 2 Hz in the σ value is obtained by utilizing this technique. It has been shown that the error correction loop (E loop) and the reference carrier technique have an amplification effect on thermal noise. Because of this fact, thermal noise is the major limiting factor in degrading the short term frequency instability for operation with ATS-1. For operation with ATS-3, the large spurious frequency components present in the 130-Hz to 200-Hz region of the error spectrum are the limiting factors.

In the SSB-PhM mode, level stability is primarily a function of the earth to S/C link. Level variations caused by long term phenomena, such as variations in earth station

EIRP, atmospheric effects, S/C receiver sensitivity and variations in the antenna pointing angle are held by the ALC (0.1 db/sec) within acceptable limits (±2.0 db) of the intended channel level. A level variation at the 1.6-Hz spin rate is beyond the control bandwidth of the ALC and therefore represents an operational limit on the SSB-PhM Mode. However, this short term variation has no noticeable effect on voice communications.

The basic multiplex channel amplitude versus frequency, envelope delay and linearity characteristics shown in figures 1.14 through 1.16 are entirely adequate for voice communications. Channel distortion due to harmonic distortion terms averaged less than 1.0 percent. However, 60-Hz and spin modulation sidebands contributed by the SSB uplink cause channel total distortion to vary from 1.9 to 4.9 percent depending on the earth station-satellite combination.

TABLE 1.12 SSB-FDMA/PhM MODE OPERATING PARAMETERS (EARTH STATIONS)

Parameters	Rosman 85' Antenna	Mojave and Cooby Creek 40' Antenna
Channel Spectrum (No. of Channels)	1200*	240**
RF Frequency (uplink)		
Transponder No. 1 (MHz)	6212.094	6212.094
Transponder No. 2 (MHz)	6301.050	6301.050
RF Frequency (downlink)		
Transponder No. 1 (MHz)	4119.597	4119.597
Transponder No. 2 (MHz)	4178.591	4178.591
Receiver IF Noise BW (nominal) (MHz)	35.5	15.5
FDM Channel bandwidth		
(unweighted) (KHz)	3.1	3.1
FDM Channel separation (KHz)	4.0	4.0
FDM Baseband Channel Spectrum (KHz)(1)	312 to 5564	312 to 1300
Weighting Improvement (FIA) (db)	3.0	3.0
Peak Deviation (downlink only)		
per channel (radians)	0.35	0.35
total baseband *** (radians)	4.84	3.06
Nominal Channel loading (db)	15.8	8.8

* Mojave is capable of 1200 channel operation with ATS-3.

** The Multiplex equipment at Mojave and Cooby Creek is limited to 240 channel operation.

*** The CCITT recommended noise loading for N channels (G-222) is applied to a baseband spectrum. Refer to paragraph (7.6) for a complete discussion of the FDM system loading - calculation assumes a peak to rms factor of 10 db.

(1) A 316 KHz to 5564 KHz noise loading spectrum is used.

TABLE 1.13 SSB-FDMA/PhM MODE PARAMETERS AND MULTIPLEX CHANNEL PERFORMANCE ①

	ATS-1				ATS-3							
	1 TWT		2 TWT's		1 TWT				2 TWT's			
Earth Antenna (ft.)	85'	40'	85'	40'	85'		40'		85'		40'	
Transponder No.	1 or 2	1 or 2	1 or 2	1 or 2	1	2	1	2	1	2 ④	1	2 ④
S/C Received Test Tone Power (dbm)	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0	-87.0
S/C Received Effective Noise Temperature (°K)	1480	1480	1480	1480	1320	1175	1320	1175	1320	1175	1320	1175
Idle System Channel Uplink TT/N (WGTD) ② (db)	48.0	48.0	48.0	48.0	48.5	49.0	48.5	49.0	48.5	49.0	48.5	49.0
Loaded System, Channel Uplink TT/N (WGTD) ② (db)	42.3	44.1	42.3	44.1	48.1	48.6	48.1	48.6	48.1	48.6	48.1	48.6
Satellite EIRP (dbm)	49.4	49.4	52.2	52.2	52.2	56.5	52.2	56.5	54.6	59.3	54.6	59.3
Earth Station G/T (db)	39.6	32.2	39.6	32.2	39.6	39.6	32.2	32.2	39.6	39.6	32.2	32.2
Downlink C/N_0 ③ (db/Hz)	90.0	82.6	92.8	85.4	92.8	97.1	85.4	89.7	95.2	99.9	87.8	92.5
Idle System, Channel Downlink TT/N (WGTD) ② (db)	46.0	38.6	48.8	41.4	48.8	53.1	41.4	45.7	51.2	55.9	43.8	48.5
Loaded System, Channel Downlink TT/N (WGTD) ② (db)	43.0	38.5	44.6	41.3	44.6	45.7	41.3	45.4	45.3	46.1	43.6	48.0
Idle System, Channel Overall TT/N (WGTD) ② (db)	43.9	38.1	45.4	40.5	45.6	47.5	40.5	44.0	46.6	48.2	42.5	45.7
Loaded System, Channel Overall TT/N (WGTD) ② (db)	39.6	37.4	40.3	39.5	42.9	43.7	40.5	43.7	43.3	44.0	42.3	45.3

① Performance calculations are based on a 1200 channel spectrum (312 kHz to 5564 kHz) at Rosman (85' antenna), and 240 channel spectrum (312 kHz to 1300 kHz) at Cooby Creek and Mojave (40' antennas).

② F1A Weighting - filter bandwidth of 31.9 db Hz.

③ C/N_0 is the ratio of received carrier power to thermal noise per Hz bandwidth.

④ Second TWT has been inoperative, thus limiting maximum S/C EIRP to 54.6 dbm.

TABLE 1.14 MULTIPLE ACCESS MODE, ATS-1, EARTH TO SATELLITE SSB LINK CALCULATION (Transponders No. 1 and No. 2)

	85' Antenna 1200 One-Way Channels	40' Antenna 240 One-Way Channels
Transmitter Average Power (dbm)	62.4	62.3
Loading Factor (db)	15.8	8.8
Channel Test Tone Power (dbm)	46.6	53.5
Ground Antenna Gain (db)	61.5	54.6
Space Attenuation (db)*	-200.8	-200.8
Receiving Antenna Gain (db)	6.2	6.2
Off Beam Center Allowance	-0.5	-0.5
Received Test Tone Power (dbm)	-87.0	-87.0
Effective Received Noise Temperature (db °K)	31.7	31.7
Receiver Noise Power Density (dbm/Hz)	-166.9	-166.9
Channel Bandwidth (3.1 kHz) (db Hz)	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0
Receiver Channel Noise (Wgtd) (dbm)	-135.0	-135.0
Test Tone/Thermal Noise (Wgtd) (db)	48.0	48.0
Transmitter Test Tone/Intermod. Noise (Wgtd) (db)	43.7	46.4
Transmitter Test Tone/Thermal Noise (Wgtd) (db)	65.5	69.2
Uplink Test Tone/Total Noise (Wgtd) (db)	42.3	44.1

*Based on a nominal slant range of 22,000 nmi.

TABLE 1.15 MULTIPLE ACCESS MODE, ATS-1, SATELLITE TO EARTH PhM LINK AND OVERALL LINK CALCULATION (ONE TWT)
(Transponders No. 1 and No. 2)

	85' Antenna 1200 One-Way Channels	40' Antenna 240 One-Way Channels
Satellite Power Output (dbm)	36.7	36.7
Satellite Antenna Gain (net) (db)	12.7	12.7
Off Beam Center Allowance (db)	-0.5	-0.5
Space Attenuation (db)*	-197.1	-197.1
Ground Antenna Gain (db)	58.4	51.0
Received Carrier Power (dbm)	-89.8	-97.2
Effective Received Noise Temp (db °K)	18.8	18.8
Receiver Noise Power Density (dbm /Hz)	-179.8	-179.8
Receiver Bandwidth (db Hz)	75.5	71.9
Receiver Noise Power (dbm)	-104.3	-107.9
Carrier/Total Noise (db)	13.5	10.7
Channel Bandwidth (db Hz)	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0
Channel Noise Power (Wgtd) (dbm)	-147.9	-147.9
Carrier/Channel Noise (Wgtd) (db)	58.1	50.7
Modulation Improvement Factor (db)	-12.1	-12.1
Test Tone/Thermal Noise (Wgtd) (db)	46.0	38.6
Transponder and Receiver Test Tone/Intermod. Noise (Wgtd) (db)	46.0	57.2
Downlink Test Tone/Total Noise (Wgtd) (db)	43.0	38.5
Uplink Contribution (db)	-3.4	-1.1
Overall Link Test Tone/Total Noise (Wgtd) (db)	39.6	37.4

*Based on a nominal slant range of 22,000 nmi

TABLE 1.16 MULTIPLE ACCESS MODE, ATS-1, SATELLITE TO EARTH PhM LINK AND OVERALL LINK CALCULATION (TWO TWT'S)
(Transponders No. 1 and No. 2)

	85' Antenna 1200 One-Way Channels	40' Antenna 240 One-Way Channels
Satellite Power Output (dbm)	39.5	39.5
Satellite Antenna Gain (net) (db)	12.7	12.7
Off Beam Center Allowance (db)	-0.5	-0.5
Space Attenuation (db)*	-197.1	-197.1
Ground Antenna Gain (db)	58.4	51.0
Received Carrier Power (dbm)	-87.0	-94.4
Effective Received Noise Temp (db °K)	18.8	18.8
Receiver Noise Power Density (dbm/Hz)	-179.8	-179.8
Receiver Bandwidth (db Hz)	75.5	71.9
Receiver Noise Power (dbm)	-104.3	-107.9
Carrier/Total Noise (db)	17.3	13.5
Channel Bandwidth (db Hz)	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0
Channel Noise Power (Wgtd) (dbm)	-147.9	-147.9
Carrier/Channel Noise (Wgtd) (db)	60.9	53.5
Modulation Improvement Factor (db)	-12.1	-12.1
Test Tone/Thermal Noise (Wgtd) (db)	48.8	41.4
Transponder and Receiver Test Tone/Intermod. Noise (Wgtd) (db)	46.6	57.2
Downlink Test Tone/Total Noise (Wgtd) (db)	44.6	41.3
Uplink Contribution (db)	-4.3	-1.8
Overall Link Test Tone/Total Noise (Wgtd) (db)	40.3	39.5

*Based on nominal slant range of 22,000nmi

TABLE 1.17 MULTIPLE ACCESS MODE, ATS-3, EARTH TO SATELLITE SSB LINK

	85' Antenna 1200 One-Way Channels		40' Antenna 240 One-Way Channels	
Transponder	No. 1	No. 2	No. 1	No. 2
Transmitting Average Power (dbm)	52.3	52.3	52.2	52.2
Loading Factor (db)	15.8	15.8	8.8	8.8
Channel Test Tone Power (dbm)	36.5	36.5	43.4	43.4
Ground Antenna Gain (db)	61.5	61.5	54.6	54.6
Space Attenuation (db)*	-200.8	-200.8	-200.8	-200.8
Receiving Antenna Gain (db)	16.3	16.3	16.3	16.3
Off Beam Center Allowance (db)	-0.5	-0.5	-0.5	-0.5
Received Test Tone Power (dbm)	-87.0	-87.0	-87.0	-87.0
Effective Received Noise Temperature (db °K)	31.2	30.7	31.2	30.7
Receiver Noise Power Density (db/Hz)	-167.4	-167.9	-167.4	-167.9
Channel Bandwidth (3.1 kHz) (db Hz)	34.9	34.9	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0	3.0	3.0
Receiver Channel Noise (Wgtd) (db)	-135.5	-136.0	-135.5	-136.0
Test Tone/Thermal Noise (Wgtd) (db)	48.5	49.0	48.5	49.0
Transmitter Test Tone/Intermod. Noise (Wgtd) (db)	56.8	56.8	68.0	68.0
Transmitter Test Tone/Thermal Noise (Wgtd) (db)	61.8	61.8	59.2	59.2
Uplink Test Tone/Total Noise (Wgtd) (db)	47.7	48.1	48.1	48.6

*Based on a nominal slant range of 22,000 nmi

TABLE 1.18 MULTIPLE ACCESS MODE, ATS-3, SATELLITE TO EARTH PhM LINK AND OVERALL LINK CALCULATION (ONE TWT)

	85' Antenna 1200 One-Way Channels		40' Antenna 240 One-Way Channels	
Transponder	No. 1	No. 2	No. 1	No. 2
Satellite Transmitter Power Output (dbm)	36.0	40.3	36.0	40.3
Satellite Antenna Gain (net) (db)	16.2	16.2	16.2	16.2
Off Beam Center Allowance (db)	-0.5	-0.5	-0.5	-0.5
Space Attenuation (db)*	-197.1	-197.1	-197.1	-197.1
Ground Antenna Gain (db)	58.4	58.4	51.0	51.0
Received Carrier Power (dbm)	-87.0	-82.7	-94.4	-90.1
Effective Received Noise Temp (db °K)	18.8	18.8	18.8	18.8
Receiver Noise Power Density (dbm/Hz)	-179.8	-179.8	-179.8	-179.8
Receiver Bandwidth (db Hz)	75.5	75.5	71.9	71.9
Receiver Noise Power (dbm)	-104.3	-104.3	-107.9	-107.9
Carrier/Total Noise (db)	17.3	21.6	13.5	17.8
Channel Bandwidth (db Hz)	34.9	34.9	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0	3.0	3.0
Channel Noise Power (Wgtd) (dbm)	-147.9	-147.9	-147.9	-147.9
Carrier/Channel Noise (Wgtd) (db)	60.9	65.2	53.5	57.8
Modulation Improvement Factor (db)	-12.1	-12.1	-12.1	-12.1
Test Tone/Thermal Noise (Wgtd) (db)	48.8	53.1	41.4	45.7
Transponder and Receiver Test Tone/Intermod. Noise (Wgtd) (db)	46.6	46.6	57.2	57.2
Downlink Test Tone/Total Noise (Wgtd) (db)	44.6	45.7	41.3	45.4
Up-Link Contribution (db)	-1.7	-2.0	-0.8	-1.7
Overall Link Test Tone/Total Noise (Wgtd) (db)	42.9	43.7	40.5	43.7

*Based on a nominal slant range of 22,000 nmi.

TABLE 1.19 MULTIPLE ACCESS MODE, ATS-3, SATELLITE TO EARTH PhM LINK AND OVERALL LINK CALCULATION (TWO TWT'S)

	85' Antenna 1200 One-Way Channels		40' Antenna 240 One-Way Channels	
Transponder	No. 1	No. 2	No. 1	No. 2
Satellite Transmitter Power Output (dbm)	38.4	43.1	38.4	43.1
Satellite Antenna Gain (net) (db)	16.2	16.2	16.2	16.2
Off Beam Center Allowance (db)	-0.5	-0.5	-0.5	-0.5
Space Attenuation (db) *	-197.1	-197.1	-197.1	-197.1
Ground Antenna Gain (db)	58.4	58.4	51.0	51.0
Received Carrier Power (dbm)	-84.6	-79.9	-92.0	-87.3
Effective Received Noise Temp (db °K)	18.8	18.8	18.8	18.8
Receiver Noise Power Density (dbm/Hz)	-179.8	-179.8	-179.8	-179.8
Receiver Bandwidth (db Hz)	75.5	75.5	71.9	71.9
Receiver Noise Power (dbm)	-104.3	-104.3	-107.9	-107.9
Carrier/Total (db)	19.7	24.4	15.9	20.6
Channel Bandwidth (Hz)	34.9	34.9	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0	3.0	3.0
Channel Noise Power (Wgtd) (dbm)	-147.9	-147.9	-147.9	-147.9
Carrier/Channel Noise (Wgtd) (db)	63.3	68.0	55.9	60.6
Modulation Improvement Factor (db)	-12.1	-12.1	-12.1	-12.1
Test Tone/Thermal Noise (Wgtd) (db)	51.2	55.9	43.8	48.5
Transponder and Receiver Test Tone/Intermod. Noise (Wgtd) (db)	46.6	46.6	57.2	57.2
Down-link Test Tone/Total Noise (Wgtd) (db)	45.3	46.1	43.6	48.0
Up-link Contribution (db)	-2.0	-2.1	-1.3	-2.7
Overall Link Test Tone/Total Noise (Wgtd) (db)	43.3	44.0	42.3	45.3

*Based on a nominal slant range of 22,000 nmi.

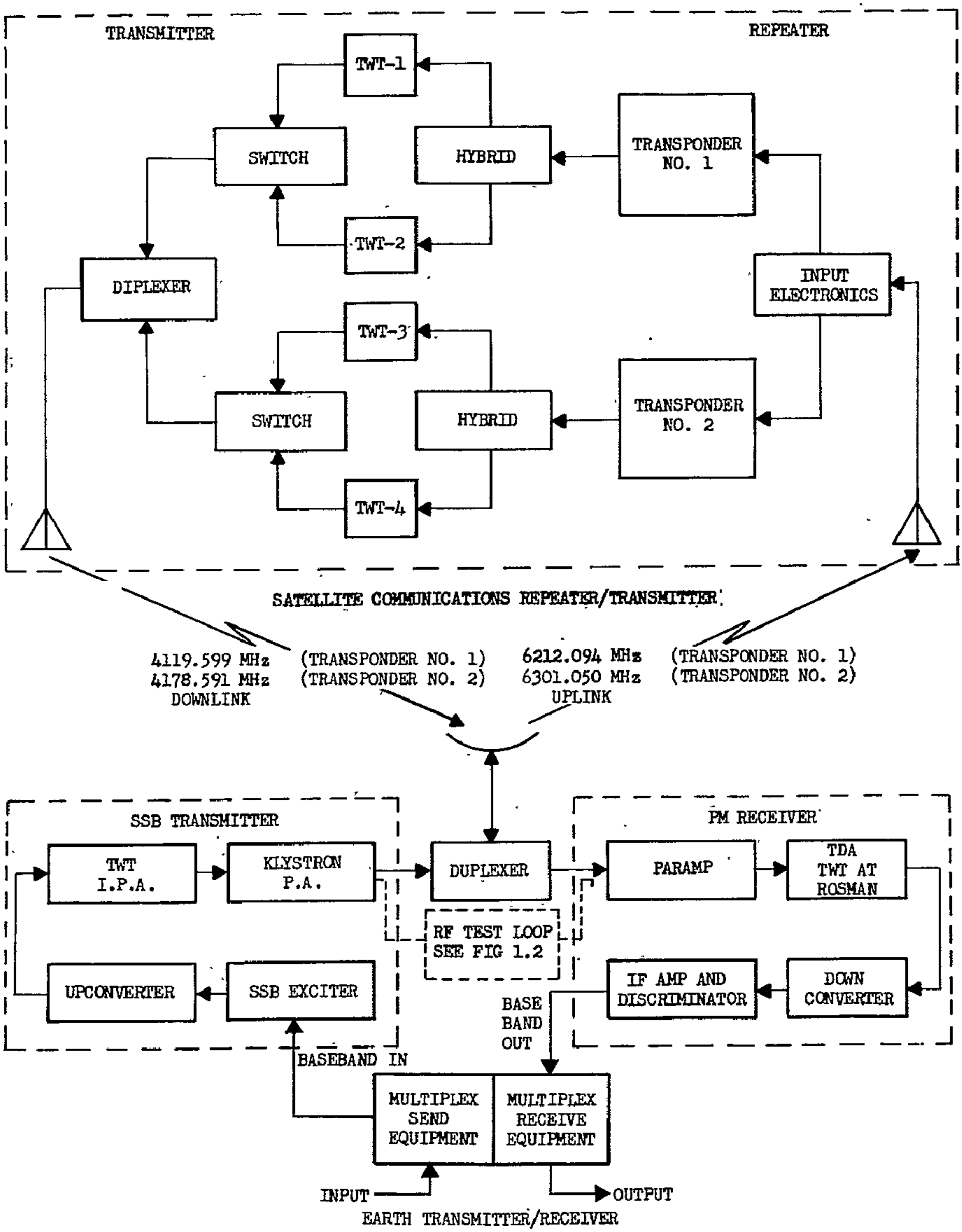
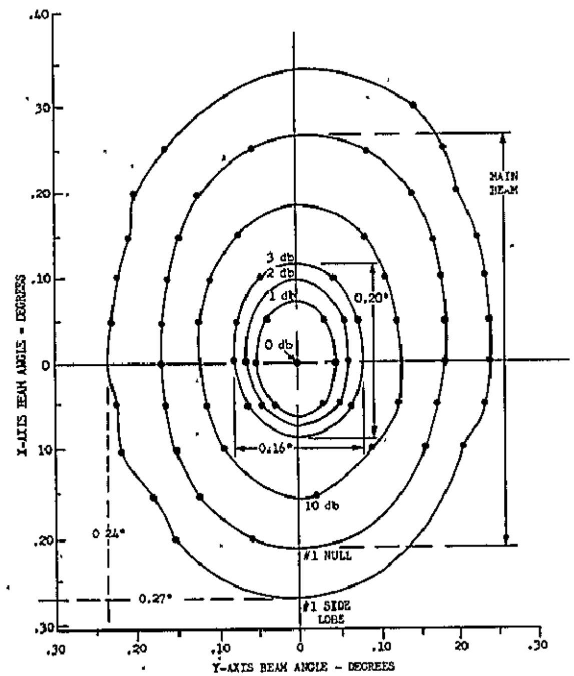
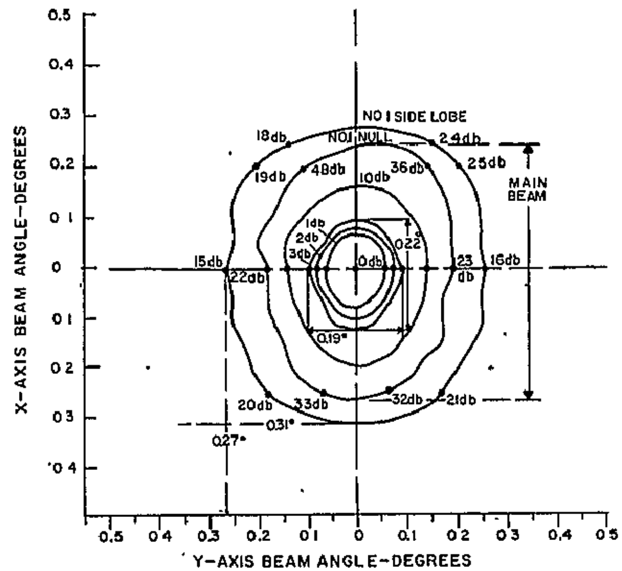


Figure 1.1. ATS SSB-FDMA/PhM Mode, SHF System Configuration

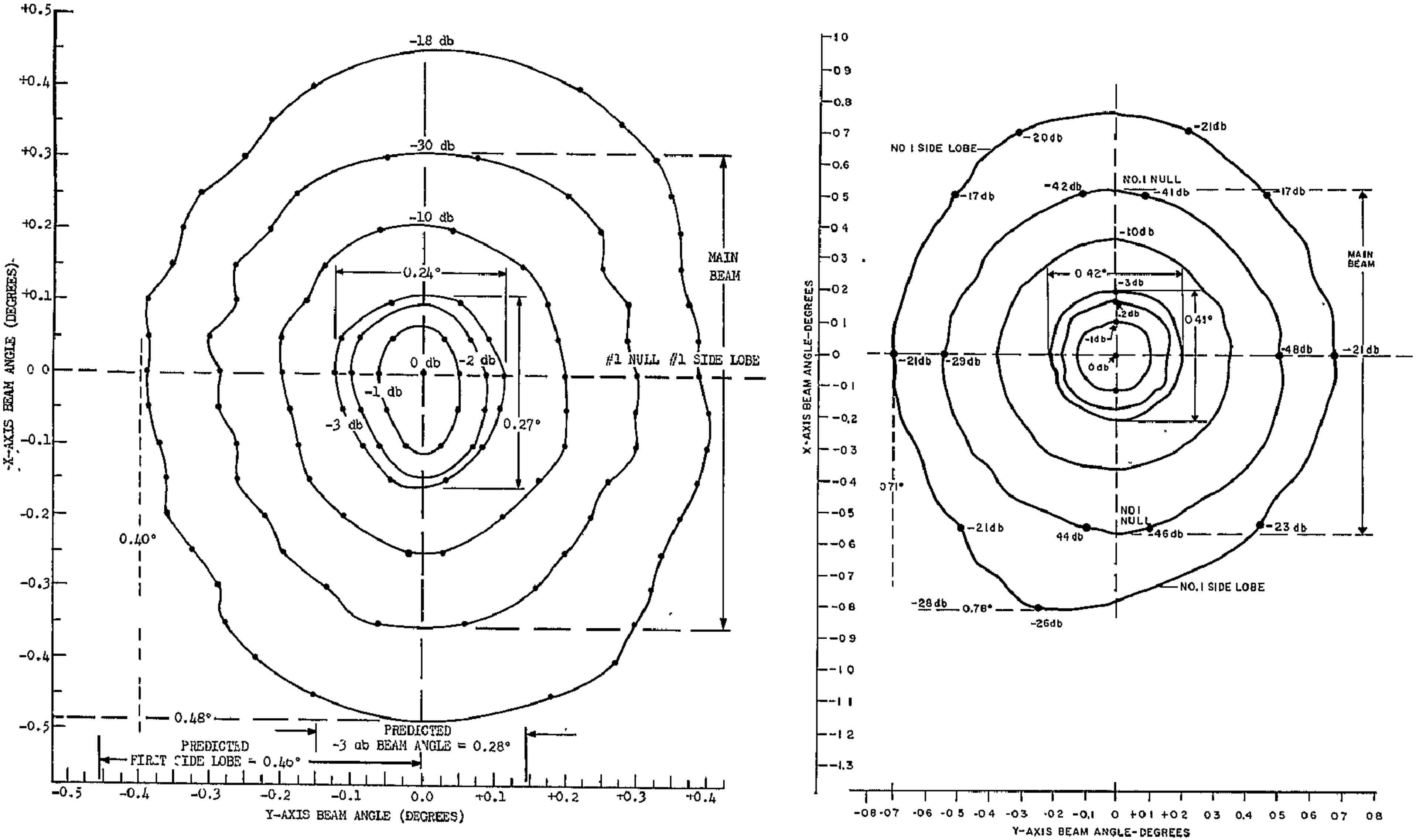


TRANSMIT PATTERN



RECEIVE PATTERN

Figure 1.2 Earth Station Antenna (85 Foot) Patterns



TRANSMIT PATTERN

RECEIVE PATTERN

Figure 1.3 Earth Station Antenna (40 Foot) Patterns

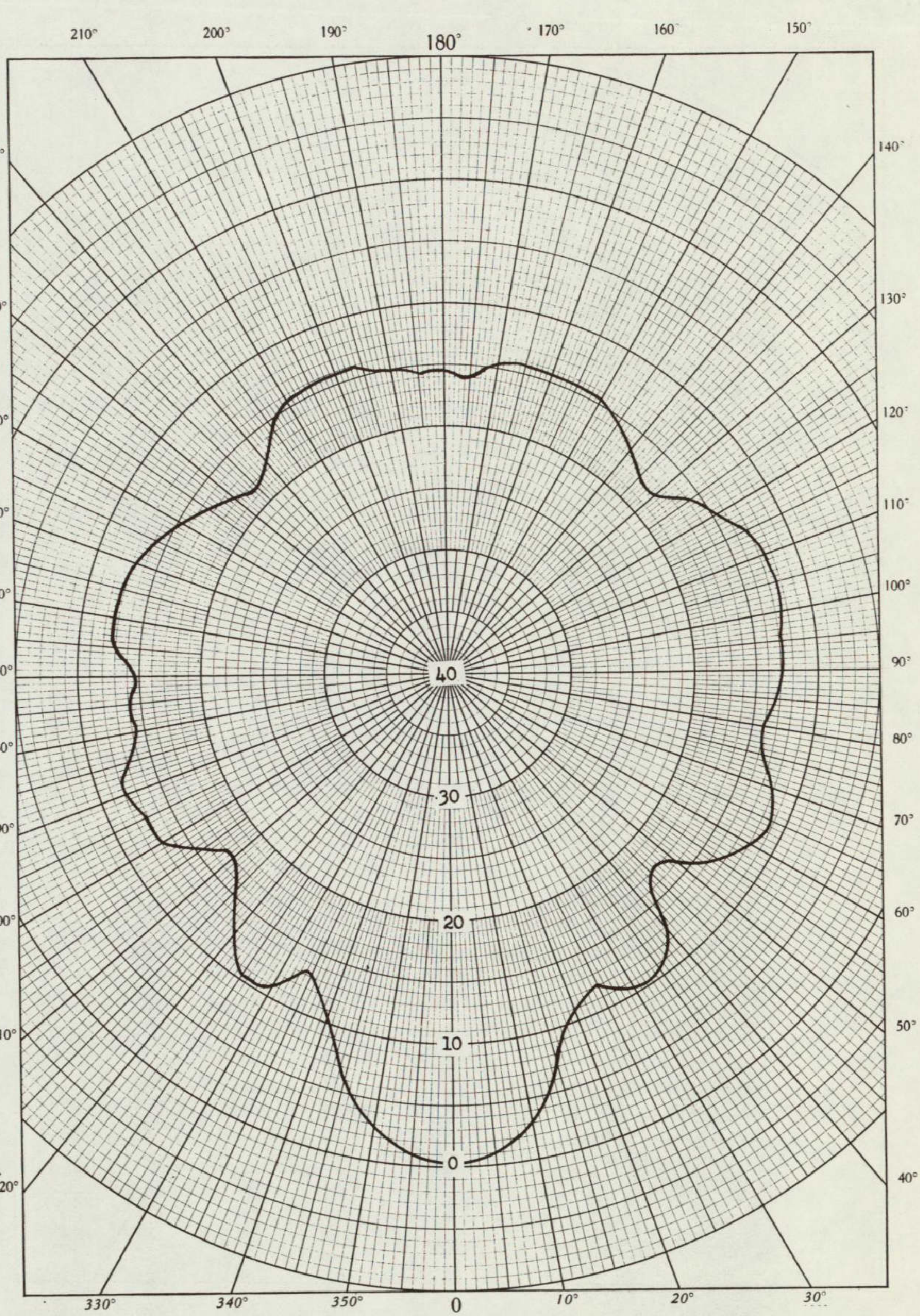


Figure 1.4 ATS-1 Transmit Antenna Pattern, Aspect Angle 85 Degrees

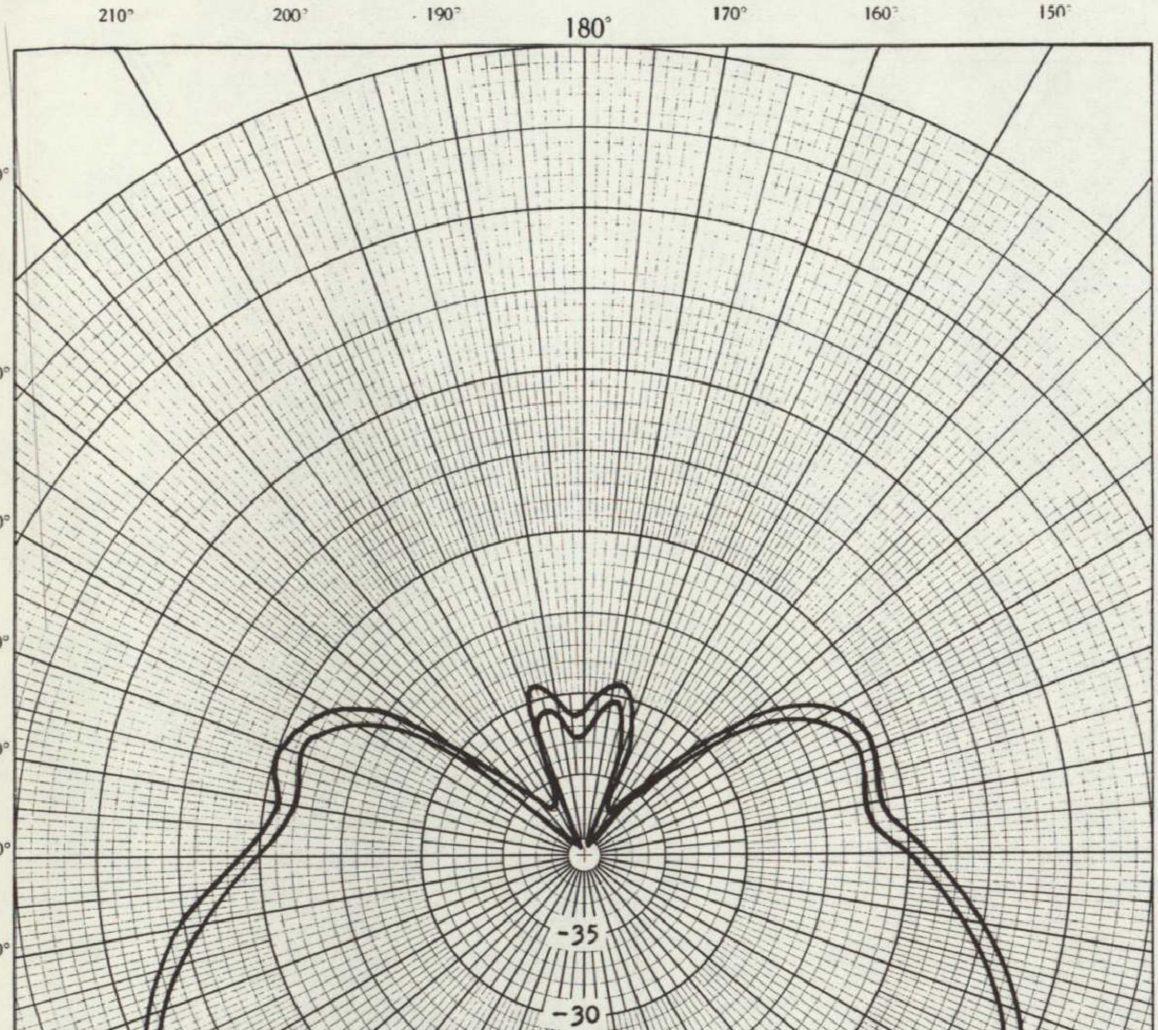


Figure 1.5 ATS-3 Transmit Antenna Pattern, Aspect Angle 84 Degrees

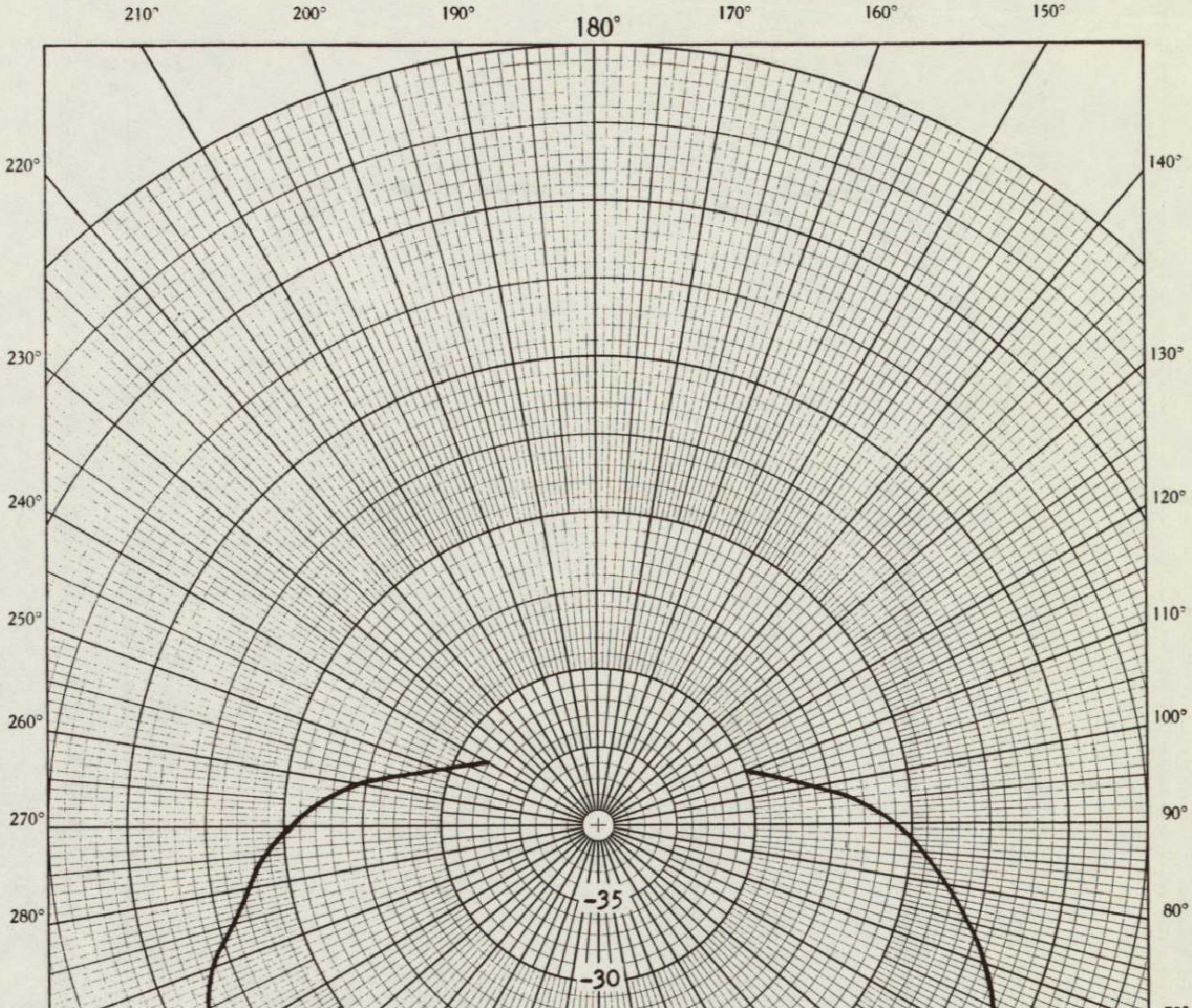


Figure 1.6 ATS-3 Receive Antenna Pattern, Aspect Angle 84 Degrees

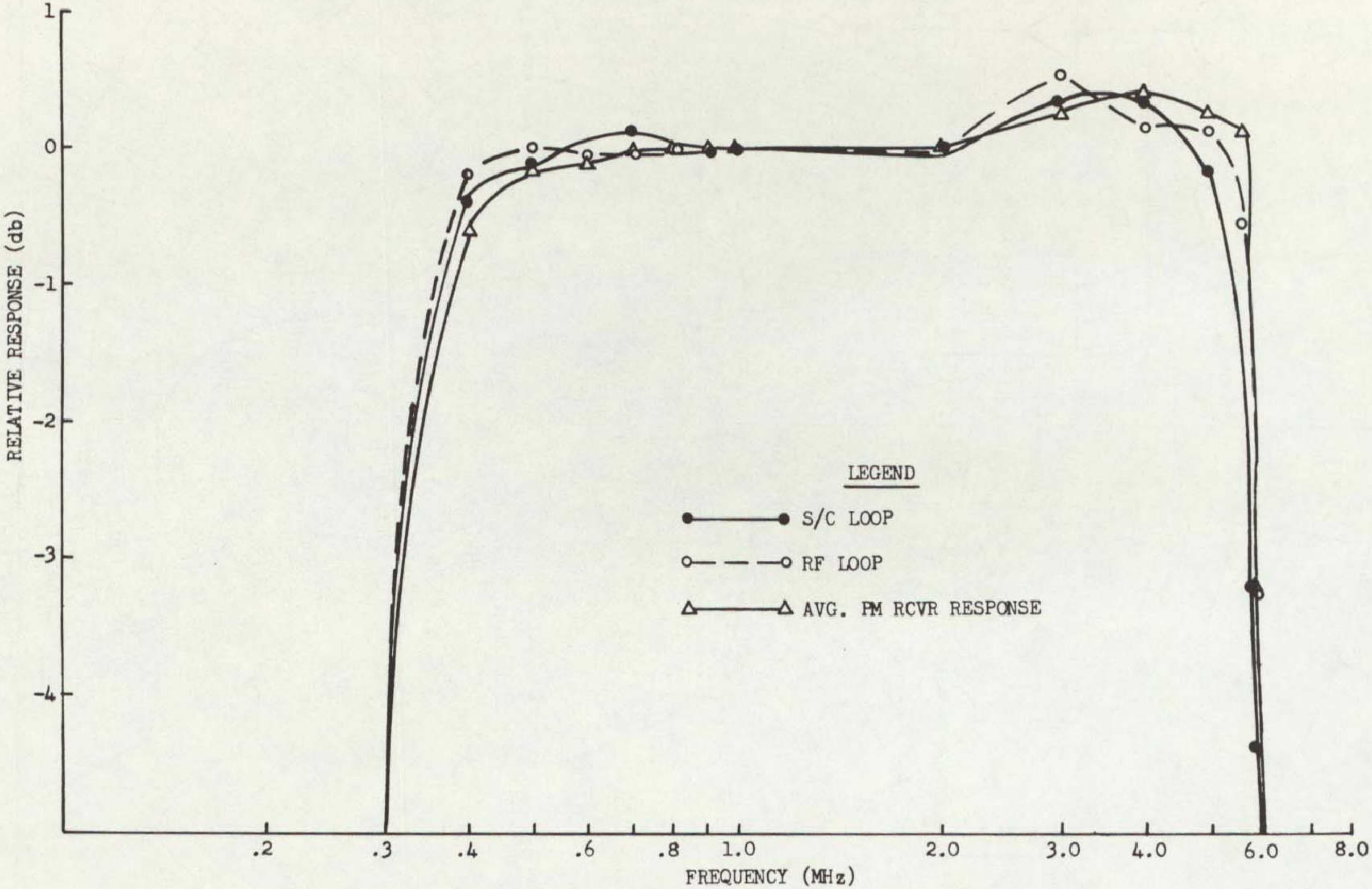


Figure 1.7 Typical Baseband Amplitude Versus Frequency, ATS-1, SSB-FDMA/PhM Mode

increase in S/C EIRP would be of little benefit to the 85-foot stion, while it would aid the TT/R performance of the 40-foot station. The foregoing discussion only considers the effects of thermal noise and does not analyze the effects of intermodulation distortion which will definitely affect any system optimization.

Of special interest in predicting availability of the system, is the data obtained during conjunction of the earth station, S/C and the sun. Tests have been conducted which show that the earth station received noise level increases as much as 25 db during conjunction. This causes the communications system to be completely inoperative for most of the conjunctio period. Approximately two minutes of degraded system performance occurs between the start of the conjunction period and the time that the earth station receiver threshold is reached. An equivalent time interval is available near the end of the period, resulting in a net system outage of 5 minutes out of a typical nine-minute conjunction period. It was also noted that the signal power in the FDM channel is suppressed by the increased noise level during the conjunction period. This is attributed to the receiver AGC which holds the carrier plus noise power constant. The measured suppression is as much as 14 db in the high channel (1251 kHz) and 8 db in the low channel (337 kHz). The actual limit of signal suppression during conjunction cannot be measured because of the masking effect of the noise power (refer to paragraph 3.4.1 for a discussion of the special conjunction test).

Analysis of the noise in FDM channels at either end of the baseband, indicates that the noise level is greater at the low end of the baseband for low values of C/N. This is consistent with prior observations that threshold noise is significant at low C/N, and tends to be greater in the lower FDM channels (see subsection 1.2.7 for a discussion of the effect).

LOADED SYSTEM TEST TONE-TO-NOISE

Loaded system test tone-to-noise (TT/N) represents the actual limitation in TT/N performance since intermodulation effects are included in this ratio. TT/N is determined in the same manner as TT/R except TT/N in one channel is measured when all other channels are loaded. This loading is accomplished by simulating voice users in the other channels with white noise as recommended by CCIR (Recommendation 353-1, Oslo, 1966). The output of the receiving channel is again passed through an F1A weighting filter rather than the CCIR recommended psophometric weighting filter. The F1A weighting provides a TT/N improvement of 3.0 db over the unweighted channel.

The intermodulation effects (intermodulation distortion or noise) are due to nonlinearities throughout the transmission path, the primary sources in the ATS system being the earth station transmitter, the spacecraft SSB to PhM converter, and the earth station

Figure 1.21 shows a plot of theoretical TT/R versus S/C EIRP for constant values of earth station sensitivity (G/T). "G/T is the ratio of receive antenna gain to the received system noise temperature." The lines of constant G/T were chosen to bracket measured and predicted G/T values representative of ATS earth stations. TT/R calculations are based on ATS-1 and ATS-3 system operating parameters listed in tables 1.12 and 1.14 through 1.19 in subsection 1.2 as well as SSB/PhM (MA mode) link calculations given in section 7. The uplink TT/R used to calculate the overall TT/R performance for all configurations was 48.5 db which is the median of the theoretical values 48.0, 48.5 and 49.0 calculated for ATS-1 (transponders 1 and 2), ATS-3 (transponder 1) and ATS-3 (transponder 2), respectively. In figure 1.14, the measured and predicted points have been normalized to an earth station receiver noise temperature (T_s) of 76°K. Normalization to a constant T_s is required to provide a basis of comparison among stations with different values of T_s.

The predicted values of TT/R are based on the theoretical antenna gains and measured prelaunch S/C EIRP for various combinations of S/C TWT's. The PhM link (MA Mode) threshold is different for the two channel capacities (240 and 1200) because the IF noise bandwidth is different and thus, downlink C/N, the limiting factor for earth station receiver threshold, is different.

The measured TT/R ratios shown in figure 1.21 are the mean of the measured TT/R ratios for an 85-foot and 40-foot earth station operating with both ATS-1 (52.2 dbm EIRP) and ATS-3 (54.6 dbm EIRP). Since these TT/R ratios are for above threshold operation, they are indicative of any channel within the 1200 channel spectrum (312 kHz to 5564 kHz) or 240 channel spectrum (312 kHz to 1300 kHz).

The measured and predicted TT/R ratios of the various ATS-earth station-satellite configurations are summarized in table 1.3, section 1.1. In this table, measured TT/R ratios were not normalized with respect to system noise temperature and 76°K was selected as the system noise temperature for the predicted TT/R ratios. Certain configurations, such as Rosman operating with ATS-1 have a higher system noise temperature thus for these configurations measured TT/R is somewhat low. The Rosman/ATS-1 configuration, because of the low antenna elevation angle (approximately 7°), is also influenced by atmospheric attenuation due to oxygen and water vapor. In addition, in the case of ATS-1, predicted TT/R ratios are somewhat high since telemetry has shown that TWT power output is about one db less than the measured prelaunch value.

As shown in figure 1.21, the uplink TT/R of 48.5 db has an appreciable effect on the overall TT/R, at high values of S/C EIRP. The measured data shows that the 85-foot station is operating at nearly optimum TT/R (overall TT/R 3 db down from uplink limitation), while the 40-foot station is definitely downlink limited (with regard to TT/R). Thus, an

1.2.6 TEST TONE-TO-NOISE

The fundamental parameter, test tone-to-noise, provides a measure of multiplex channel performance. Evaluation of the ATS SSB-FDMA/PhM mode is based on idle test tone-to-noise (TT/R) ratio and loaded system test tone-to-noise (TT/N) ratio. This section presents and discusses the experimental results of these two ratios for above threshold operation. These results are compared to the CCIR recommendation of 50 db. (Rec. 353-1, Oslo, 1966)

IDLE TEST TONE-TO-NOISE

Idle test tone-to-noise (TT/R) represents the theoretical limitation in system test tone-to-noise performance, since modulation and crosstalk effects of other FDM channels are absent. TT/R is determined by measuring the ratio of the nominal test tone power in an FDM channel to the noise power in the channel without the test tone applied. This measurement is made when the system is essentially unloaded; that is, only one tone is transmitted using one FDM channel. The output of the received channel is passed through an F1A weighting filter which provides a 3.0-db improvement in TT/R (CCIR recommended psophometric weighting is not used. For this type of weighting, an improvement of 2.5 db is expected over the unweighted condition).

The received idle noise power is a function of thermal noise generated in the receiving equipment and the sky and earth noise seen by the antenna. The ATS system uses low noise front ends, thus sky noise appears as the largest contributor to received system noise temperature (T_s). Section 3.2.1 contains plots of T_s versus time for each ATS system configuration. Station average T_s and T_s variation is summarized below for a two year period of operation.

STATION	SYSTEM NOISE TEMPERATURE (T_S) - °K					
	ATS-1			ATS-3		
	AVERAGE	MAX	MIN	AVERAGE	MAX	MIN
COOBY CREEK	85	130	68	NOT VISIBLE		
MOJAVE	71	104	50	83	115	56
ROSMAN	90	130	53	75	88	52

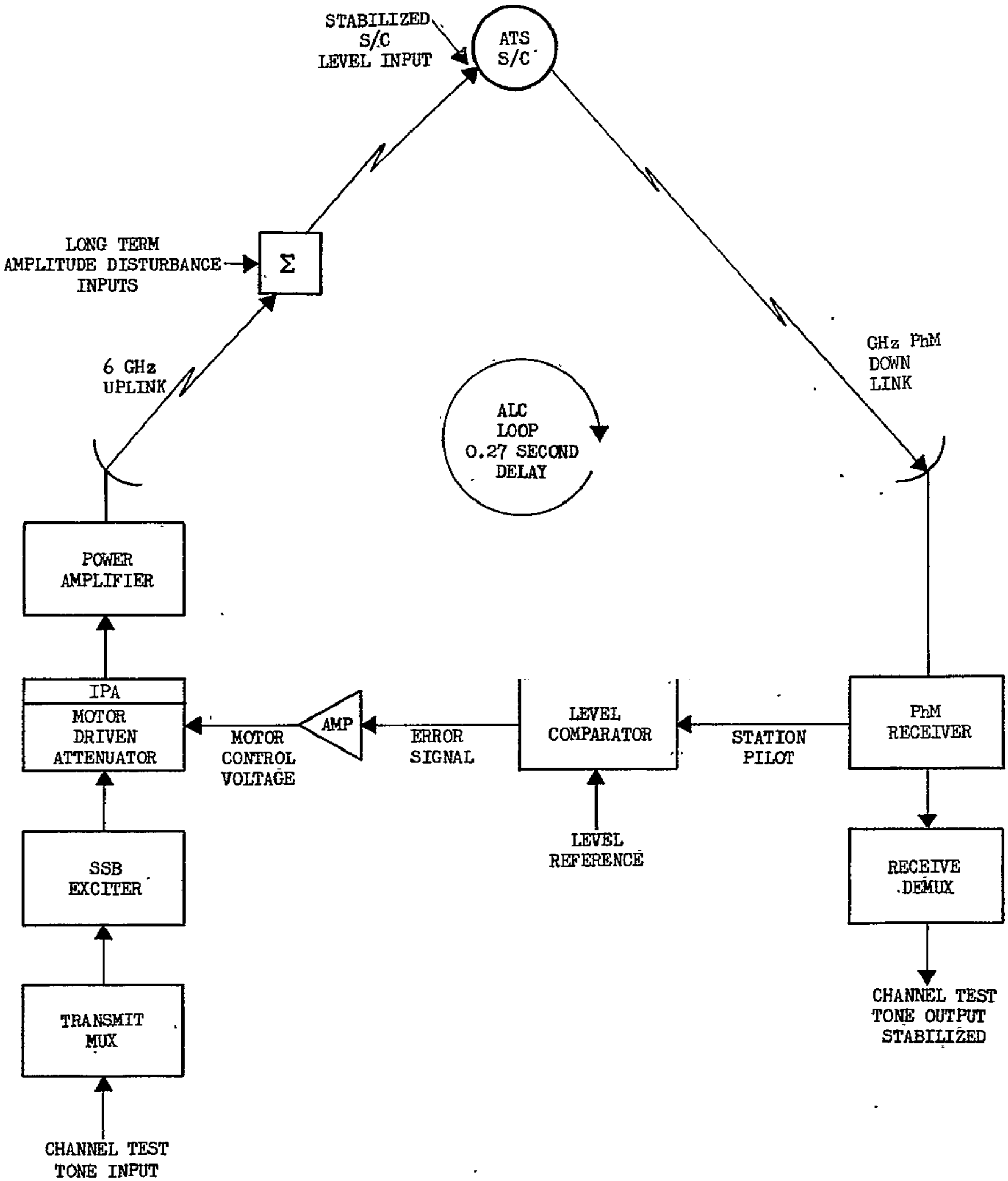


Figure 1.20. Simplified Block Diagram of ALC System

variations in the antenna pointing angle. Any one or all of these factors can cause changes in the S/C receiver input level which are translated to a level variation in the receiver multiplex channel. However, these long term variations are considerably reduced or eliminated by the servo action of the ALC loop. A complete presentation of the data obtained on the level variations of the multiplex channel of the SSB system is contained in section 3.3.2. In general, however, it can be said that long term level variations have not been a major problem for the ATS system.

1.2.5.4 Effect of Spacecraft Spin on Level Stability

One of the most noticeable level variations, experienced on both ATS-1 and ATS-3, is the approximate 1.6 Hz-amplitude fluctuation. The 1.6 Hz variation is also the spin rate of the S/C; therefore, it follows that its presence is related in some way to the S/C spin. Since this frequency is beyond the control bandwidth of the ALC system, it cannot be corrected, and therefore represents an operational limit of the ATS SSB-FDMA/PhM mode. A complete presentation of measured data of spin effect on level stability is contained in section 3.6.2.

A fourier analysis of the amplitude variations on ATS-1 indicates the presence of the first, second, and eighth harmonic of the S/C spin rate. The percent AM for the first and second harmonic is 4 percent and the eighth harmonic percent AM is 1 percent. The presence of the eighth harmonic is attributed to the eight VHF telemetry whips that revolve around the SHF antenna. The presence of the first and second harmonic could possibly be attributed to an asymmetrical receive antenna radiation pattern.

The same analysis on ATS-3 indicates the presence once again of the first harmonic of the S/C spin rate. It also indicates the presence of the eighth harmonic and many multiples of the eighth. The eighth harmonic is larger (amplitude) than the first. The first harmonic is attributed to a variation in gain of the receive antenna as a function of the spin of the spacecraft. The dominant eighth harmonic and its multiples are due to the VHF telemetry whip antennas passing in front of the SHF receive antenna, thus causing a change in receive level. Since there is a large number of multiples of the eighth harmonic, the effect is approaching a rectangular pulse train.

1.2.5 LEVEL STABILITY

1.2.5.1 Introduction

Test results obtained through experimentation on both ATS-1 and ATS-3 have indicated that, in general, level stability can be maintained to within acceptable limits (within ±2 db of the intended channel level). In considering the overall level stability problem, it appears that the multiplex channel level variations at the ground receiver are caused by variations in satellite received signal level. This is due to the SSB to PhM conversion in the S/C where the modulation index of the PhM downlink, and hence the downlink channel signal level, is determined by the received signal level at the S/C transponder input. Nominally, the system is configured to yield a peak test tone modulation index of 0.35 radians for a received input level at the S/C of -87 dbm. The transfer function of the S/C is such that any variation in the received signal level will produce an equal change in the multiplex channel level at the ground receiver. Therefore, it is important to note that level instability can only be caused by an anomalistic behavior of the ground to S/C link and is not affected by variations in the downlink system (assuming, of course, above threshold operation and hard limiting in the ground receiver).

1.2.5.2 Automatic Level Control Loop

The necessity for maintaining a constant level at the multiplex channel output in the presence of received S/C signal level variations has established a requirement for providing an automatic level control system. A simplified block diagram of the ALC system is shown in figure 1.20. As can be seen, level disturbances on the uplink signal will be sensed as a level change on the station pilot frequency. After amplification, this error signal is used to automatically adjust the output power level of the ground transmitter to compensate for the disturbances introduced on the uplink. The open loop response characteristic of the ALC system is constrained by similar considerations which dictated the design of the closed loop AFC system discussed earlier in paragraph 1.2.2.4. Because of the large 0.27-second round trip S/C time delay, the loop response (and hence the bandwidth of the loop) is limited to about 0.1 db/second. Therefore, the ALC system cannot correct for amplitude disturbances occuring at rates beyond 0.1 db per second. A complete description of the ALC system can be found in the manufacturers equipment manuals (references 33 and 38) and test results are reported in section 3.3.3.

1.2.5.3 Long Term Effects

With the exception of level variations caused by S/C antenna effects which are discussed later, the majority of level variations are caused by long term phenomena such as variations in ground transmitter EIRP, atmospheric effects, S/C receiver sensitivity, and

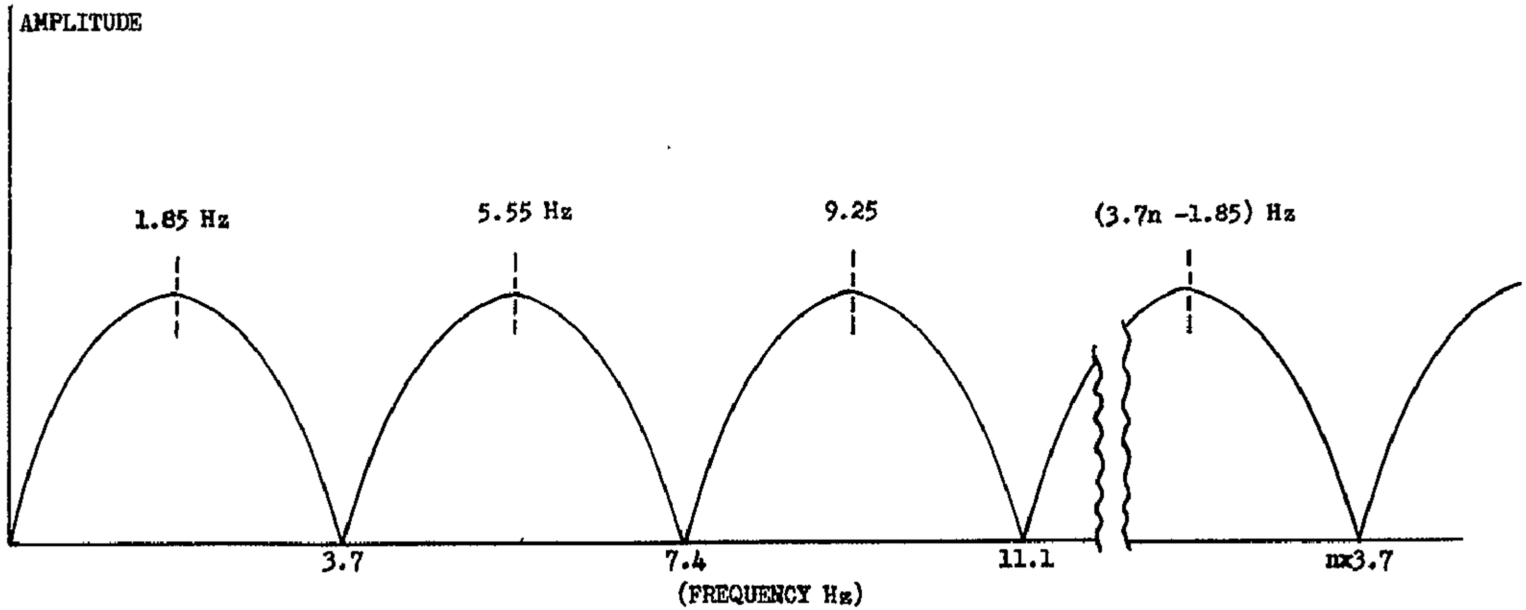


Figure 1.19. One-Sided Response Characteristic of the Error Cancellation Circuits

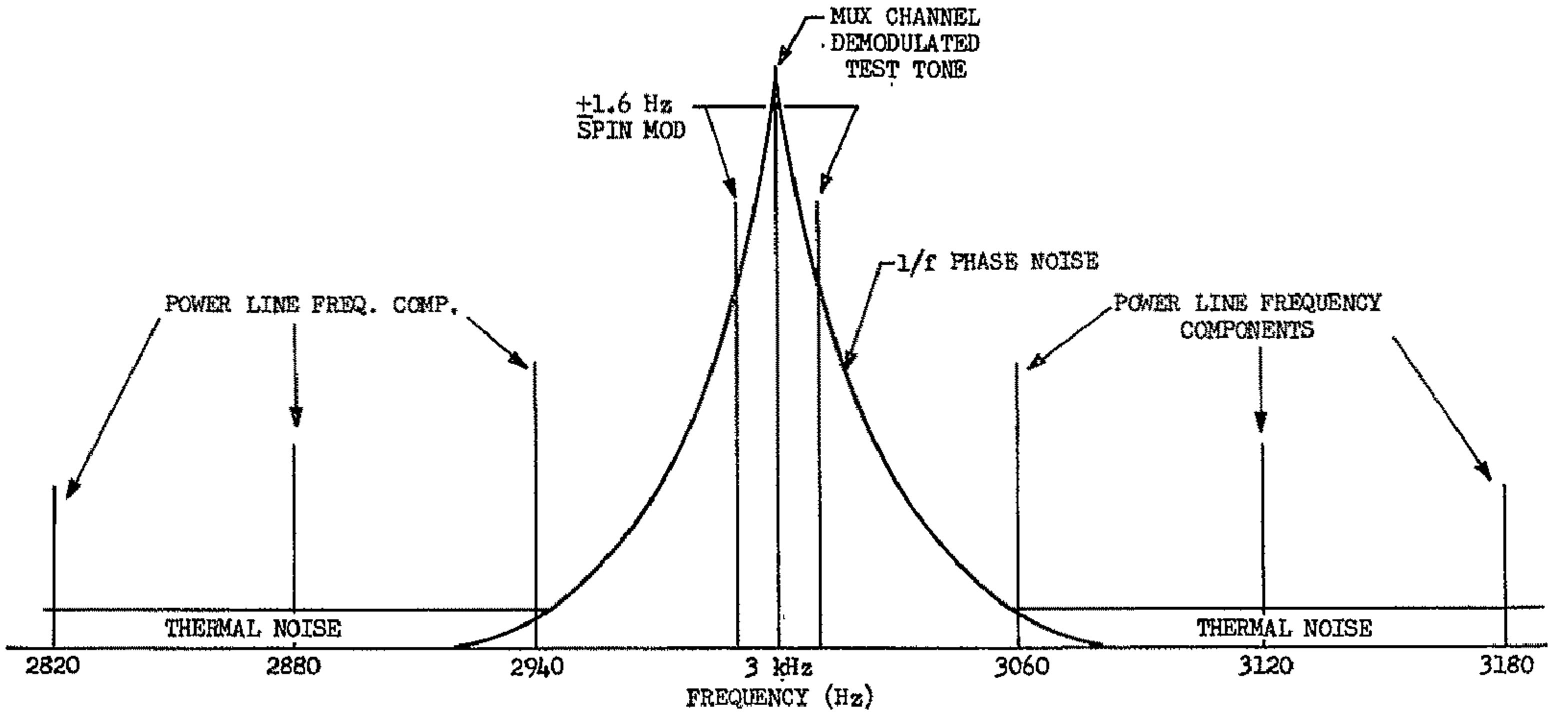


Figure 1.18. Typical Representation of Multiplex Channel Short-Term Frequency Stability Components

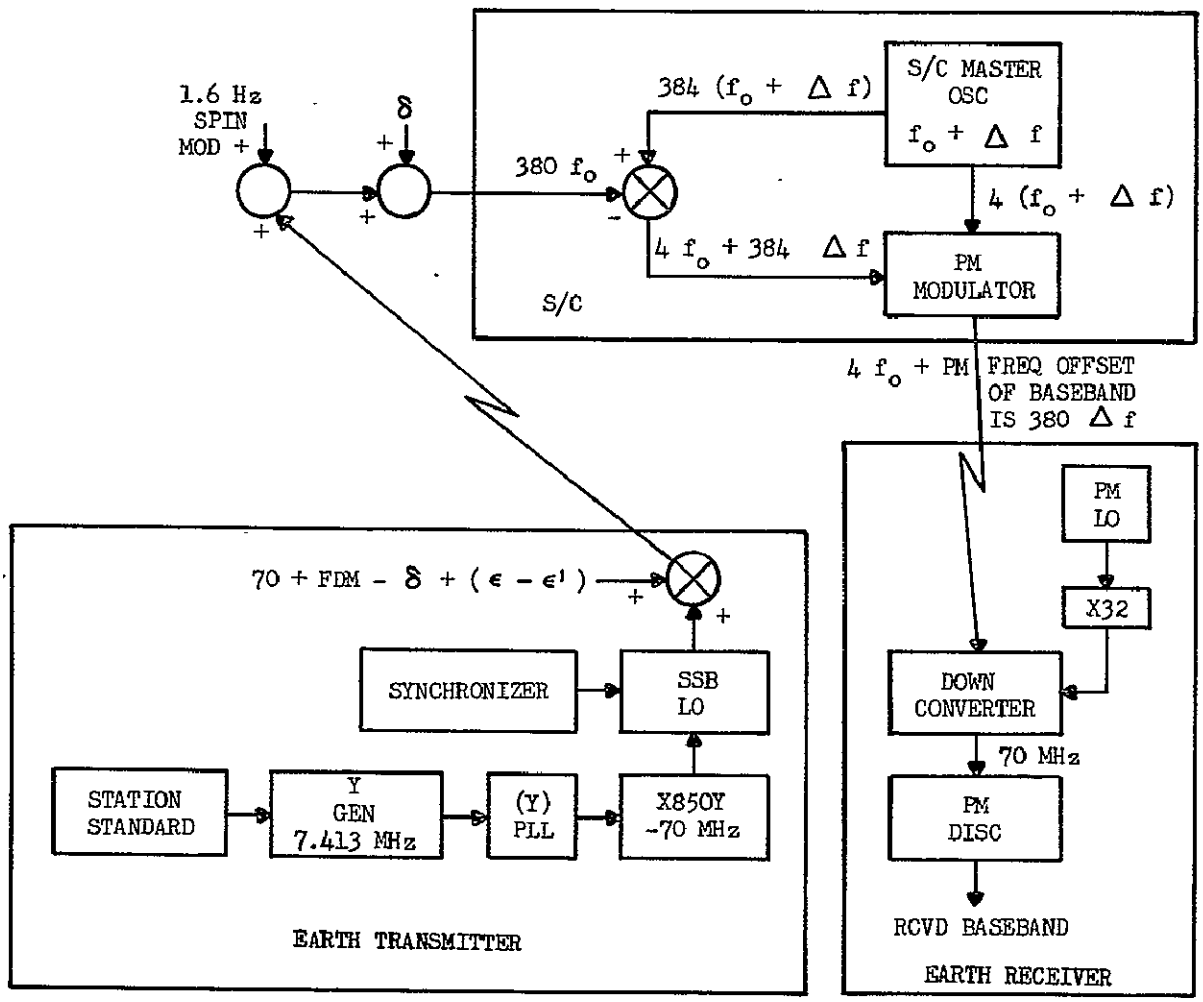


Figure 1.17. SSB-FDMA/PhM Mode Frequency Characteristics

TABLE 1.21. REFERENCE CARRIER TEST RESULTS (ATS-1)

Test Configuration	Multiplex Channel TT/N (db)	Standard Deviation (σ - H_Z)	
		Without Reference Carrier	With Reference Carrier
Multiplex back-to-back loop E Loop out	37	1.66	2.36
Spacecraft loop E loop out	37	3.16	2.31
Multiplex back-to-back loop E loop out	43	0.91	1.23
Spacecraft loop E loop out	43	3	1.12
Spacecraft loop E loop in	37	3.74	-

It is logical to conclude that the 50-baud rate with its corresponding 30-Hz frequency deviation is the most critical test condition from the standpoint of frequency instability The results of this condition are discussed next.

The error rate (P_e) of an FSK digital signal is relatively insensitive to the peak-to-peak frequency jitter impressed on the signal. For a 30 Hz frequency deviation of a 50 baud signal, a peak-to-peak jitter value of 100 Hz was shown to produce a P_e of 10^{-5}. This is equivalent to a σ of 16 Hz. If the adjacent multiplex channels are loaded with a continuous mark and space frequency in different channels, a peak-to-peak jitter of 50 Hz is required to produce a P_e of 10^{-5}. This is equivalent to a σ of 8 Hz. This critical condition is not realized in an operational system. The 8-Hz value is only given to define the lower limit for σ for the 50-baud case which utilizes a frequency deviation of 30 Hz.

TABLE 1.20. FREQUENCY STABILITY TEST RESULTS

Test Configuration	σ (Hz)	TT/N (db)
Collimation Tower Loop E Loop In	3.65	40
Collimation Tower Loop E Loop Out	3.31	40
ATS-1 E Loop In	4.02	33.5
ATS-1 E Loop Out	3.39	33.5
ATS-3 E Loop In	9.45	37
ATS-3 E Loop Out	8.45	37

Note: E Loop refers to the error correction loop.

3) The lock threshold for the F_p level is not altered when noise loading up to 1200 channels is employed by a single station or a combination of stations.

4) A maximum one db compression of the pilot tone occurrs when 1200 channel noise loading is applied.

5) With two stations locked up and receiving information in a number of multiple channels and with a third station sweeping and attempting to lock up, the only detrimental effect is an increase in the bit error rate in those channels carrying digital information in the lower part of the baseband for one of the locked up stations. For a 1200 baud rate an average of 4 errors per sweep was measured for 5 sweeps of the station attempting lock. For a 1500 baud rate and the above station sweeping at a 380 Hz/sec rate, an average of 9 errors per sweep was measured for 6 sweeps; at a 830 Hz/sec rate, an average of 4 errors per sweep was measured.

6) The maximum sweep rate that can be employed for acquisition is 1200 Hz/sec.

From the above it is concluded that a station attempting acquisition will produce data errors inthe receive channels of stations already operating with the spacecraft. This disadvantage can be rectified by operating at the highest sweep rate possible and holding the sweep interval to a minimum or by spacing the pilots so that they do not sweep over each other. No degradation in the voice channels was noticed during the time a station was attempting acquisition.

1.2.4.5 System Effects

From a system standpoint, the effect of the test tone frequency instability on the types of intelligence that are sent over the system should be considered. These types are voice, digital data and perhaps music.

From subjective testing performed on the system, it was found that high level 60 Hz components and multiples thereof affected voice intelligibility. It was also determined that if these components were kept at least 35 db below the nominal test tone level, their effect was inaudible. Another important source of distortion with regard to voice usage is the condition of unequal LO frequencies in the transmit and receive multiplex units. This condition involves the destruction of the harmonic relationships of the frequencies making up the voice or music signals. No detrimental effects on the above signals were determined from the above conditions in the various tests performed on the system.

Tests were performed to determine the effects of frequency instability, plus random noise on the error rate, P_e, of an FSK digital signal transmitted over a specific multiplex channel. In these tests, rates of 50, 100, and 200 bits per second were employed. The peak deviations were 30 Hz, 60 Hz and 120 Hz, respectively.

As explained in paragraph 5.5.1 of the report, the error correction loop (E loop) test tone error spectrum varies in a sinusoidal manner. This is shown in figure 1.19. Specifically, the transfer function is 2 sin π fT, where T is the time delay between the residual frequency errors that are present in the E loop and the AFC loop. For a S/C loop test configuration, T would be the S/C loop transport lag, 0.27 seconds. For this value of T it can be shown that frequency errors are cancelled if they fall at multiples of 3.7 Hz. Also, the frequency components at 1.85 Hz and multiples thereof, are increased by a factor of 6 db. In the 60-Hz region, the sinusoid peaks at 61.05 Hz. From the above it is concluded that the E loop actually amplifies the spin modulation and incidental modulation components.

The effect of reducing T on the E loop performance is shown in the collimation tower loop σ values in table 1.20. The σ values for this loop configuration stay basically the same regardless of the insertion of the E loop in the system. The error spectra with and without the E loop show that the loop definitely decreases the error spectrum within the 0 to 10 Hz interval. However, in the 30-Hz to 120-Hz region the loop amplifies the spectrum components. In the higher frequency regions the spectra are basically the same for both test conditions. As the TT/N increases, the shape of the spectra with and without the E loop inserted tends to converge. It is concluded that the E loop has an amplification effect on noise in addition to its sinusoidal response characteristic.

1.2.4.4 Acquisition

As discussed in paragraph 1.2.2.3, a received pilot tone, F_p, must pass through a narrow band pass filter to complete the loop when operating with a spacecraft. To complete the loop, an acquisition or search phase is initiated in which the 15-MHz VCXO in the primary AFC loop is swept over a range of about +42 kHz to -45 kHz. Acquisition (or lock) is said to be accomplished when the search mode has ended and the received pilot tone is firmly placed within the above filter. Acquisition is not in effect when the AFC system must initiate the search mode.

Multistation tests were performed to determine the operational characteristics of the acquisition phase of the AFC. The following factors were determined:

1) With no baseband noise loading, the amplitude of F_p can be decreased to -20 dbm0* before loss of lock occurs.

2) With two stations locked up and a third station sweeping at rates between 380Hz/sec and 830 Hz/sec, the former stations can maintain lock if their F_p levels are at least -20 dbm0.

*dbm0 is defined as test tone level at a particular reference point.

A complete analysis of the ATS-SSB-closed loop AFC system can be found in section 5.5.1. Also, additional information regarding the philosophy and design of both the open and closed loop AFC systems can be found in references 31 through 33.

For the present system, the closed loop AFC unit must be employed with a synchronous satellite because of the excessive drift of the S/C local oscillator. When either the ATS-1 or ATS-3 SSB transponder is first turned on, the S/C local oscillator can be as much as 50 kHz off frequency, and even after several hours the offset is rarely less than 10 kHz. For this reason it is generally not possible to use the open loop frequency correction technique even with a synchronous S/C as discussed earlier because of the large error in the received pilot tones due to the S/C local oscillator. Even after the S/C oscillator has settled out, sufficient error can exist to cause interference with the combined baseband. Because of this phenomena, the closed loop correction technique is used almost exclusively with the ATS spacecrafts.

The major limitation of the present AFC system is the bandwidth constraint due to the large transport lag. This limitation is present in any feedback loop that must operate over a S/C path for a geostationary satellite. Hence, alternate AFC systems would only compensate for long term frequency drifts but would not affect the short term frequency instabilities. The first five instability factors previously listed can not be compensated by the AFC system (bandwidth equal 0.32 Hz); therefore, their collective magnitude determines the received test tone short term frequency instability. The last two factors are compensated by the AFC loop because their rate of variation is within the bandwidth constraint of the loop.

As previously stated, the magnitude of the short term frequency instability is given in terms of the factor σ. In table 1.20, σ values are listed for various loop configurations and corresponding TT/N ratios (flat weighted). As shown, a σ of 4.02 Hz is realized for operation with ATS-1 and a $\sigma =$ 9.45 Hz is obtained for operation with ATS-3. The large σ value for ATS-3 operation is mainly due to the fact that large spurious frequency components are present in the 130 Hz to 200 Hz region of the test tone error spectrum. The reason for these components is not known. Since they do not occur in the ATS-1 loop, it follows that they are generated in the ATS-3 spacecraft. It should also be pointed out that the σ values for the various loop configurations are time variant to within an interval of about ±0.5 Hz.

From the data shown in table 1.20, it appears that the error-correction loop (E loop) causes an amplification of the σ value for the various loop configurations. This amplification factor is due to the loop's effect on thermal noise, the 1.6-Hz spin-modulation component, and the 60-Hz (and multiples thereof) components due to incidental FM modulation.

LONG TERM FREQUENCY STABILITY

In assessing the long term frequency stability of the ATS system, the CCITT G. 225 Recommendation is used for comparison. Site operation and method of testing multiplex channel frequency stability preclude direct application of RETMA specification, stated in section 3.3.1 of this report.

The results of the automated tests (paragraph 3.3, tables 3.9 through 3.11) based on secondly averages of the multiplex channel frequency errors, show that in nearly 100 percent of the tests considered, the test mean and median frequency errors are less than 2 Hz. The rms variation of the test means is less than 2 Hz in all cases. Generally, about 25 percent of the automated tests show worst case minutely means greater than 2 Hz, with a median worst case minutely mean at Cooby Creek in the order of 0.6 Hz. Perhaps the most meaningful statistic from a user point of view is the time availability. This statistical value, for all test data from all stations, shows that when the system is operating normally, less than 10 percent of secondly frequency errors are greater than 2 Hz. It is concluded, then, that the AFC system in the SSB transmitter is sufficient for meeting the CCITT G. 225 specification, as well as the RETMA TR-141 specification.

The long term frequency variations are mainly due to doppler shifts and frequency offsets of the system oscillators. The former factor for the case of the geostationary satellites is less than 100 Hz. It is caused by the relative motion between the S/C and ground station. The latter factor is mainly caused by the frequency offset of the S/C master oscillator. As shown in figure 1.17, the total offset is actually 380 times the frequency offset of the master oscillator.

1.2.4.3 Automatic Frequency Control Systems

As previously stated, the system AFC unit is composed of both an open (E loop) and closed loop form of automatic frequency control. The open loop technique is provided specifically for use with a synchronous altitude S/C where doppler frequency offsets are small (probably less than 100 Hz.) In this case the frequency shift on a specifically provided pilot (also translated through the S/C) is used to offset the earth transmitter frequency such that the FDM spectrum arrives at the S/C in the proper frequency slots. In this system no attempt is made to correct the actual shift on the pilot frequency itself. This is perfectly valid provided the frequency error is not so large as to shift the pilot frequency into the FDM baseband or into adjacent pilot channels. In the case of an asynchronous S/C where the doppler can approach 30 kHz, open loop correction is inadequate due to the large shift in the pilot frequency. In this case the closed loop AFC system must be provided so that the frequency shift on the pilot can be also reduced to acceptable limits.

Thermal (idle) noise is present in all systems. It can cause short term frequency variation of the test tone by the vector addition of the signal vector and the quadrature component of the noise vector. Tests were performed to determine the amount of frequency instability caused by the quadrature component. This was accomplished by determining the standard deviation of the frequency distribution histogram as a function of the multiplex channel TT/N ratio. Applicable TT/N ratios for the various system conditions are about 36 db and 40 db. For the former, σ is 1.96 Hz, and for the latter ratio it is 1.24 Hz. Since the operational TT/N ratios are in the above range, it follows that the above σ values set an absolute lower limit on the system test tone short term stability.

In order to reduce the magnitude of the components that affect short term frequency stability a reference carrier stabilization technique was developed and evaluated. A detailed discussion of the technique is given in paragraph 5.1.13 of this report. From the 0-600 Hz error spectrum displays, it can be shown that the technique substantially reduces the spectrum components in the lower part of the frequency band. In the 360-Hz region, the response with the reference carrier technique approaches the response obtained with normal system operation with the error correction loop (E loop) off.

Table 1.21 shows the σ values for various test loop configurations when operating with a normal system and with the reference carrier unit inserted in the system. The σ value for the multiplex back-to-back loop shows the effect of thermal noise on the formal and reference carrier test configurations. As shown, the reference carrier technique has an amplification effect on the thermal noise. It is noticed that for both TT/N ratios, the σ values for the reference carrier condition are essentially equal for the multiplex back-to-back loop and the S/C loop (e.g., for an TT/N of 37 db, σ = 2.36 Hz and 2.31 Hz). Therefore, it is concluded that the reference carrier technique reduces the effects of all components causing the short term instability other than thermal noise. It is shown in paragraph 5.1.13, that these components are reduced by a factor that is greater than 40 db. This fact supports the above statement.

Since thermal noise is the main factor in determining σ for the reference carrier technique, it follows that the effect on σ of the incidental modulation factors, the spin modulation component and the 1/f phase noise can be obtained by comparing the σ values for the normal system and reference carrier test configurations in the S/C loop. For a TT/N of 37 db the difference is 0.85 Hz. For a TT/N of 43 db, it is 1.88 Hz. From the above results, it is concluded that thermal noise is the main limiting factor in reducing the short-term frequency instability for operation with ATS-1.

frequency stability. This method utilizes Fourier techniques to obtain an error spectrum and a frequency of occurrence histogram for the signal that represents the frequency perturbations of the received test tone frequency. The standard deviation of the above histogram is chosen as a logical measure of the test tone frequency instability.

Using the measurement techniques described above, the following factors which affect the received test tone frequency stability were measured:

1) 60 Hz sidebands and multiples thereof (incidental modulation)
2) Spin modulation components (approx. 1.6 Hz) due to S/C spin effect.
3) Oscillator 1/f phase noise
4) Quadrature component of the normally distributed thermal noise.
5) Spurious frequencies at the high end of the frequency test band (ATS-3), spacecraft source unknown.
6) Frequency offsets of the system oscillators.
7) Doppler shifts.

A pictorial representation of the first four factors is shown in figure 1.18. Due to the extremely small bandwidth of the AFC loop, it follows that only very low frequency rates can be handled by the loop. It has been found that items (6) and (7) fall into the low rate category; hence, the AFC loop can negate their effect. However, the effect of the other five factors cannot be negated so they cause short term variations of the test tone frequency.

The 1.6-Hz spin modulation sidebands are impressed on the 6 GHz signal because of either an electrical or mechanical phase misalignment (see sections 3.6.2 and 5.1.8) of the S/C receive antenna with respect to its geometric phase center. As a result, as the S/C spins, there is a change in the relative phase of the received 6 GHz signal which eventually is translated to an angle modulation of the received test tone.

The 1/f phase noise is produced in the various oscillators of the units making up the overall system. This type of noise is characteristic of all oscillators. Ideally, an oscillator should produce a single line spectrum. In actual practice the continuouse 1/f spectrum is obtained and this property adversely affects the short term stability of the oscillator. Since the error correction unit has a sinusoidal characteristic, it follows that the 1/f spectrum is drastically reduced near the test tone frequency. In this region, the effective f is quite small; hence, the amplitude of the sine function also is small. For more details see Section 7.4.

4) For a spin-stabilized S/C such as ATS-1 and ATS-3, a special problem exists due to an undesirable phase modulation of the uplink 6-GHz frequency at the S/C spin rate. For both ATS-1 and ATS-3 this is about 1.6 Hz.

5) It is generally practicable in an SSB system to consider the possibility of transmitting a low level reference subcarrier for use at the receiver for synchronous demodulation of the SSB signal. (Reference carrier technique). This approach has been instrumented and it has been shown that it can significantly reduce the short term test tone instability. Its integration into the system would reduce the overall versatility of the random access characteristics of the system.

Frequency stability can be considered as either a long term or short term effect. Long term instability includes such effects as frequency drift due to system oscillator aging and thermally induced changes in component characteristics, and frequency change due to doppler effects resulting from movements in the relative S/C position with respect to the earth station. Short term instability includes such effects as the basic oscillator phase noise, power line frequency modulation, thermal noise, and 1.6-Hz S/C spin modulation.

1.2.4.2 Stability Factors

Figure 1.17 shows functionally where the various factors that cause short and long term instability are introduced in the system. The 60 Hz and multiple sidebands are inserted in the system at the SSB earth transmitter. These signals are impressed on the Y frequency standard by incidental FM modulation of the standard. They become a problem because the resulting modulation index is effectively multiplied by a factor of over 800 in the process of translating the baseband to the 6 GHz frequency range. For a more detailed discussion, see Section 5.1.10.

SHORT TERM FREQUENCY STABILITY

Utilizing a wave analyzer and distortion meter, it is possible to detect harmonics of a 1-kHz test tone plus 60-Hz components and multiples thereof when operating with the ATS-1 S/C loop. Of the two components measured, the harmonic levels are negligible relative to the 60-Hz component levels. When operating with the ATS-3 loop, the above components are detected along with large spurious components in the 130-Hz to 200-Hz region. Also, strip chart recordings of the received test tone level indicate the presence of strong 1.6-Hz components and multiples thereof.

Due to the resolution and bandwidth limitations of the above measurement techniques, another method was developed to obtain a more precise quatitative measure of

1.2.4 FREQUENCY STABILITY

1.2.4.1 Introduction

In this section all aspects of the frequency stability characteristics of the SSB-FDMA/PhM mode are considered. This includes various operational aspects of the AFC system as well as the various factors that determine the long and short term frequency stability characteristics of the test tone that is received in a multiplex channel. The above stability characteristics are defined in terms of the stabilization effect that the AFC unit exercises on the various components causing the instability. Also for completeness the acquisition characteristics of the AFC system are presented along with the effects of the instability on voice and FSK digital data.

A satellite communications SSB system is unique in several respects as contrasted to terrestrial SSB systems from the standpoint of realizing the necessary frequency purity of the RF signal. It is well known that in any SSBSC modulation scheme the information bearing signal is transmitted without a carrier reference. This imposes the requirement for providing a stable carrier reference at the receiver for demodulation of the transmitted information. As a result, uncorrelated frequency instability either in the transmitter, the spacecraft or the receiver results in undesirable frequency errors in the demodulated signal. A satellite system is further complicated by the following system constraints:

1) In addition to the ground transmitter stability requirements, a correspondingly rigid stability specification must be placed on the S/C master oscillator. This, coupled with the overall reliability constraints of a S/C system, further complicates the problem.

2) A satellite communications system operating at 6 GHz, requires a frequency multiplication factor of over 1000 when referenced to a 5-MHz frequency standard. This represents a degradation of more than 60 db in the intrinsic stability of the 5-MHz standard. Obviously an exceptionally good standard and noise free multiplication process is mandatory.

3) It is possible to, and in fact the ATS system does, employ an AFC system through the tranmission link to correct for frequency errors ; however, because of the exceptionally large propagation delay (transport lag), nominally about 0.27 second for a S/C in synchronous orbit, the AFC bandwidth is limited to about 0.32 Hz. Therefore, it is not possible to correct for fast or short term frequency variations originating in the ground transmitter system.

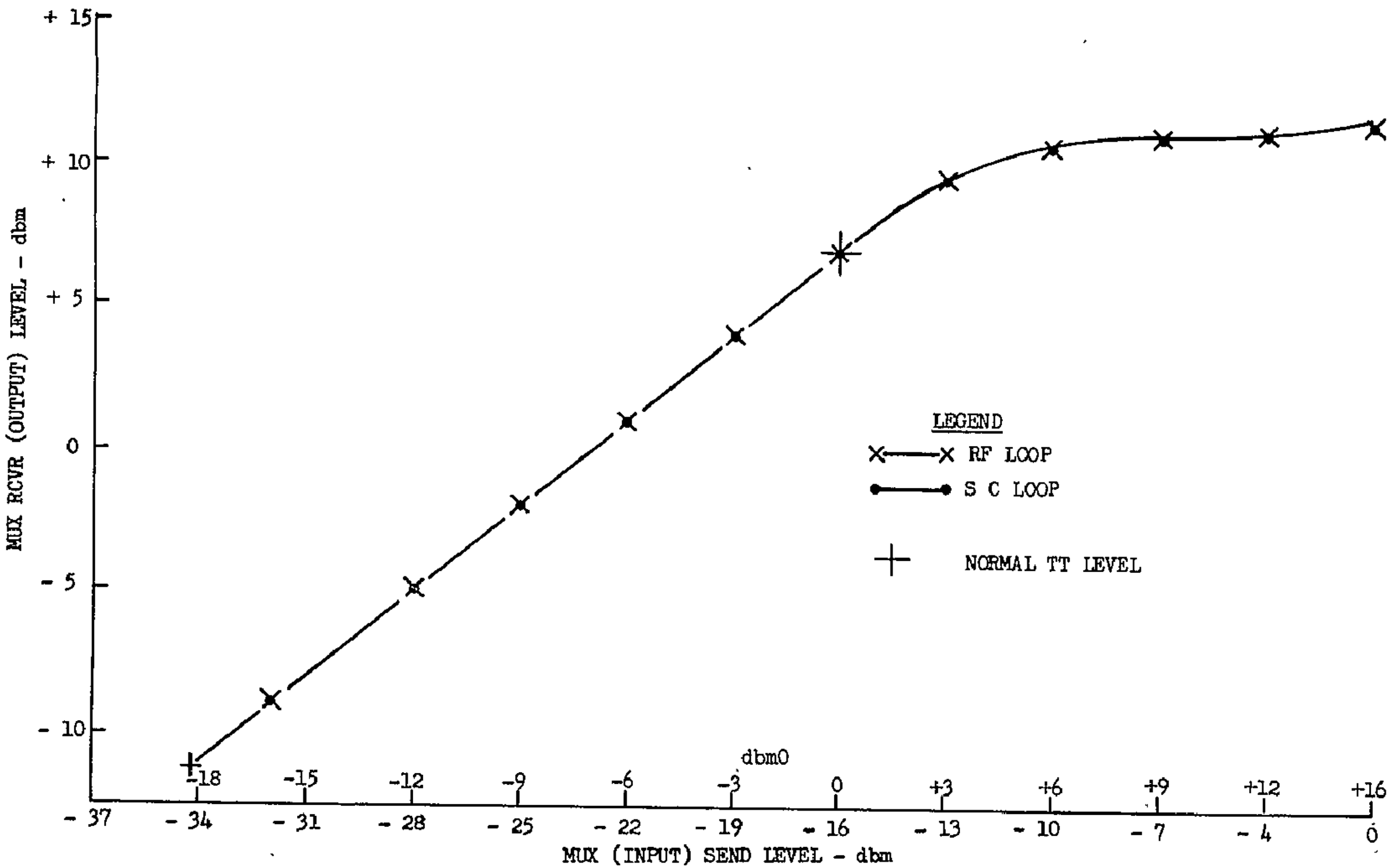


Figure 1.16. Typical Multiplex Channel Linearity

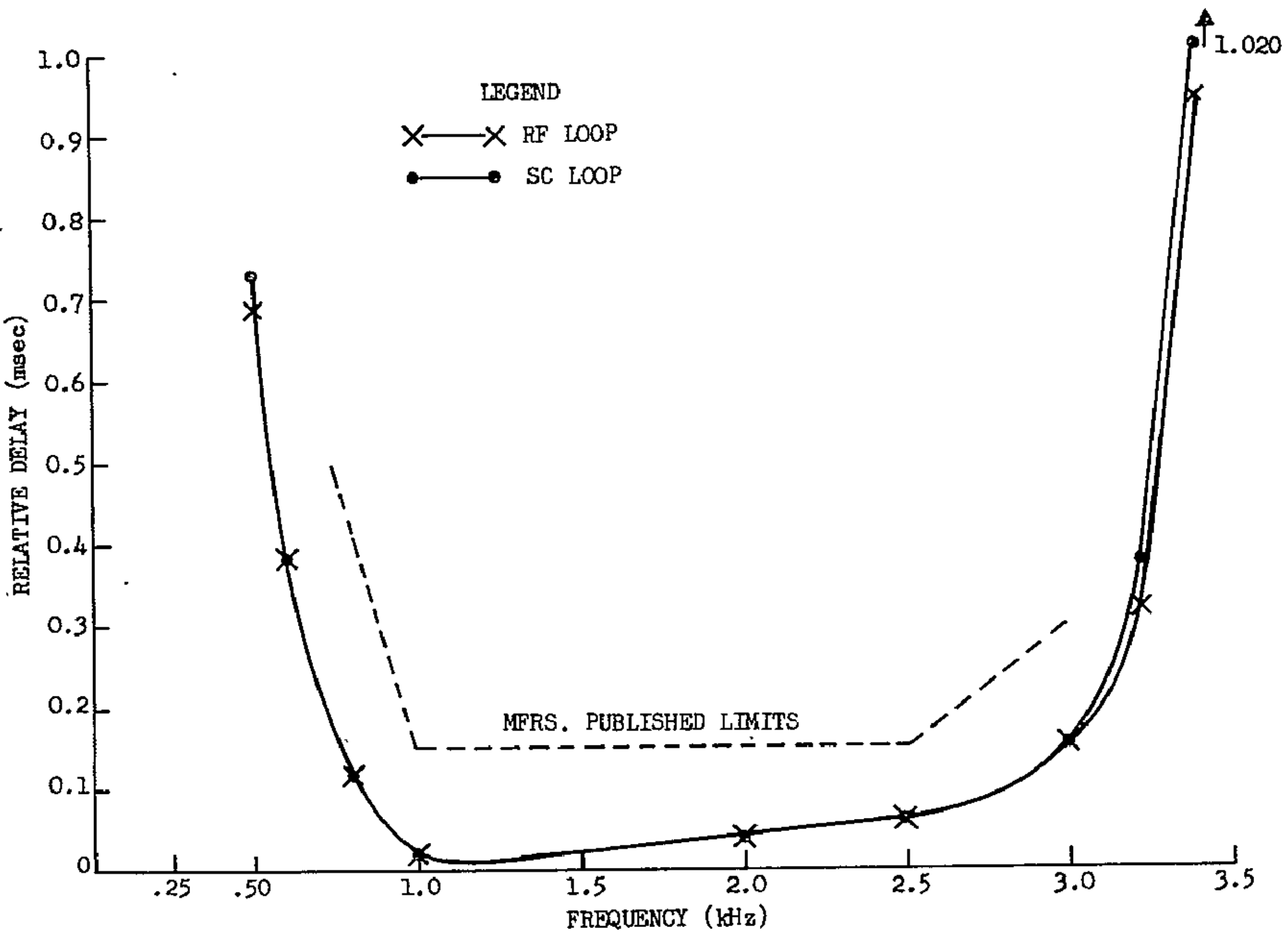


Figure 1.15. Typical Multiplex Channel Audio Envelop Delay

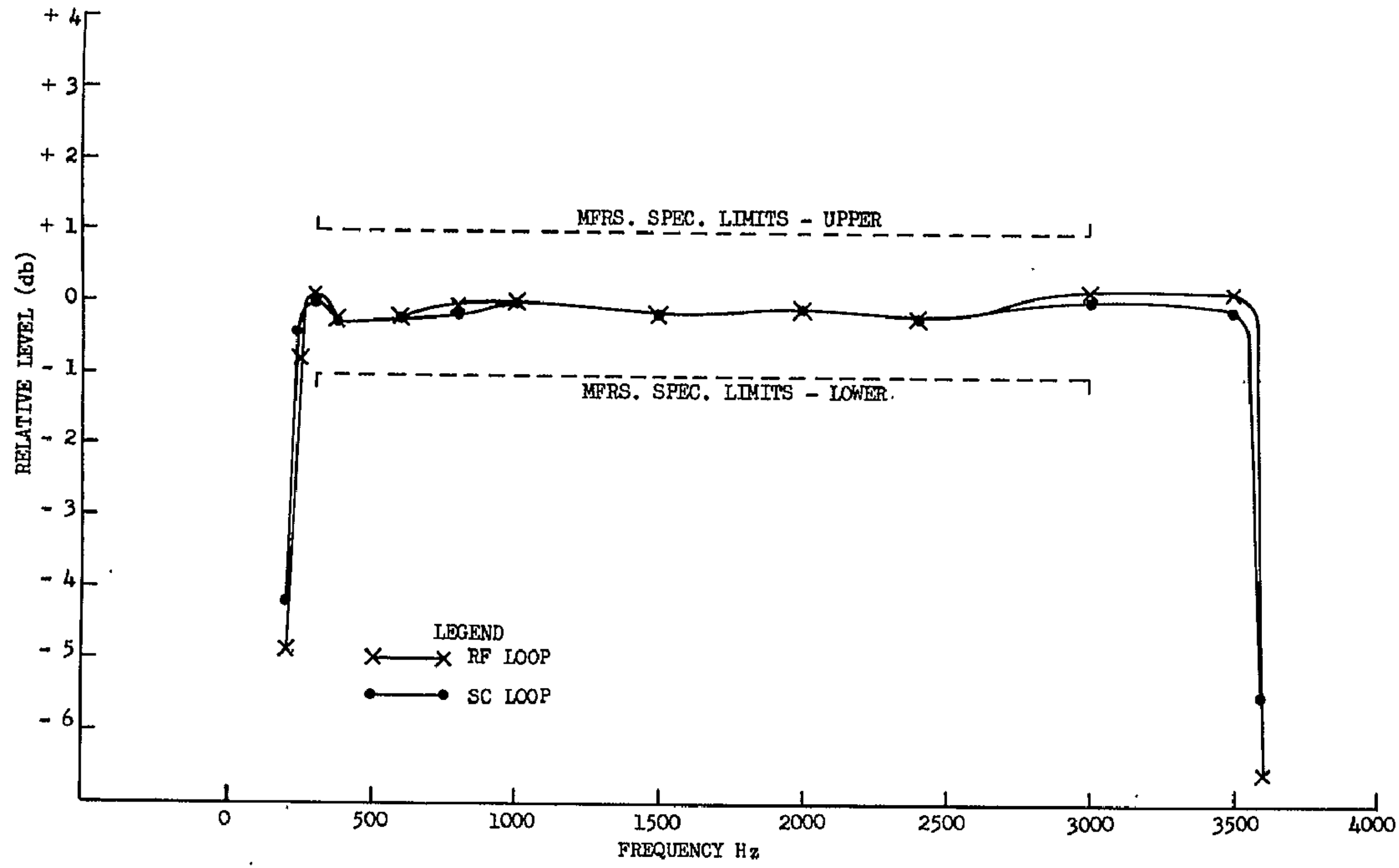


Figure 1.14. Typical Multiplex Channel Amplitude Versus Frequency

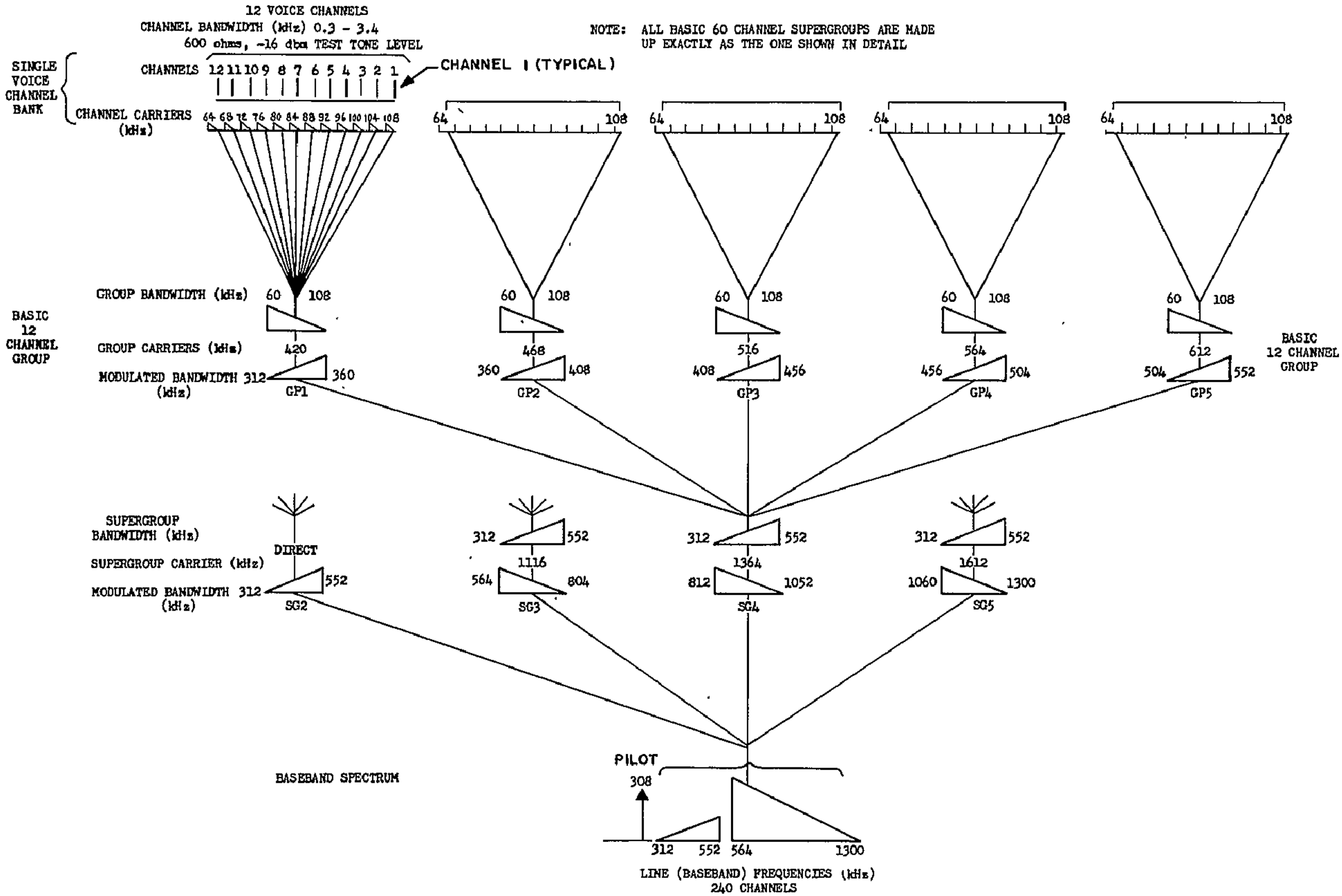


Figure 1.13. Frequency and Modulation Plan, (240 Channels)

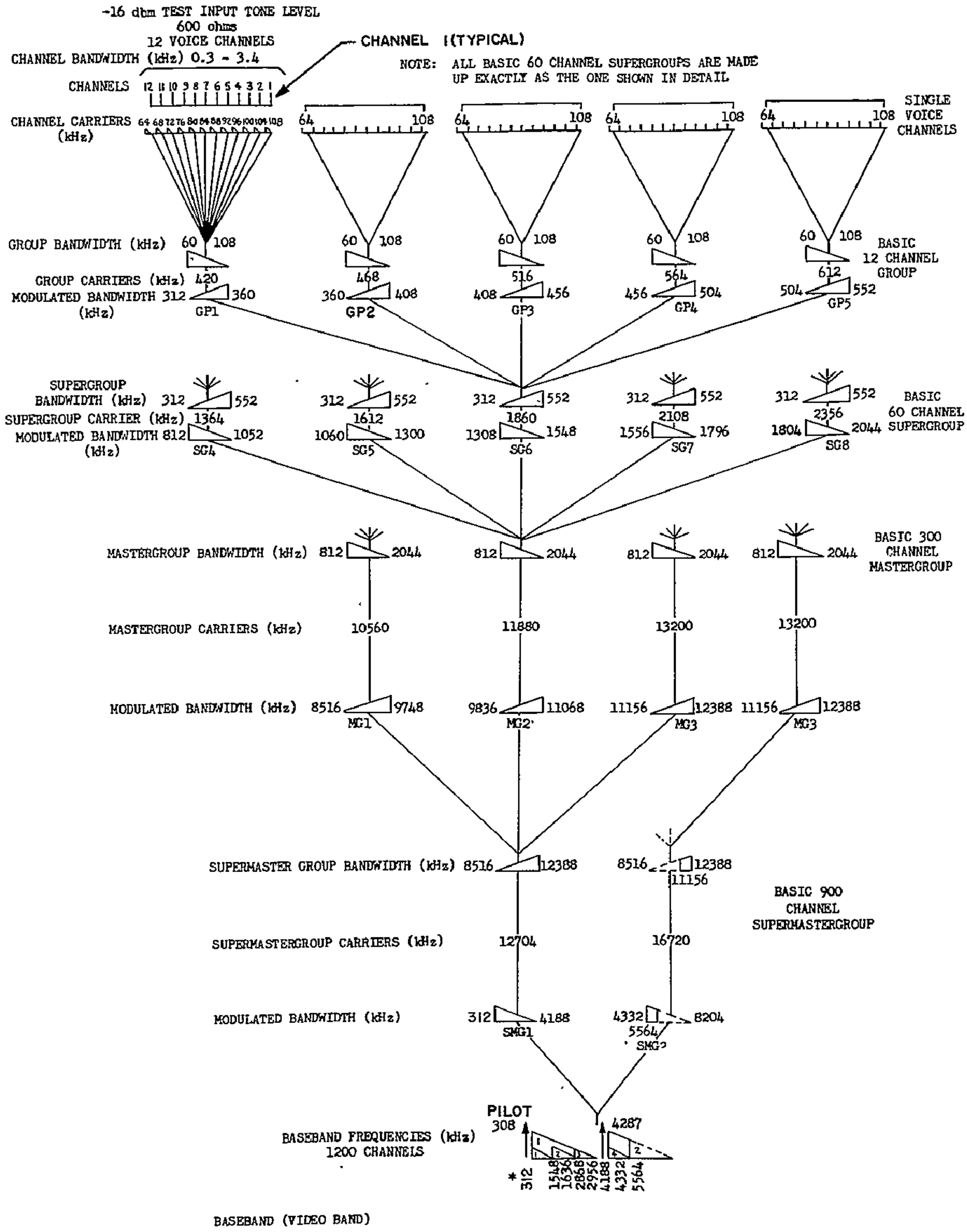


Figure 1.12 Frequency and Modulation Plan, (1200 Channels)

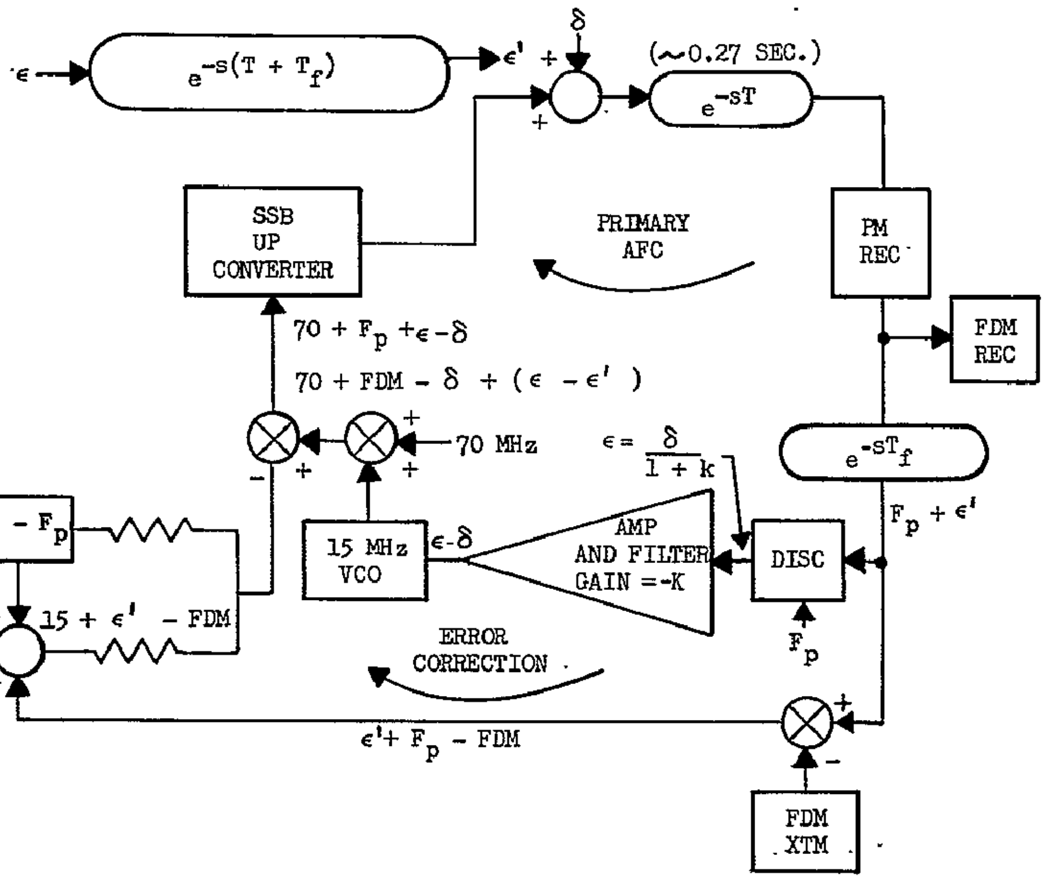
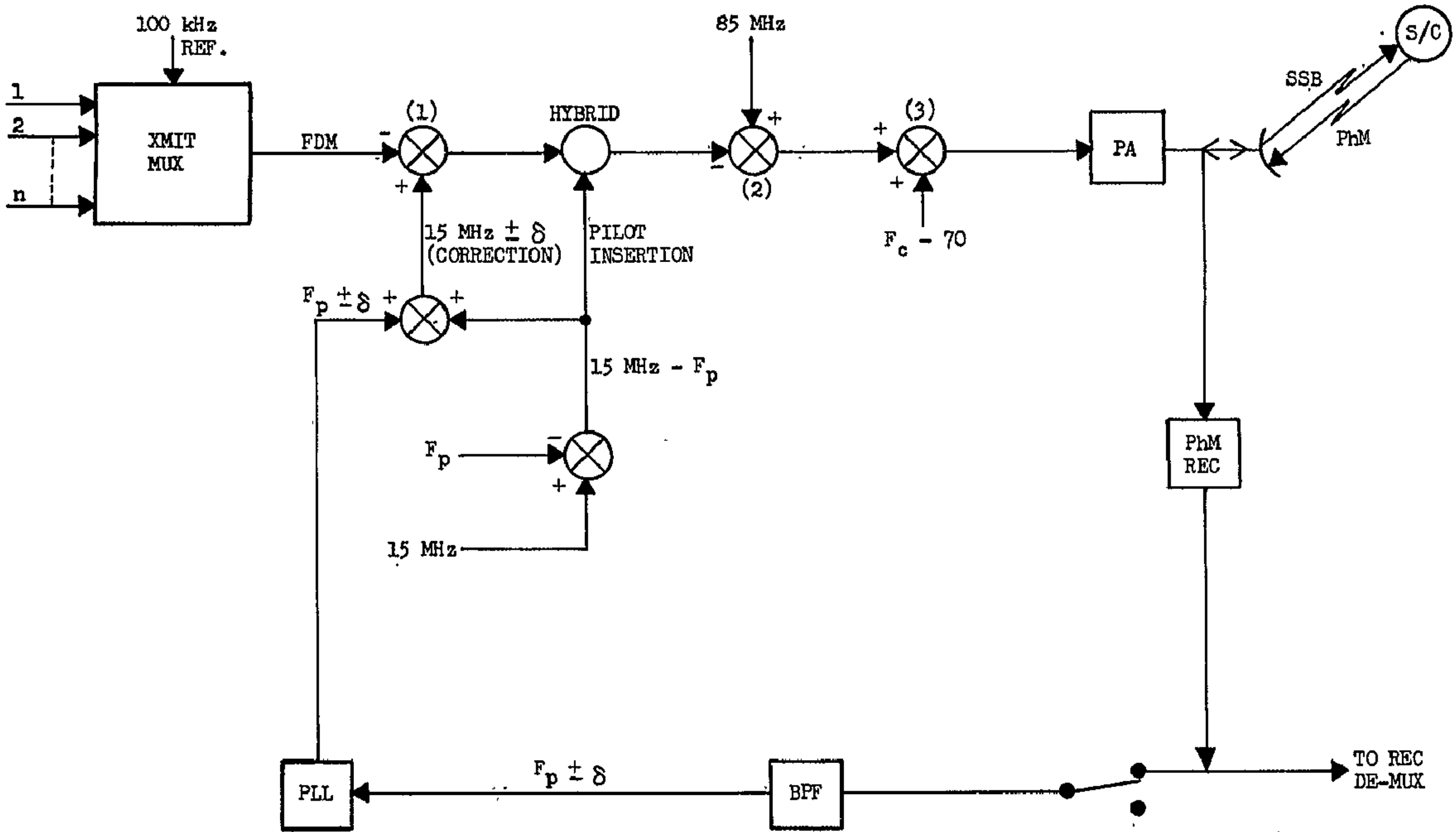


Figure 1.11 AFC and Error Correction Loops



MIXER (1) 15 MHz ± δ - FDM

MIXER (2) 70 MHz ∓ δ + FDM
70 MHz + F_p

MIXER (3) F_c ∓ δ + FDM
F_c + F_p

δ = UPLINK DOPPLER SHIFT AND S/C OSC. DRIFT
F_c = 6 GHz UPLINK FREQ
F_p = STATION PILOT

Figure 1.10 Open Loop AFC Configuration (Error Correction Loop)

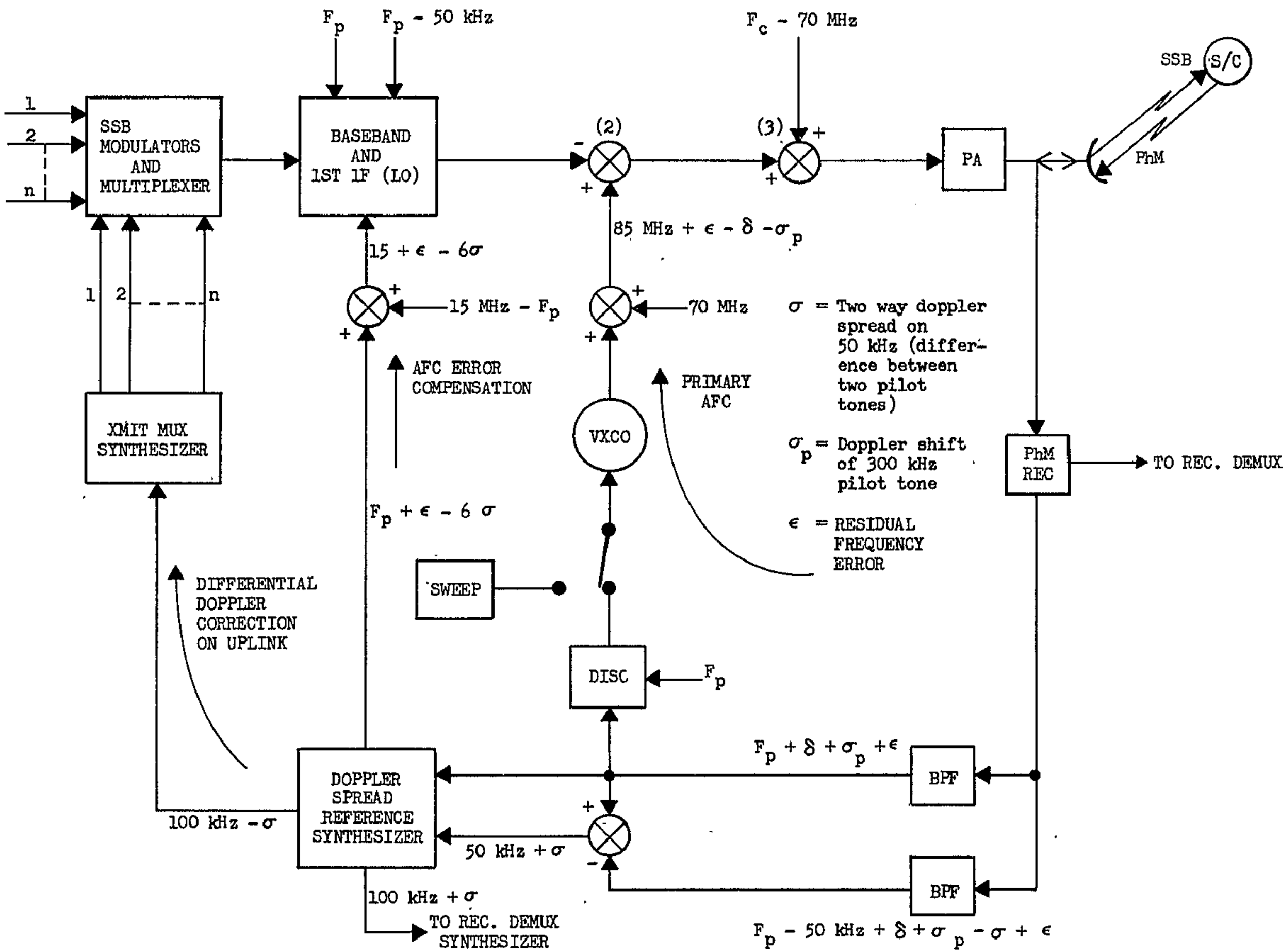


Figure 1.9 Primary (Closed) Loop AFC Configuration

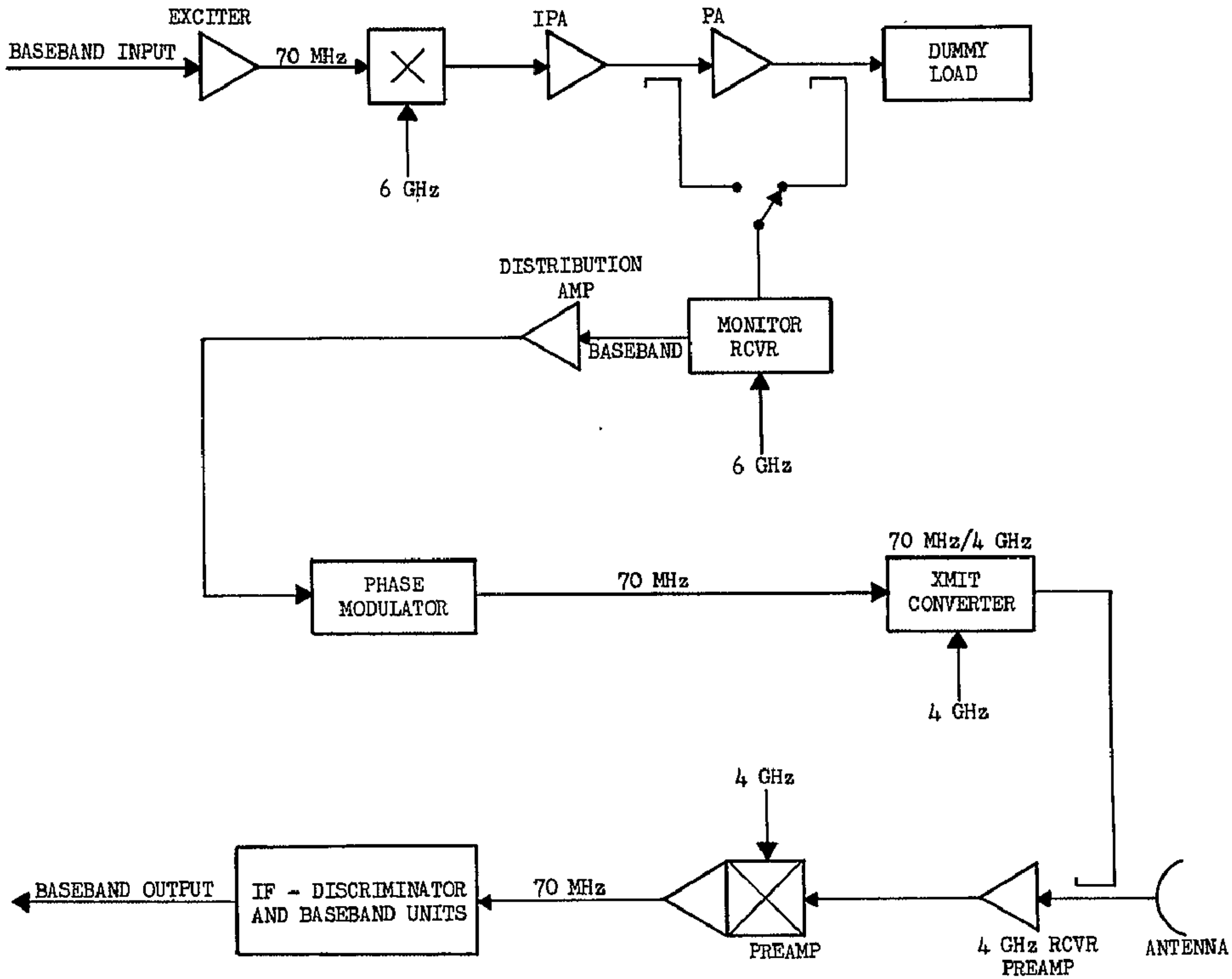


Figure 1.8 RF Test Loop for the SSB-FDMA/PhM Mode

receiver. The contributions of these three major elements are determined from total noise power ratio (NPR) and thermal noise power ratio (TPR) measurements taken in various loop configurations as follows:

Loop Configuration	Element measured
Transmitter loop	Earth station transmitter and monitor Receiver
Receiver Loop	Earth station test modulator and receiver
Spacecraft loop	Earth station transmitter, spacecraft and earth station receiver

Assuming that the monitor receiver introduces negligible distortion, the transmitter loop test may be used to determine the contribution from the earth station transmitter. This value is expressed as a ratio of the F1A weighted test tone-to-intermodulation noise ratio (K_2). Another figure of interest is the combined effect of the spacecraft and earth station receiver test tone-to-intermodulation ratio (K_{ov}). Data from the spacecraft and transmitter loops is used to determine the magnitude of the K_{ov} term. This result is then compared with the receiver loop data to determine the relative effects of the spacecraft and earth station receiver. Measurements of K_2 and K_{ov} were made for several slot frequencies across the baseband. The results of the measurements show that the K_2 and K_{ov} terms are only slightly dependent upon baseband frequency, and that one curve may be used to represent the function across the entire baseband. Figures 1.22 and 1.23 present the intermodulation noise contributions of the various elements for the earth station using 85-foot and 40 foot diameter antennas, respectively. It should be noted that the NPR/TPR measurement is only accurate to within ±1.0 db. Also, when the intermodulation noise is small relative to thermal noise (NPR and TPR are essentially equal), the test tone-to-intermodulation noise (TT/I) ratio can be in error by a significant amount.

Predicted and measured TT/N ratios are given in table 1.3. The predicted TT/N ratios are derived from an overall system analysis, based on SSB and PhM theory, prelaunch system parameters modified where possible by post-launch measurements and using the K_2 and K_{ov} ratios shown in figures 1.22 and 1.23. Any comparison between measured and predicted TT/N ratios is valid only for C/N ratios above threshold since threshold effects are not included in the predicted TT/N ratios.

At nominal P_{rs}, and 240 channel loading, figure 1.23 shows that the best TT/I the earth station, with a 40-foot antenna and using ATS-1, can provide is approximately 46 db. Based on a TT/I of 46 db and the TT/R of 40.5 db shown in table 1.3 for Mojave and ATS-1 (EIRP of 52.2 dbm), the best TT/N is about 39 db. Table 1.3 shows a predicted TT/N of 39.5 db while measured TT/N is 37.4 db in the low channel and 38.7 db in the high channel.

On the other hand, this same earth station transmitter, using ATS-3, yields a TT/I of 68 db, however, the spacecraft now limits TT/I such that the best overall system TT/I (K_{ov}) is about 57 db. With 1200 channel loading the overall TT/I is agin limited by the S/C at about 46 db. The earth station transmitter, with an 85-foot antenna and using ATS-1 and 1200 channel loading (see figure 1.22) provides a TT/I of approximately 43 db. This earth station with ATS-3 is again limited by the spacecraft such that the system TT/I is still about 46 db. Based on this 46 db TT/I ratio and the TT/R ratio of about 47 db, shown in table 1.3, the best TT/N is about 43.5 db and this occurs at the Rosman earth station (85-foot antenna) using ATS-3 (56.5 dbm EIRP). Table 1.3 shows a predicted TT/N of 43.7 db and a measured TT/N of 43.3 db. This TT/N does not meet the 50 db TT/N recommended by the CCIR. In order to meet a 50 db TT/N ratio without compandors, both TT/I and TT/R should be increased to 53 db.

The influence of weather conditions on received TT/N ratio is indicated by tests performed under extreme weather conditions. During a heavy rainstorm with the earth station antenna at a low elevation angle (approximately 7°), a maximum decrease of 4 db from nominal TT/N was observed. At higher elevation angles (approximately 36°), the maximum observed decrease in multiplex channel TT/N was 2 db. In another test, a maximum decrease of 2 db was observed when the earth station antenna was covered with snow.

In addition, automated tests were conducted on ATS-1 and ATS-3 at the three earth stations. The observed maximum deviation from the mean of the measured TT/N is plus 0.2 db/minus 0.5 db and this occurs within a 14-minute period, while the TT/R variations are somewhat larger (1.1 db). Although these tests were somewhat limited, they provide an indication of both long and short term TT/N variation. These measured variations using automated tests do not appear to be significant with respect to the operating system TT/N and probably no more than one db margin for variation with time is required to compensate for uncontrolled variables such as path loss variations, S/C antenna pointing fluctuations and system noise temperature variations.

The statistical nature of TT/N variations depend on weather conditions which further depend on geographical location. This fact must be considered along with measured data to arrive at the proper system margin to compensate for these conditions. Based on the location of the ATS earth stations, and considering TT/N variations due to the above causes, a system margin of 2 db appears adequate to realize the mean TT/N shown as measured values in table 1.3.

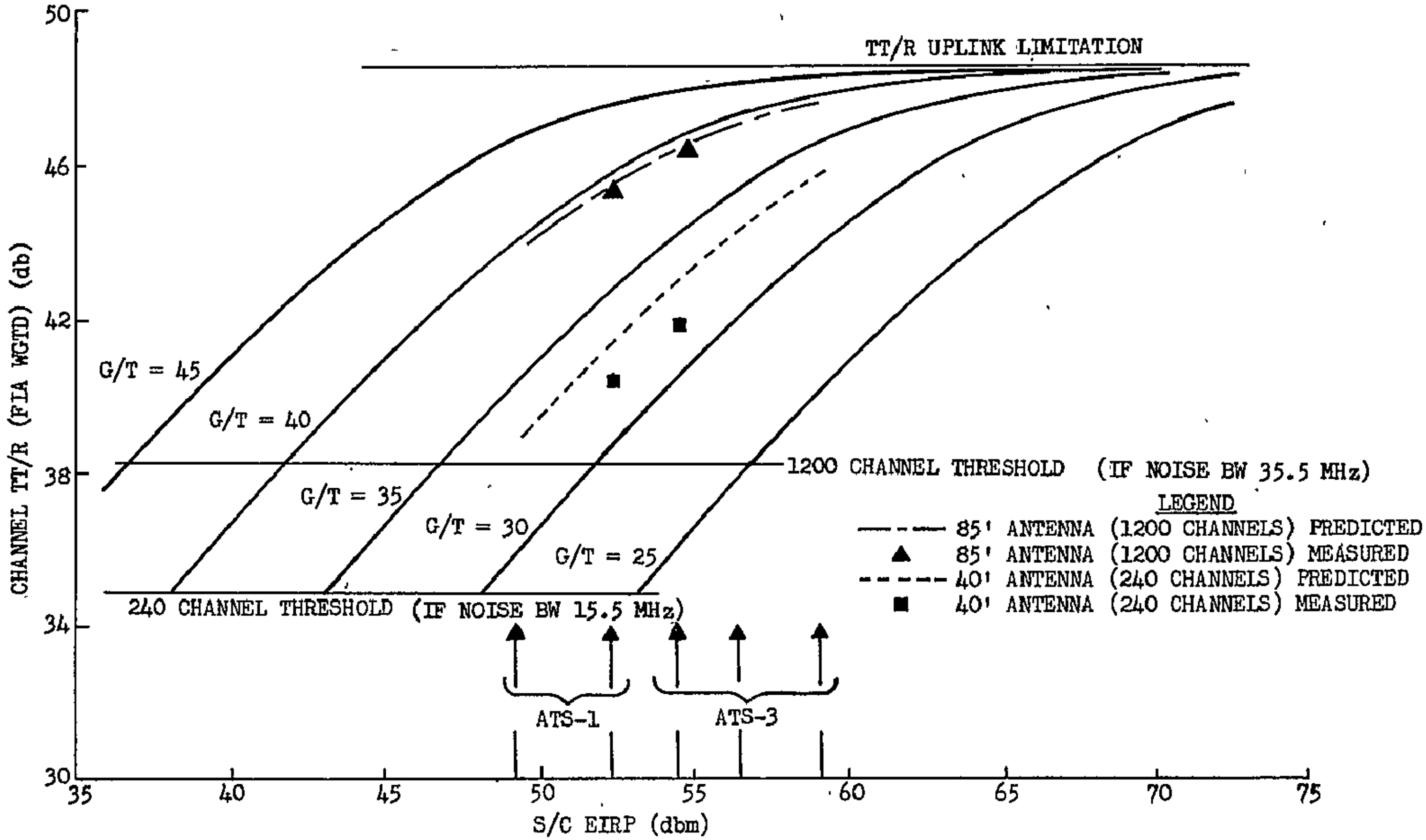


Figure 1.21. FDM Channel Thermal TT/R Ratios (MA Mode)

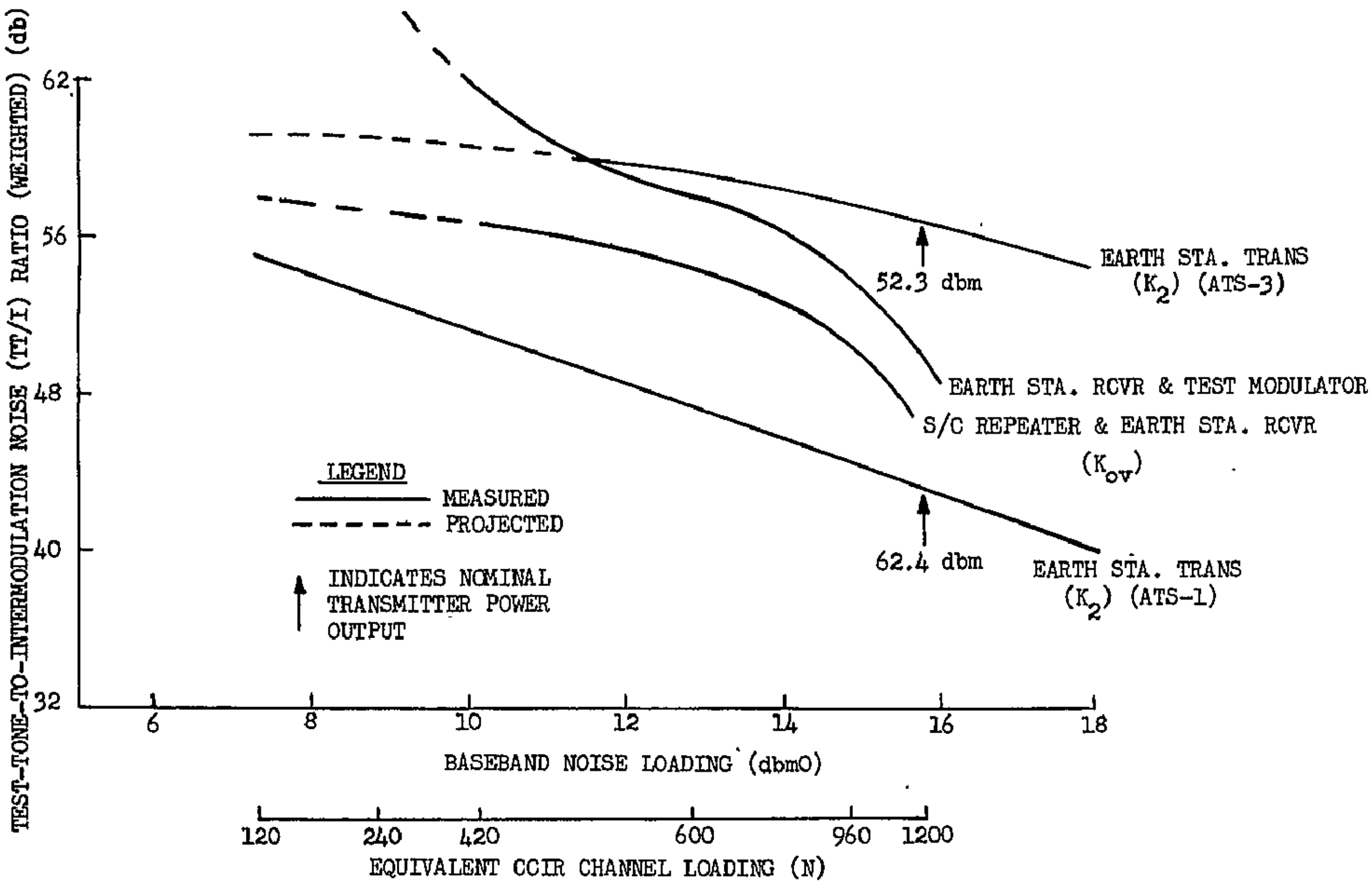


Figure 1.22: System Test Tone-to-Intermodulation Noise (TT/I)(85' Antenna)

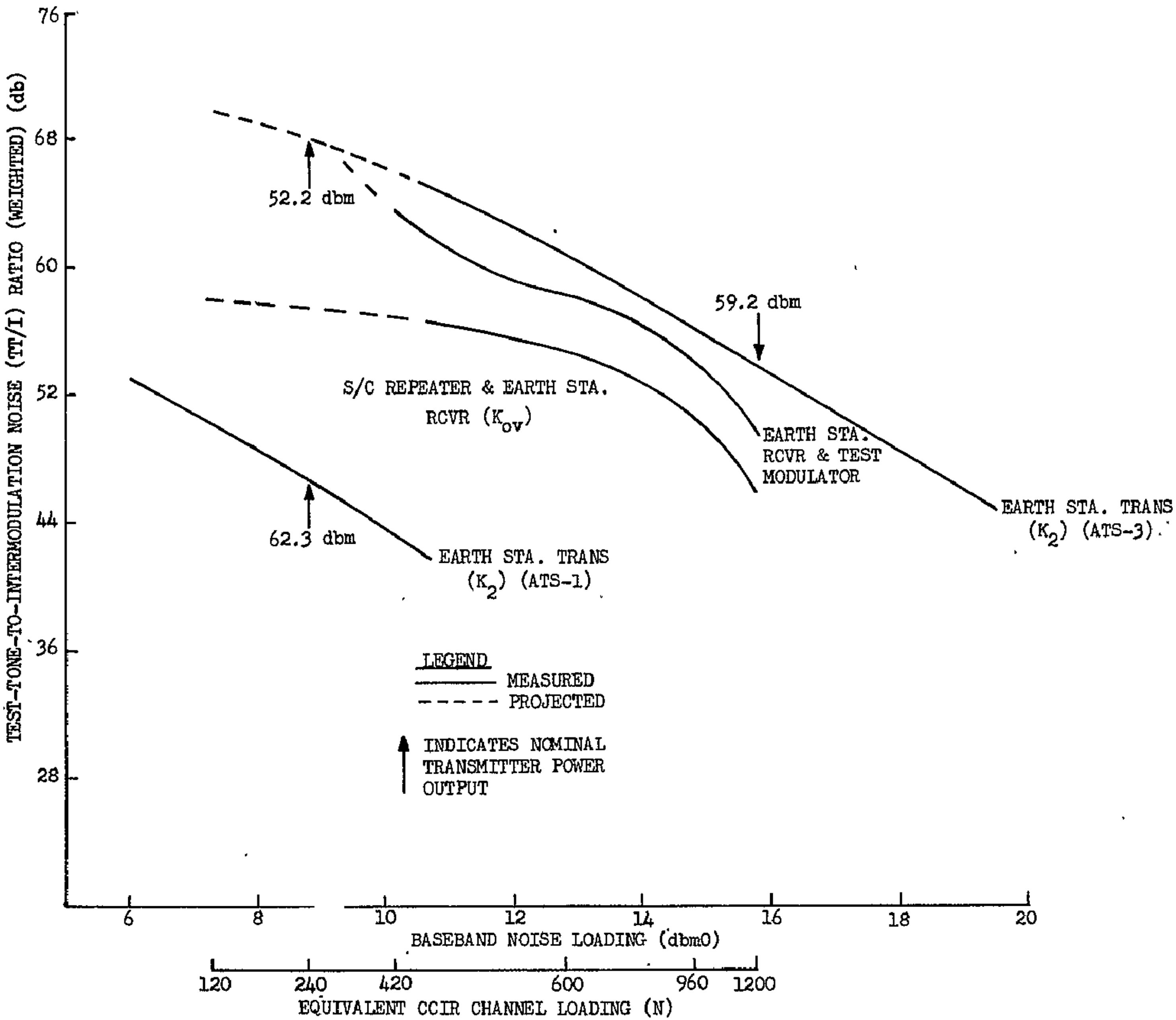


Figure 1.23. System Test Tone-to-Intermodulation Noise (TT/I) (40' Antenna)

1.2.7 NOISE CHARACTERISTICS OF THE SSB/PhM MODE

INTRODUCTION

The performance limits of the SSB/PhM mode for a specified system condition depends on the magnitude and spectral characteristics of the noise types that exist for the specified condition. As a result of the experimental program, the two basic types of noise, thermal noise (R) and intermodulation noise (I) were noted and measured. In addition thermal and intermodulation noise as modified by threshold operation, and defined as threshold noise were also measured. This section presents the magnitude and spectral characteristics of the above noise types and also shows the functional relationship between these noise types and specific system parameters. It also considers the dominant order of intermodulation noise contributed by the various elements comprising the SSB/PhM mode.

The magnitude of the C/N ratio (carrier-to-noise defined in the IF bandwidth) is the primary factor that determines which of the above noise types predominate. In the ATS system, a variety of C/N ratios exist depending on the size of the earth station antenna (40 foot or 85 foot) and the satellite employed, ATS-1 or ATS-3. At the extremes, a C/N of 7 db is obtained at Mojave and Cooby Creek for multistation operation when employing ATS-1. For this case, threshold noise predominates. A C/N of 20 db is obtained at Rosman with ATS-3. In this case, (I) noise essentially predominates. Intermediate C/N values are obtained by employing various combinations of the earth stations and satellites.

The characteristics of threshold noise (magnitude and spectral properties) are defined along with its functional relationship to C/N and the degree and form of the type of modulation employed for the ATS system.

Thermal noise is the dominant factor in the intermediate range of C/N values, which for the ATS system is 11 to approximately 15 db. The upper limit of this range (15 db) is the point at which intermodulation (I) and thermal (R) noise are equal. The lower limit (below 11 db) is defined as threshold.

The following subsections contain the results (analytical and measured) of the investigation of thermal, threshold and intermodulation noise in the ATS SSB-FDMA/PhM mode.

THERMAL NOISE

In the SSB/PhM mode, the spectral characteristics of the thermal noise (R) at the baseband output of the PhM receiver are mainly determined by the characteristics of the detector. In this case, the detector consists of an FM discriminator followed by a 6 db/ octave de-emphasis filter (integrator). It is a known fact that the power spectral characteristics of (R) noise at the output of a discriminator vary as the square of the baseband frequency, ω, for high values of C/N. Stated mathematically the noise power density N_D is,

$$N_D = \frac{K\omega^2}{\left(\frac{C}{N_o}\right)}$$

where:

$\left(\frac{C}{N_o}\right)$ is the carrier-to-noise ratio at the input to the discriminator defined in a unit bandwidth. K is the discriminator constant.

If the above spectrum is passed through a de-emphasis circuit with a transfer function of $1/(1 + \frac{\omega}{\omega a})$, the output is independent of ω for values of ω in which $K \frac{\omega}{\omega a} \gg 1$ (ωa is the frequency at which the response is down by 3 db). Therefore, it follows that for high values of C/N the baseband noise spectrum is flat with respect to frequency. Also the noise level varies directly with C/N. This fact was confirmed by actual measurements of the baseband noise spectrum. An important fact to remember is that a flat spectrum at the output of the de-emphasis filter is only realized when the input power spectrum varies as the square of the baseband frequency.

THRESHOLD NOISE

For C/N ratios of 10 db or less it was noted in baseband noise measurements that the noise level peaked in the lower end of the baseband region (342 kHz, 768 kHz region). This noise peaking became apparent in multistation tests performed with Mojave and Cooby Creek. For these stations, the operational C/N ratios varied in a range of 7 to 9 db.

The change in the baseband noise spectral characteristics from a uniform shape can be explained by noting that the baseband noise is essentially made up of two components: (1) the parabolic noise component (2) a flat noise component that is a critical function of C/N. The latter component is the impulse noise contribution to the total baseband noise that becomes quite prevalent in the threshold region. The reasons for this impulsive character of the noise and the fact that the resulting spectrum is flat is covered in detail in a number of publications. The flat output spectrum follows from the fact that the output signal from a baseband filter with a transfer function of $H(j\omega)$ is $H(j\omega)$ for an impulse input. The $H(j\omega)$ is in reality the baseband frequency response which is essentially flat across the baseband. For high C/N ratios the contribution of the impulse component is minimal. As the C/N decreases this component becomes dominant in the lower end of the baseband relative to the parabolic noise component. The addition of these two components causes a flattening of the resultant spectrum at the lower end of the baseband. At the higher end, the resultant spectrum maintains its parabolic character due to the fact that the parabolic noise component is a much larger percentage of the total noise. When the composite spectrum is passed through the de-emphasis filter, the output spectrum peaks for that portion of the input spectrum that is flat and is flat for that portion that is parabolic.

From the above discussion it follows that the baseband threshold noise is made up of the following components:

(I) = Intermodulation noise which varies with the degree and form of modulation and is caused by system non-linearities, but is not a function of C/N ratio.

(R) = Thermal noise which varies linearily with decreasing C/N_o (carrier-to-noise density ratio).

(N_i) = Threshold noise due to impulse (or "click") noise that is a function of C/N and varies in a non-linear manner with C/N.

(Δ) = Threshold noise due to impulse noise that is not only a function of C/N (varies in a non-linear manner with C/N ratio) but also the degree and form of modulation employed.

Characteristic values for the above noise components are shown from measured data in figures 1.27 through 1.29 for C/N values of 20 db, 12 db and 8 db respectively. This data was obtained by utilizing the FM receiver. The (Δ+ I) component was measured by applying a 40 kHz tone to the FM modulator. The peak frequency deviation was set at ±10 MHz. The actual measured data was then altered by the transfer function of the de-emphasis network to determine the shape of the noise spectrum for the output of the PhM receiver. A single sinusoidal modulation tone was chosen since intermodulation or harmonic products occur at discrete frequencies and could thus be eliminated in determining the continuous noise spectrum. Admittedly, using the above modulating frequency, the effect of modulation with a band of white noise modulation cannot realistically be approximated. However, at low C/N, the values of Δ shown in these figures gives an indication of the components that are present.

It is noticed from figure 1.29 that the (Δ+ I) component predominates up to 2 MHz. For a C/N of 12 db the (R) component predominates from 300 kHz and higher. At a C/N of 20 db, the (R) component predominates. In the actual SSB/PhM system, with 1200 channel noise loading, the (I) component is higher than the (R) component.

Due to the relatively high value of the (Δ+ I) component at the lower C/N values, it follows that errors in the measurement of the correct NPR and TPR for these conditions can occur. This is seen from the following mathematical expressions:

$$(NPR)_m = \frac{((RL) + R + N_i + \Delta + I)}{R + N_i + \Delta + I} \qquad (2)$$

$$(TPR)_m = \frac{(RL) + R + N_i + \Delta + I}{R + N_i} \quad (3)$$

$$(NPR)_c = \frac{(RL)}{R + N_i + \Delta + I} \quad (4)$$

$$(TPR)_c = \frac{(RL)}{R + N_i} \quad (5)$$

where:

$(NPR)_m$ = Measured NPR value

$(TPR)_m$ = Measured TPR value

$(NPR)_c$ = Correct NPR value

$(TPR)_c$ = Correct TPR value

(RL) = Correct reference level

By utilizing equations (2), (3), (4) and (5) it is possible to show that,

$$(NPR)_c = (NPR)_m - 1$$

$$(TPR)_c = (TPR)_m \left[1 - \frac{1}{(NPR)_m}\right]$$

$$\frac{(\Delta + I)}{R + N_i} = \frac{(TPR)_m}{(NPR)_m} - 1$$

It is apparent from the above equations that if the $(NPR)_m > 10$ db the measured values are accurate measures of the correct NPR and TPR values.

INTERMODULATION NOISE

Intermodulation noise is the limiting factor for system operation at high levels of C/N. This condition is apparent when Rosman is operating with ATS-3 (C/N = 20 db). At lower C/N values, the importance of intermodulation noise depends on the sytem operating point from the standpoint of test tone level on the uplink and the overall PhM modulation index on the downlink.

In the downlink portion of the SSB-PhM (MA) mode there are essentially three separate sources of baseband intermodulation distortion caused in the IF-RF transmission medium; amplitude response non-linearities, phase response non-linearities, and spectrum truncation of the modulated signals. These affect the modulated signal spectrum in such a way that linear distortion occurs. It is not until the demodulator operates on the IF signal spectrum that new frequencies or intermodulation noise is generated in the baseband. Also any non-linear dynamic transfer characteristics in the S/C phase modulator and the earth station discriminator will be important causes of intermodulation noise.

In the uplink portion of the SSB-PhM (MA) mode, particularly the SSB transmitter amplifiers, the chief cause of non-linear noise is the non-linear dynamic amplitude transfer characteristic.

The sensitivity of the system to amplitude response variations of the phase modulated downlink signal is reduced as the index of modulation is increased. Since for nominal 1200-channel conditions the modulation index is large, the importance of amplitude response variations is greatly reduced and thus is not considered significant for the ATS modes of operation.

The intermodulation noise characteristics of the system were determined by measuring the functional relationship between the intermodulation noise level and baseband frequency by utilizing the NPR/TPR factors and two tone test data.

It should be noted that harmonic distortion is insignificant compared to intermodulation when a white noise-like signal is used for modulation. The harmonic distortion is insignificant for two reasons: (1) the number of harmonic products of any particular order is at least an order of magnitude less than intermodulation products of the same order; and (2) the magnitude of the harmonic products is several db below the level of the intermodulation products of the same order.

The results of noise loading tests are used to determine the level of intermodulation noise and the total intermodulation baseband spectrum for various ATS earth station/spacecraft configurations. In these noise loading tests, the system is modulated with a white noise-like signal (which simulates multichannel telephony) in a manner which follows CCIR recommendation 353-1, OSLO, 1966. The noise loading tests yield directly two terms (NPR and TPR) which are defined as follows:

NPR - The ratio of the noise power in a channel in the baseband when the system is noise loaded, to the noise in the channel when the noise loading is removed from that channel. This ratio is a measure of the total noise present in the channel.

TPR - The ratio of the signal noise power in a channel in the baseband when the system is noise loaded to the noise in the channel when the noise loading is removed from the system. This ratio is a measure of the idle noise present in a channel.

By removing the contribution of the idle noise from the total noise the signal density-to-intermodulation noise density ratio (K) may be determined from the following:

$$K = \frac{(NPR)\ (TPR)}{(TPR) - (NPR)} \qquad \text{(numeric)}$$

The ratio K is a measure of the total intermodulation present in the channel. This equation applies whenever the C/N ratio is above threshold. In the threshold region it should be noted that the above equation yields the signal density-to-intermodulation plus Δ density ratio, thus it cannot be used to determine K.

There is a definite relationship between the results of two tone tests and signal density-to-intermodulation noise density ratio determined from the NPR/TPR results. These relationships are quite complex from the standpoint that the relative spectra of various orders of intermodulation noise must be determined for all significant causes of intermodulation noise, the sum total of which combines into the total nonlinear noise spectrum that exists at the baseband output of the earth station receiver. These relationships have been developed in several papers for most of the causes of nonlinear noise previously discussed (39, 26, & 49 in section 6). Typical relationships are derived in subsection

The individual output power spectrums are calculated by first determining the autocorrelation function of the baseband output signal. Using the system model (model is represented by a power series expansion of the transfer characteristics of the units making up the system and is assumed quasi-stationary) to visualize of the various causes of intermodulation in the system, the autocorrelation function of the output signal can be written in terms of the auto-correlation function of the input signal. Using the Wiener-Khintchine theorem (autocorrelation function and the power spectrum are Fourier transforms of each other); the auto-correlation function of the input signal is written in terms of the input power spectrum of the modulating signal. Again, by use of the Wiener-Khintchine theorem the output power spectrum can be derived from the input power spectrum without the actual calculation of auto-correlation functions.

For the PhM receiver care must be taken in the analysis of these results. The PhM receivers at the ATS earth stations consist of an FM discriminator followed by a 6 db/octave de-emphasis network. The de-emphasis network is a linear passive filter and therefore no intermodulation products can be generated as a result of this filter. The analysis technique used for the dynamic non-linearity of the PhM receiver is based on a series expansion approximating the transfer characteristics of the discriminator. The equivalent frequency distribution (or spectrum) of the PhM signal (modulated with bandlimited white gaussian noise) is used as the input signal to the discriminator to determine the intermodulation spectrum resulting from the discriminator. This intermodulation spectrum at the output of the discriminator is then altered by the transfer function of the de-emphasis network.

The intermodulation spectrum resulting from the phase variations in the IF-RF downlink is developed on the basis that the non-linear phase variation causes distortion of the effective frequency distribution (or spectrum) of the modulated wave. The effective frequency of the signal (modulated with bandlimited white gaussian noise) at the output of the S/C phase modulator is modified by phase transfer characteristics in the IF-RF region of the downlink. This signal is operated on by the FM discriminator and then the intermodulation spectrum is passed through the 6 db/octave de-emphasis network. For linear group delay (parabolic phase variation) the dominant intermodulation spectrum is second order (i.e., made up of a continuous spectrum of products such as $f_2 \pm f_1$). Similarily, the dominant intermodulation spectrum for parabolic group delay is third order.

For dynamic non-linearity of the S/C phase modulator or the SSB transmitter the intermodulation spectra are based upon a band limited white Gaussian input signal. In the S/C phase modulator a baseband input signal is used, while in the SSB transmitter an IF signal is used. For the dynamic non-linearity of these two causes, the output baseband spectrum shapes are obtained by convolving the input signal (band limited white gaussian noise) a number of times equal to the degree of the desired order minus one. This result is arrived at by using the analysis involving the Wiener-Khintchine theorem. As an example, the third order intermodulation noise spectrum is obtained by convolving the input signal twice.

The magnitudes of amplitudes of intermodulation products produced in multitone testing are used to determine the coefficients of the series expansion of the transfer characteristics for the various non-linear noise sources in the system. The conditions of the multitone tests are varied to isolate the intermodulation products caused by various sources in the system. For example, the frequencies of the fundamental tones are varied and multistation and single station two tone tests are conducted. As an illustration of this technique the following analysis is used to determine the coefficients of SSB transmitter non-linear transfer characteristics. In the single station two tone tests (see figure 1.24), the third order $2f_1$-f_2 type products are large (30 db below total fundamental power). However, this type of product is not present in multistation tests (see figure 1.25) in which each station transmitted one tone each. Therefore, it is concluded that the $2f_1$-f_2 third order intermodulation products are caused primarily by the SSB earth station transmitter in these single station tests. Similar results and conclusions are obtained for the fifth order $3f_1$-$2f_2$ type products. It is noted that second order ($f_1 \pm f_2$), third order ($2f_1 + f_2$) and fourth order ($2f_1 \pm 2f_2$ and $3f_1 \pm f_2$) products caused in the IF-RF region of the SSB transmitter are not measurable in the output baseband because these products fall outside the IF-RF bandwidth. It is also concluded that the only types of intermodulation products in the system output caused by the SSB transmitter are the $2f_1$-f_2 type and the $3f_1$-$2f_2$ type (considering fifth order or less).

In general, the power density of the intermodulation spectrum arising from various orders of intermodulation products for a particular source (band-limited white gaussian noise modulation), is linearily related to the corresponding amplitudes of intermodulation products from two tone tests (exceptions can occur when equalization is applied to reduce group delay). However, the constant of proportionalty is different for various intermodulation orders and causes of intermodulation. This constant is developed in subsection 7.7 for important sources of intermodulation in the SSB/PhM (MA) mode based on the Wiener-Khintchine theorem and the system models employed.

Based on theoretical equations, calculated spectra, and results of multitone single station and multistation tests, the predominant second and third order signal density-to-intermodulation noise density ratios are shown in figure 1.26 when bandlimited white noise modulation is used. Depending upon the actual ATS earth station/spacecraft system configuration, the relative levels shown in figure 1.26 will change. For example, operating at one of the earth stations and comparing the resulting intermodulations spectra when using ATS-1 and ATS-3, the third order intermodulation noise density due to the SSB transmitter is higher for ATS-1 than for ATS-3. This result occurs because of the difference in the S/C received antenna gain. For ATS system operation a constant test tone level is maintained at the spacecraft receiver input. Since an increased SSB transmitter power output is necessary to make up the loss of antenna gain with ATS-1 (as compared to ATS-3), it is expected that the intermodulation noise due to the SSB transmitter will be larger when operating with ATS-1 rather than ATS-3. As shown in figure 1.26, for ATS-3 operation the dominant intermodulation sources are the SSB transmitter, downlink parabolic group delay and the S/C modulator.

Also, the signal density-to-total intermodulation noise density computed from NPR/TPR results is shown in figure 1.26 for comparison. It can be seen that the signal density-to-total intermodulation noise density based upon multitone tests and the NPR/TPR measurements agree within ± 2 db across the baseband.

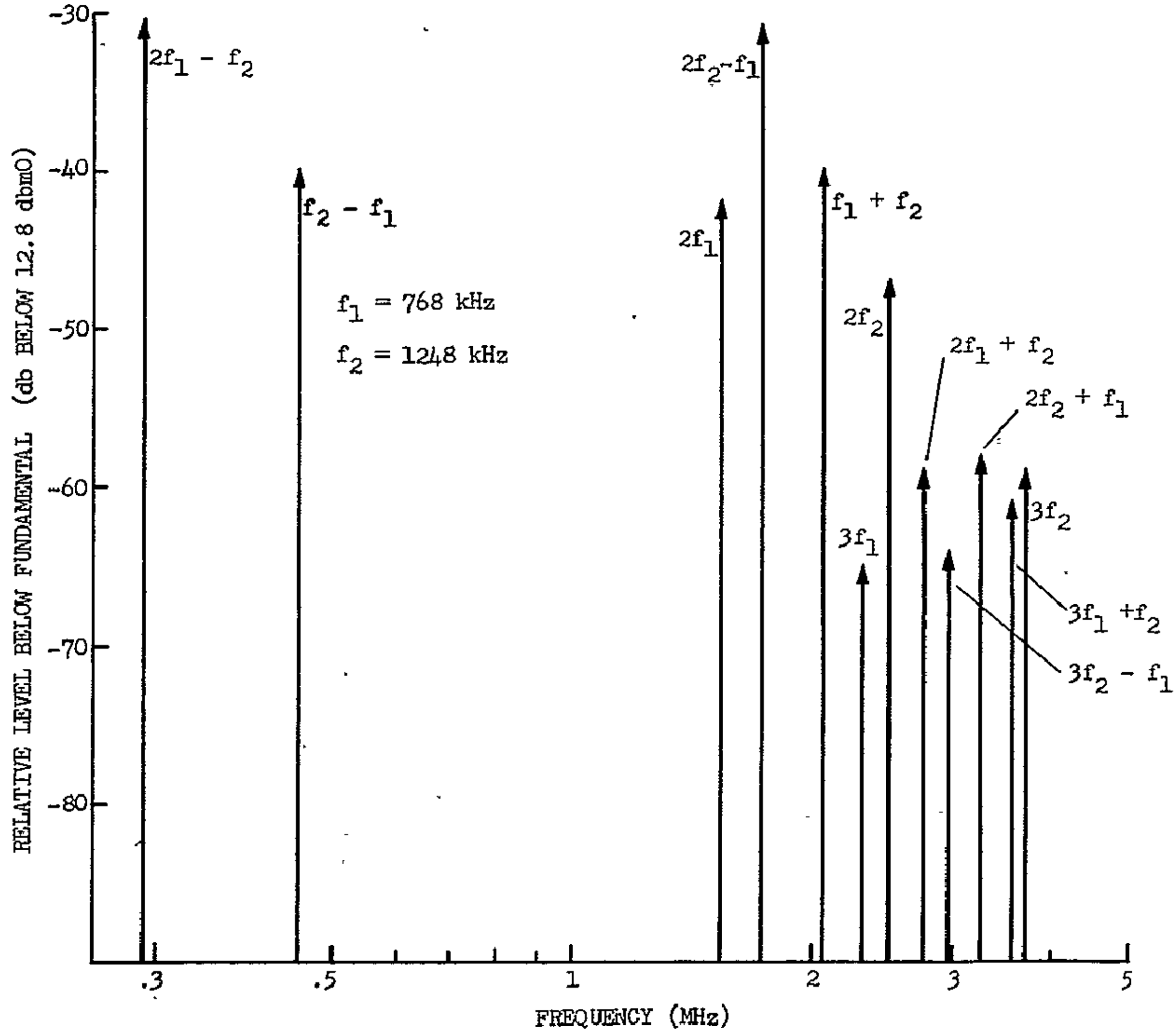


Figure 1.24: Two Tone Test (Rosman, MA Mode, ATS-3)

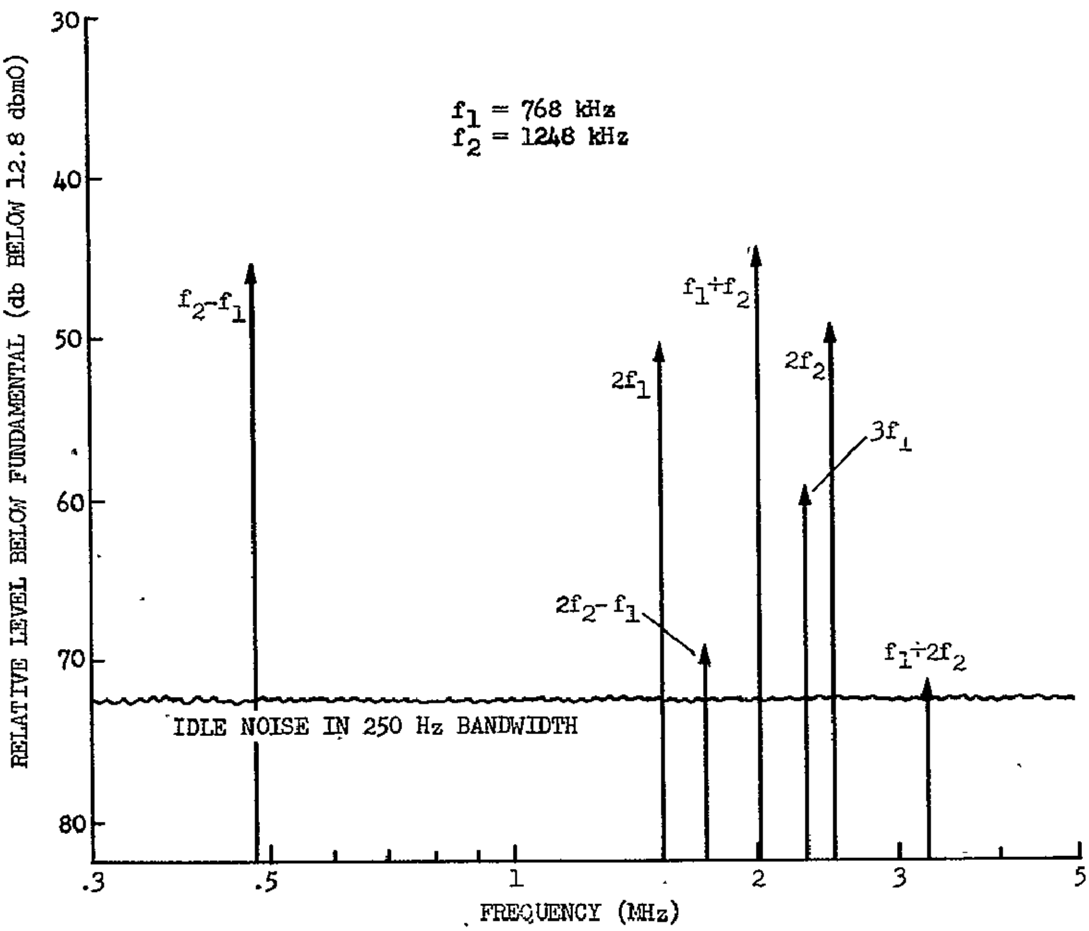


Figure 1.25. Two Station, Two Tone Test, Rosman Receiving Earth Station (ATS-3, EIRP = 54.6 dbm)

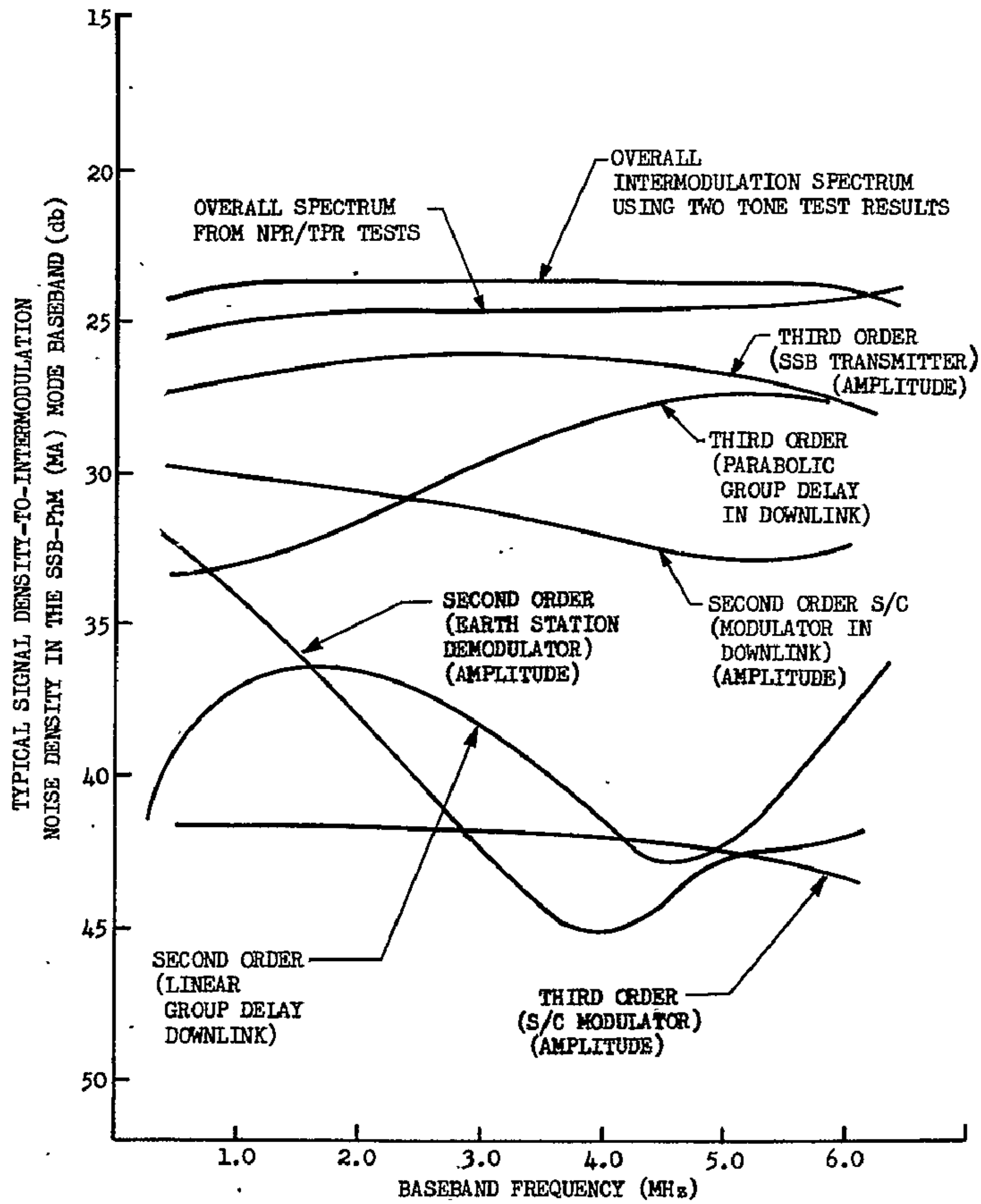


Figure 1.26. Typical Intermodulation Noise Power Ratio for Second and Third Order Noise Spectra (MA Mode, 1200 Channels, ATS-3)

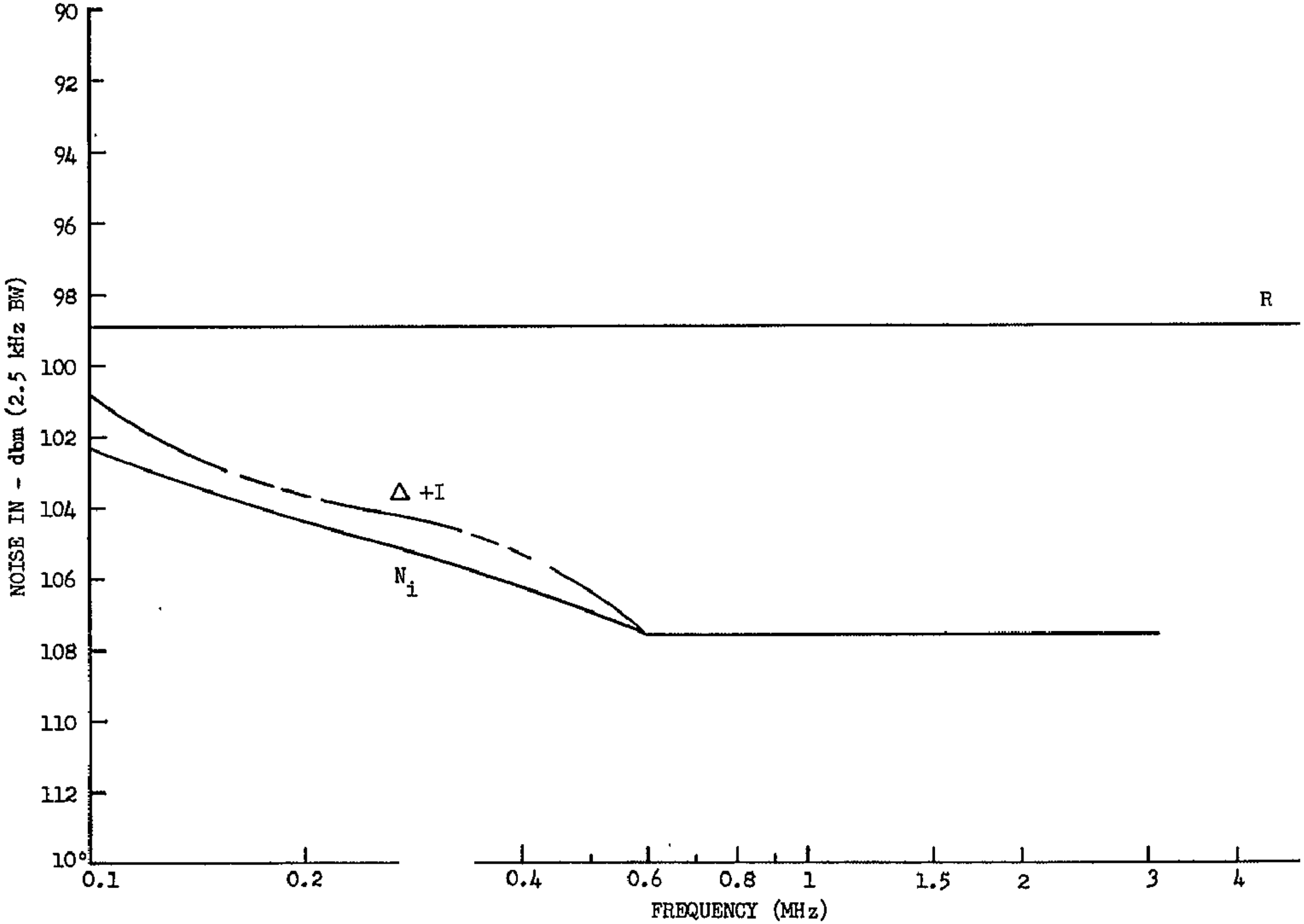


Figure 1.27. Baseband Noise Spectrum C/N = 20 db

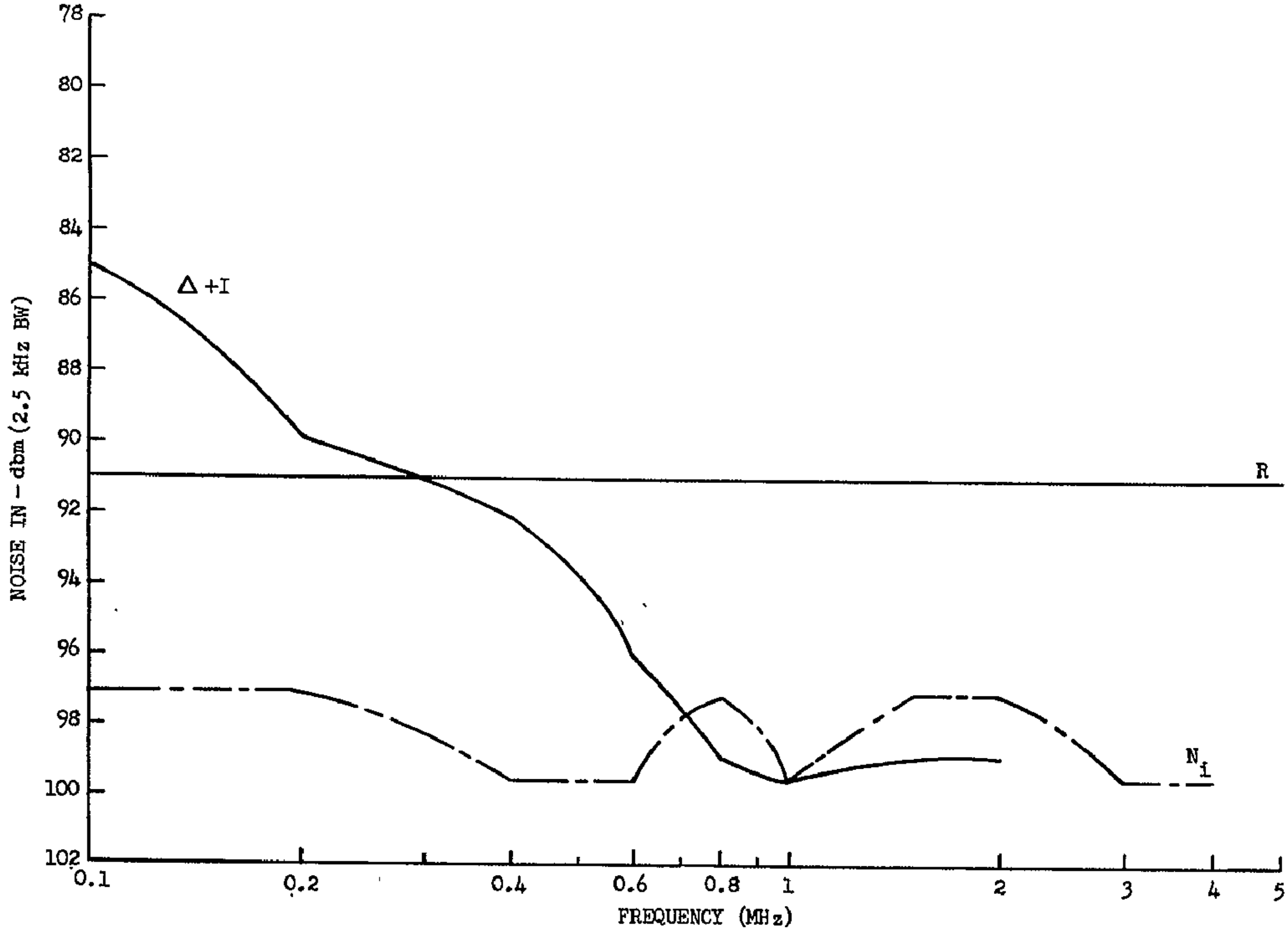


Figure 1.28. Baseband Noise Spectrum C/N = 12 db

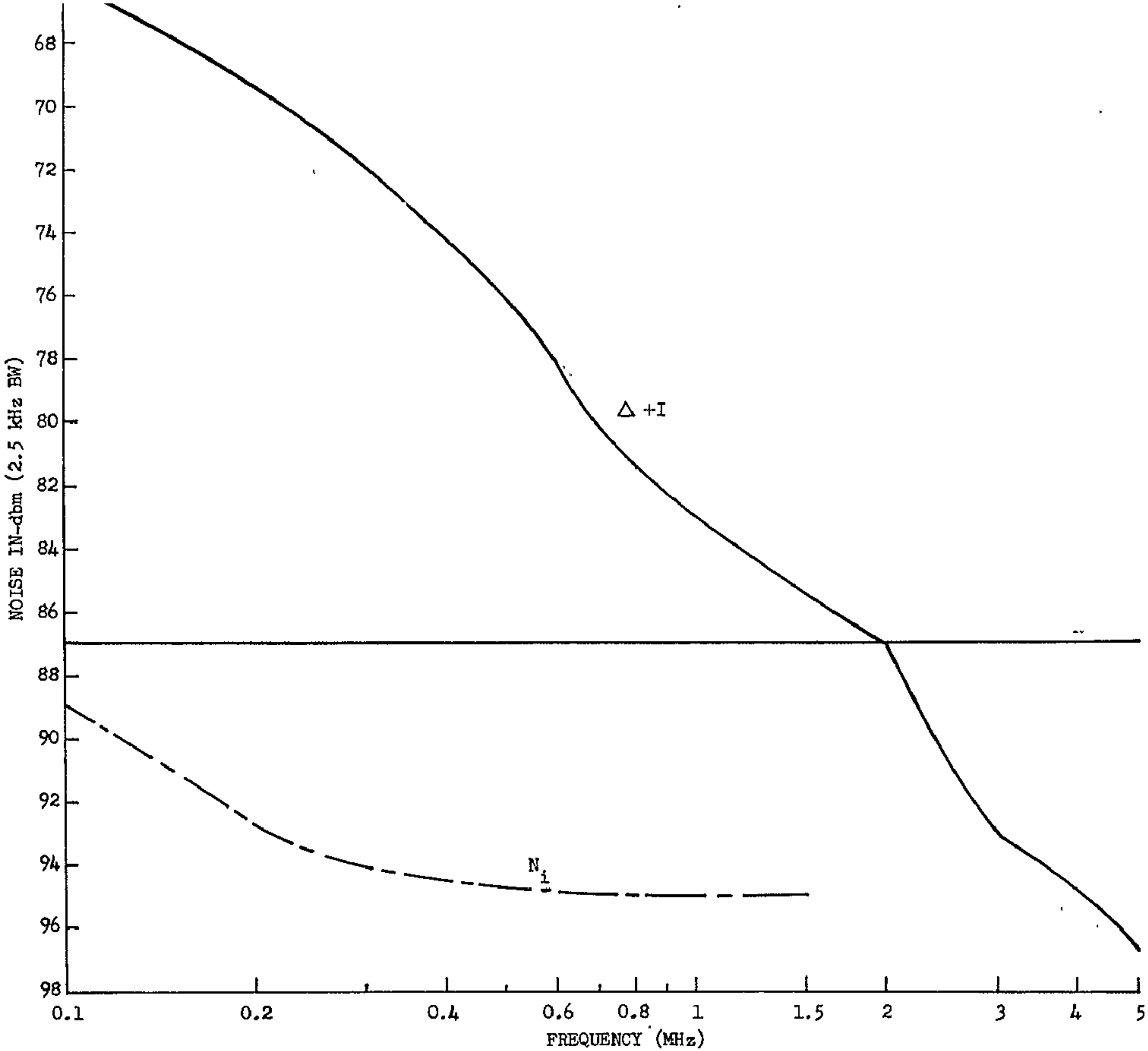


Figure 1.29. Baseband Noise Spectrum C/N = 8 db

1.2.8 DATA ERROR RATE

This section discusses the quality of frequency shift keyed (FSK) digital transmission obtained in a standard FDM voice channel. The bit rate tone frequencies for the "mark" and "space" were selected to be compatible with the nominal FDM voice channel. The form of FSK used is known as discontinuous phase (which results from obtaining the frequency shift by switching between two different oscillators set to the "mark" and "space" frequencies). The amplitude spectrum of a continuous mark-space bit stream is found[40] to consist of carriers at the mark and space frequencies along with odd order sidebands of the modulating frequency (reciprocal of the bit rate period) spaced around each carrier. The ATS system uses a pseudo-random code word of 2047 bits. (Refer to table 1.23 for a list of FDM-FM data channel characteristics.)

Figure 1.30 shows the amplitude spectra for three modulation situations:

A) Alternate mark-space pulses at a bit rate of 1800 bps.

B) Alternate mark-space pulses at a bit rate of 1200 bps.

C) Non return to zero (NRZ) pseudo-random code at a bit rate of 1200 bps.

The mark and space frequencies are set at 2252.5 Hz and 1232.5 Hz, respectively. The amplitude of each spectral line is shown relative to the unmodulated amplitude of the mark or space frequency. It may be seen from (A) and (B) of figure 1.30 that, as the bit rate decreases, more of the sideband energy associated with each carrier will be contained within the channel bandwidth, thus, increasing the detected signal power. As more mark or space pulses are placed in sequence, the amplitude spectrum approaches that of lower bit rates, until, in the limit, all of the sideband energy will be at its respective carrier frequency (bit rate equal to zero). Item (C) in figure 1.30 shows the amplitude spectrum envelope which occurs when the mark-space sequence is derived from a pseudo-random (PN) code. In this case, the spectral line spacing is a function of the P/N word length. The minimum spacing, Δf, is given by:

$$\Delta f = \frac{B}{L}$$

where

L = P/N word length (bits)

B = bit rate (bits per second)

The ATS system uses a P/N word length of 2047 bits, thus, for 1200 bps:

$$\Delta f = \frac{1200}{2047} = 0.586 \text{ Hz}$$

The spectral lines which actually occur are dependent upon the mark-space sequencing, and are separated from the appropriate carrier by an integral multiple of Δf.

Figure 1.30 shows that as the bit rate increases (1200 bps to 1800 bps), distortion of the detected bit occurs (due to loss of sideband energy), and the likelihood of bit errors increases (due to mark carrier sideband energy located near the space carrier frequency, and vice-versa). The maximum bit rate is, in the extreme limit, determined by losing the first order sidebands. As shown in (A) of figure 1.30, the lower sideband of the space pulse frequency is nearly out of the 3.1 kHz channel bandwidth for a bit rate of 1800 bps. Selection of 1200 bps allows use of standard equipment while also providing good separation between the mark and space pulse frequency spectrums.

The performance of FSK systems is treated extensively in the literature and will not be examined here, however, a comparison between the ideal case and the observed FSK system will be made. Figure 1.31 shows plots of the probability of bit error versus the energy contrast factor E/N_o for three system conditions, as follows:

1) The ideal curve for non-coherent FSK[41] (this condition presupposes an ideal bit rate/bandwidth relationship so that all of the sideband energy is recovered).

2) The measured results of a spacecraft loop test. The test results are also presented in table 1.22. As indicated, the bit error rates at E/N_o of 16.6 and 36.6 db could not be established since no errors occurred during the times that the test was performed.

3) The measured results of a multiplex back-to-back loop Bit Error Rate test conducted at Cooby Creek and Mojave for different E/N_o levels. The E/N_o was varied by changing the level of the noise being injected in a multiplex channel.

The error rate probability, P_e, for a non-coherent FSK system is given as[2];

$$P_e = \frac{1}{2} e^{-E/2N_o}$$

where:

E = energy per bit

N_o = spectral noise density

The relationship between E/N_o and the channel TT/N value is:

$$\frac{E}{N_o} = \frac{TT}{N} \cdot \frac{B}{H}$$

where:

B is the bandwidth in which the TT/N is defined. (3.1 kHz = 34.9 db/Hz)

H is the bit rate (1200 bps = 30.8 db)

From (1) and (2) it may be seen that the error rate, P_e, is independent of bit rate for constant E/N_o factors, thus idealy, the curves shown in figure 1.31 should be coincident. The reason that the curves are not coincident is chiefly due to bandwidth limitation, which causes sideband energy to be lost, thus decreasing E from its maximum value.

Because of the high test tone-to-noise ratios obtained at the standard test tone levels (30 db) the bit error rate is essentially zero. To determine the error rate as a function of TT/N ratio, a special test was performed at Cooby Creek. This was accomplished by attenuating the transmitted FSK digital signal level 20, 25, and 30 db to provide TT/N ratios of 12.5, 7.5, and 2.5 db, respectively. The results of this test are shown in table 1.22 and figure 1.31. The FSK tones were set to the same rms level as the standard test tone level normally used. E/N_o values corresponding to the measured TT/N ratios are shown in table 1.2 to provide a comparison to the ideal curve for non-coherent FSK of E/N_o versus bit error rate, shown in figure 1.31. It should be noted that the ideal curve is based upon a statistical noise distribution which may be somewhat different from the noise distribution which actually exists in the FDM channel. Such is apparently the case since, as shown in figure 1.31, the measured MUX back to back test results indicate performance slightly better than that predicted under ideal conditions.

Considering the above values of B and H, the nominal TT/N ratio of 32.5 db with the 20 db attenuation factor corresponds to an E/N_o value of 16.6 db. At this relatively high level, the corresponding P_e value is so low that excessive test time would be required to obtain a bit error sample.

For the 25-db attenuation factor, the corresponding E/N_o is 11.6 db. For this value, a 9-minute test period produced an error rate less than 6.0×10^{-3}. For the 30-db attenuation factor, the E/N_o value is 6.6 db. In this case, the bit error rate was 0.120. These results are compared to the ideal curve shown in figure 1.31.

Included in figure 1.31 are the results of a special Bit Error Rate test conducted at Cooby Creek and Mojave for different TT/N levels at two different bit error rates with the multiplex equipment in a back-to-back configuration. In these tests, the TT/N level was varied by changing the level of noise injected in the MUX channel. The MUX back-to-back configuration was used in order to determine what bit rate limitation was imposed on the system by the data channel bandwidth. The FDM equipment was required in order to properly connect the data mod-demod units, and is assumed to have relatively little effect upon the error rate. As shown in figure 1.31, the voice channel bandwidth and the selected mark and space frequencies limit the transmission rate to somewhere between 1200 bps and 1500 bps. The limitation is readily apparent when the error rates at E/N_o of 13 db are considered (2×10^{-5} error rate at 1200 bps vs 6.5×10^{-4} error rate at 1500 bps). This limiting effect is even more pronounced at higher values of E/N_0. Data taken at bit rates lower than 1200 bps showed essentially no change in error rate from that observed at 1200 bps.

Significant bit error rate data was obtained from a single test using ATS-3 performed at Rosman on 18 March 1968. A total of 1,584,000 bits were transmitted without error, establishing that the bit error rate was less than 6.3×10^{-7}. The test was performed during an eclipse period, during which time the TT/N varied from about 30 to 40 db(E/N_0 of 34.1 db to 44.1 db).

Referring to (A) and (B) of figure 1.30, it may readily be seen that increasing the bit rate will increase the frequency separation between the various sidebands of the mark and space frequencies. It may also be determined that decreasing the frequency separation between the mark and space frequencies results in moving the entire spectrum closer to the center frequency of the channel. (This will also tend to increase the interference between the mark and space frequency distributions as seen by (C) in figure 1.30.

TABLE 1.22. DIGITAL DATA ERROR RATE VERSUS CHANNEL TT/N (COOBY CREEK, ATS-1)

Data Channel TT/N (db)	Energy Contrast Factor (E/N_0 (db))	Error Rate, P_e	Number of BITS Transmitted
32.5	36.6	$< 5.6 \times 10^{-6}$	180,000
12.5	16.6	$< 2.1 \times 10^{-5}$	48,000
7.5	11.6	6.0×10^{-3}	108,000
2.5	6.6	0.120	108,000

TABLE 1.23. FDM-FM DATA CHANNEL CHARACTERISTICS

Data Bit Rate	1200 bits/sec
Data Word Length	2047 bits, pseudo random
Modulation	Non-coherent FSK
FSK "SPACE" PULSE FREQUENCY	1232.5 Hz
FSK "MARK" PULSE FREQUENCY	2252.5 Hz
FDM Data Channel BW	3.1 kHz
FDM Data Channel Group Location	80 kHz
FDM Data Channel Baseband Location	336 kHz

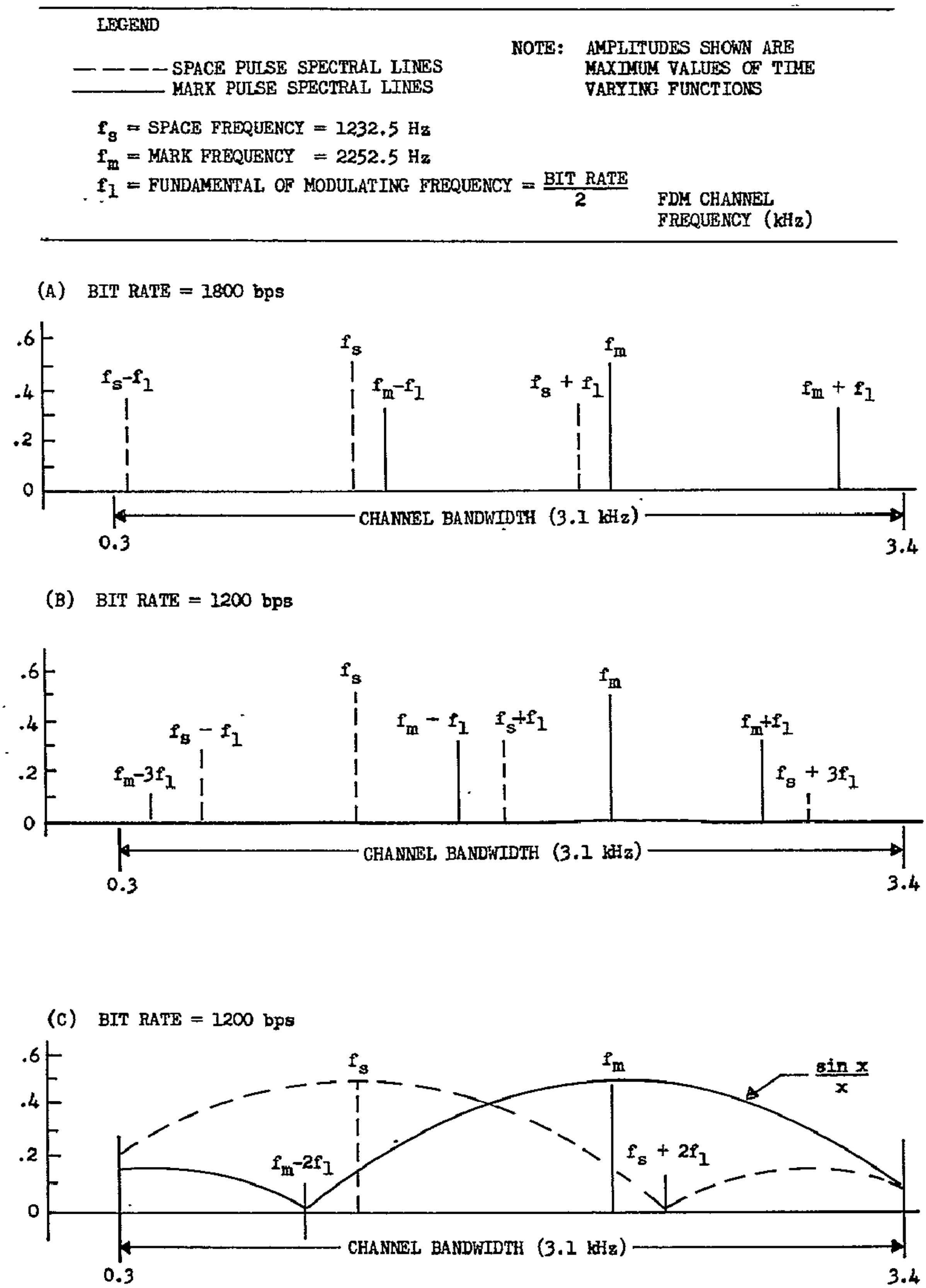


Figure 1.30. FSK Data Channel Amplitude Spectrum

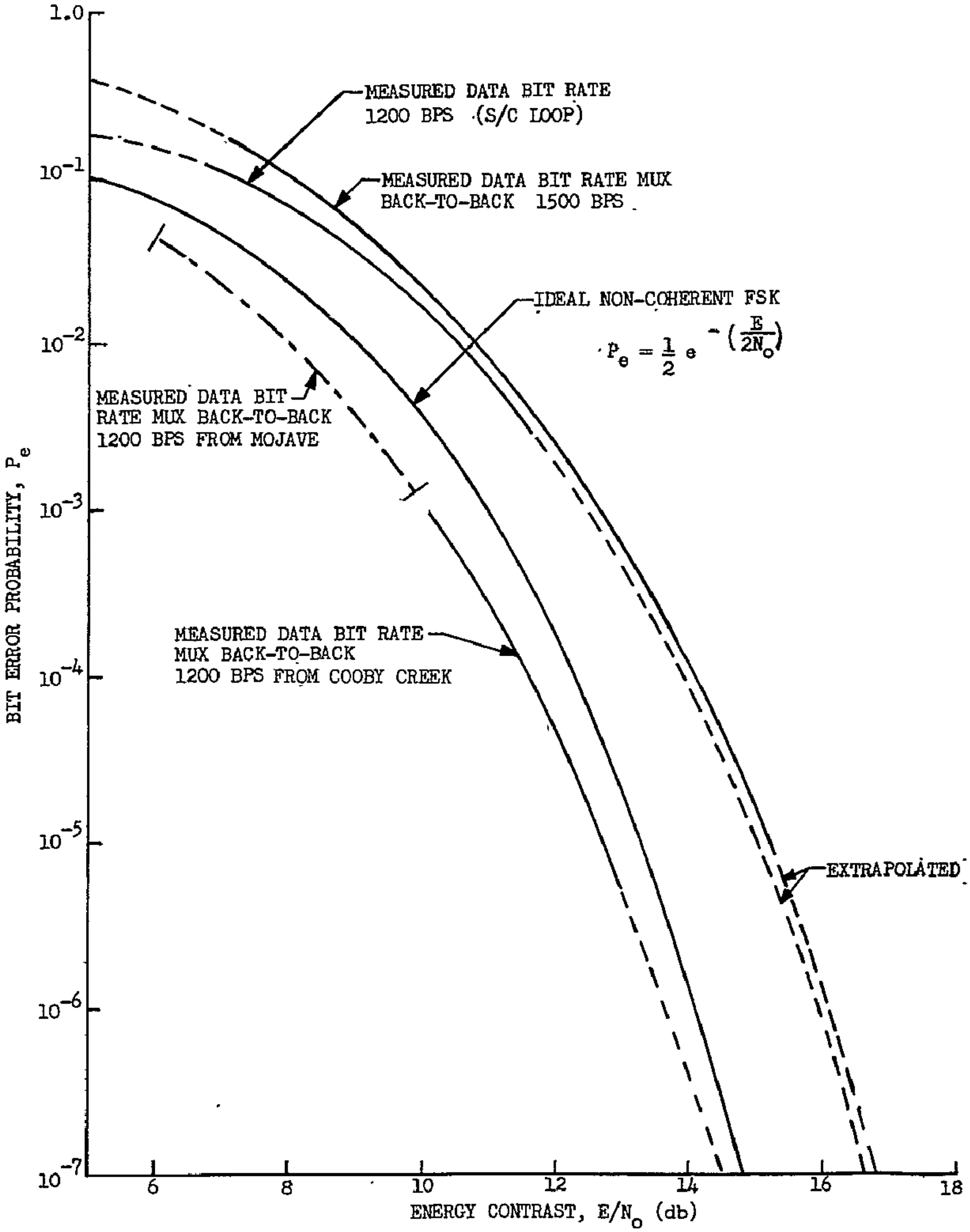


Figure 1.31. Data Error Rate Versus Energy Contrast (Cooby Creek, ATS-1)

1.2.9 MULTISTATION PERFORMANCE

This section discusses and presents the ATS multiple access capability with either two or three earth stations participating. Performance is given in terms of multiplex channel test tone-to-noise (TT/N) ratio as a function of satellite loading and baseband frequency for various values of earth station carrier-to-noise (C/N) ratio. Performance is evaluated by comparing these TT/N ratios to the single station measured and predicted SSB-FDMA/PhM mode performance data presented in table 1.3, section 1.1).

Satellite loading for multiple access operation is calculated in accordance with CCITT Recommendation G222 for a repeater which is common to both directions of transmission (see section 7.6.3 on Noise Loading.). For example, 1200 channel loading at the satellite requires the mean absolute power level of the uniform spectrum random noise test signal to be 15.8 dbm0, which is apportioned among the earth stations. Limited earth station flexibility (due to limited availability of noise shaping filters) restricts two of the three ATS earth stations to 120 channels each with the large station making up the remainder such that the satellite can be loaded up to the 1200 channel system capacity. Multiplex channel TT/N versus baseband frequency as a function of satellite loading (number of channels) is shown in figures 1.32, 1.33 and 1.34. More detailed test results and procedures are found in section 3.4.1.

In the ATS system, multiple-access operation with the three earth stations is limited to the ATS-1 satellite because of the location of the other spacecraft. The combination of ATS-1 (52.2 dbm EIRP) and the medium earth station sensitivity (G/T of 32.2 db) produces C/N ratios at or approaching threshold (assumed 10 db) when the satellite antenna beam is positioned to favor the medium stations. For multiple access operation, the satellite antenna beam is positioned such that each medium station receives approximately the same C/N ratio. Figure 1.35, which gives earth station C/N ratio variation as a function of the ATS-1 antenna beam position, shows that for multiple access operation (approximately 2.5 degrees west of the subsatellite point) the medium station C/N ratio will be about 1.0 db below that obtained when the satellite antenna beam is pointed on station.

With 1200 channel loading at the satellite (ATS-1 or ATS-3), multistation operation requires that all earth stations demodulate the entire PhM spectrum which in turn requires an IF filter bandwidth of 30 MHz nominal. As a result of satellite antenna positioning and IF filter requirements, C/N ratios (7.4 db to 9.1 db) are below threshold at the medium earth stations (40-foot antennas). Depending on earth station-satellite configuration, C/N ratios vary from below threshold up to 20.7 db. TT/N ratios as a function of C/N ratios are also shown in figures 1.32, 1.33, and 1.34.

At C/N ratios varying between 7.4 db and 9.1 db (figure 1.32) and with 1200 channel loading, multiplex channel TT/N ratio in the low channel (342 kHz) drops to about 24 db or to about one-half of the recommended CCIR 50 db TT/N ratio. Similar performance is indicated for the low channel by the data in table 1.24, obtained by means of an automated test which provides a 12 sample mean of TT/N and TT/R each minute of the test interval. In the high channel (5340 kHz), the TT/N ratio of about 36 db shown in figure 1.32 is within 1.0 db of the predicted TT/N ratio for this condition. Thus medium station performance can be improved by assigning channels at the high end of the baseband to the medium earth stations. In this case, TT/N is improved by some 12 db. Performance can also be improved by limiting system capacity. For example, with 640 channel loading, TT/N is improved some 12 db in the low frequency (342 kHz) channel.

A further indication of the threshold characteristic at low C/N ratios is seen in figure 1.36 which shows the medium station TT/N variation over the 312 kHz to 5564 kHz baseband as a function of C/N ratio. That TT/N variation is a critical function of C/N ratio below threshold operation, particularly at the low baseband frequencies, is quite apparent, since a 2-db change in C/N ratio causes TT/N to change 6 db in the 342-kHz channel. This data tends to confirm that threshold for the SSB-FDMA/PhM mode is in the neighborhood of 10 db. The drop in TT/N at the low and high ends of the curve for the 10 db C/N ratio, is attributed to baseband frequency response which is down about one db at 342 kHz and 2 db to 3 db at 5340 kHz.

The variation of TT/N over the baseband at low C/N ratios suggests the possibility of using higher deviation at the lower end of the baseband than at the upper to improve TT/N ratio when the medium station is receiving a group of channels in the lower portion of the baseband. Figure 1.37 summarizes the results of 60 and 120 channel over-deviation at the low end of the baseband. Sixty channel (312 kHz to 552 kHz) overdeviation shows practically a 1 to 1 db TT/N improvement at the medium-receiving station for up to 9 db of overdeviation by the transmitting station. Reception at the large station also shows an improvement which begins to limit and then decrease at about 6 db overdeviation. Since the large station thermal noise is low (high C/N ratio) compared to the medium station, it begins to see the effects of intermodulation noise build-up sooner than the medium station. In this case, the intermodulation noise is most likely due to the medium station transmitter. No noticeable degradation was observed in multiplex channels outside the overdeviated 60 channel spectrum. Figure 1.37 also shows that by increasing the number of channels over-deviated at the medium transmitting station to 120 (312 kHz to 808 kHz), the effect of inter-modulation noise build-up is now seen at the medium station at about 6 db compared to 2 db at the large station.

Tests were conducted to determine if overdeviation of the higher baseband frequencies would appear to offer the medium station a means for even greater TT/N improvement. Figure 1.38 summarizes the results of 60 channel (5322 kHz to 5558 kHz) and 120 channel (5066 kHz to 5558 kHz) overdeviation at the high baseband frequencies. In this case, the intermodulation noise build-up degrades all channels outside the overdeviated spectrum at both the medium and large stations. The total noise in any channel is now proportional to the magnitude of the intermodulation noise caused by the overdeviation and either the magnitude of the thermal noise at the high C/N ratio (14 db - large station) or the magnitude of the threshold noise at the low C/N ratio (8.6 db - medium station). Data for the large station shows that the intermodulation noise predominates, it increases with decreasing baseband frequency and thus TT/N degradation is most severe in the low frequency (342 kHz) channel. At the medium station, however, threshold noise predominates in the 342 kHz channel. Threshold noise decreases with increasing baseband frequency. Its level in the 534-kHz channel is sufficiently low so that as the intermodulation noise increases with increased overdeviation levels, TT/N begins to decrease at a faster rate relative to the 342-kHz channel.

TT/N degradation is also dependent on the number of channels being overdeviated. Figure 1.38 shows that 120 channel overdeviation at the high end of the baseband causes the intermodulation noise in the low frequency channels to increase at a faster rate than for 60 channel overdeviation.

Overdeviation at the low end of the baseband to improve medium station TT/N ratio means that the transmitting station which provides the overdeviation, must be given a larger share of the satellites available power. It also means that the SSB transmitter linearity must be able to support this overdeviation without generating excessive intermodulation noise. Depending on the mix of medium and large stations and on the links between stations, overdeviation at the transmitting station to improve medium station TT/N would become quite complex and is not considered a practical solution. However, a practical solution would be to have the proper pre-emphasis in the satellite. It follows that this solution would reduce station transmitter power requirements as well as more stringent transmitter linearity requirements.

The threshold noise effect has been the subject of several technical papers (44) (45) and also of experimentation at the Cooby Creek earth station utilizing the frequency translation mode of operation. An analysis of this effect is also presented in section 1.2.7. This is somewhat academic since normal system design should provide an adequate operating margin. At higher C/N ratios as shown in figures 1.33 and 1.34, TT/N ratios approach the predicted TT/N ratios for single station operation listed in table 1.3 and are reasonably consistent across the baseband. It follows that the design of a random access multiple access system using SSB-FDMA/PhM, requires these higher C/N ratios (adequate margin above threshold at each earth station to provide an acceptable TT/N ratio). This is assumed to be at least 6 db in the satellite-to-earth link relative to a nominal C/N ratio at threshold of 10 db as indicated in CCIR report 211-1 (reference 46 of section 6).

TABLE 1.24. DATA SUMMARY OF MULTISTATION TESTS, MULTIPLEX CHANNEL TT/N AND TT/R RATIO (db) AND STANDARD DEVIATION σ

Station	Sat.	Sat EIRP (dbm)	No. of Sta. (1)	C/N (db)	1200 Channel Loading at Satellite - 15.8 dbm0							
					342 kHz Channel				1248 kHz Channel			
					TT/N	σ	TT/R	σ	TT/N	σ	TT/R	σ
Cooby Creek 40 ft. ant.	ATS-1	52.2	3	6.2 - 7.4	28.5	0.90	46.8	0.84	32.3	0.52	39.5	0.37
Mojave 40 ft. ant.	ATS-1	52.2	3	7.7	23.3	0.41	35.2	0.21	33.2	0.45	39.3	0.22
	ATS-3	54.6	2	11.7	41.2	0.15	42.7	0.14	36.9	0.40	41.0	0.26
Rosman 85 ft. ant.	ATS-1	52.2	3	13.0	39.9	0.26	44.1	0.26	42.0	0.14	45.4	0.26
	ATS-3	54.6	2	20.0	43.3	0.44	44.7	0.50	45.0	0.60	47.3	0.71

(1) With 3 station operation, Cooby Creek and Mojave each load the spacecraft with 120 channels, Rosman loads the remaining 960 channels. With 2 station operation, Mojave loads the spacecraft with 240 channels, Rosman loads the remaining 960 channels.

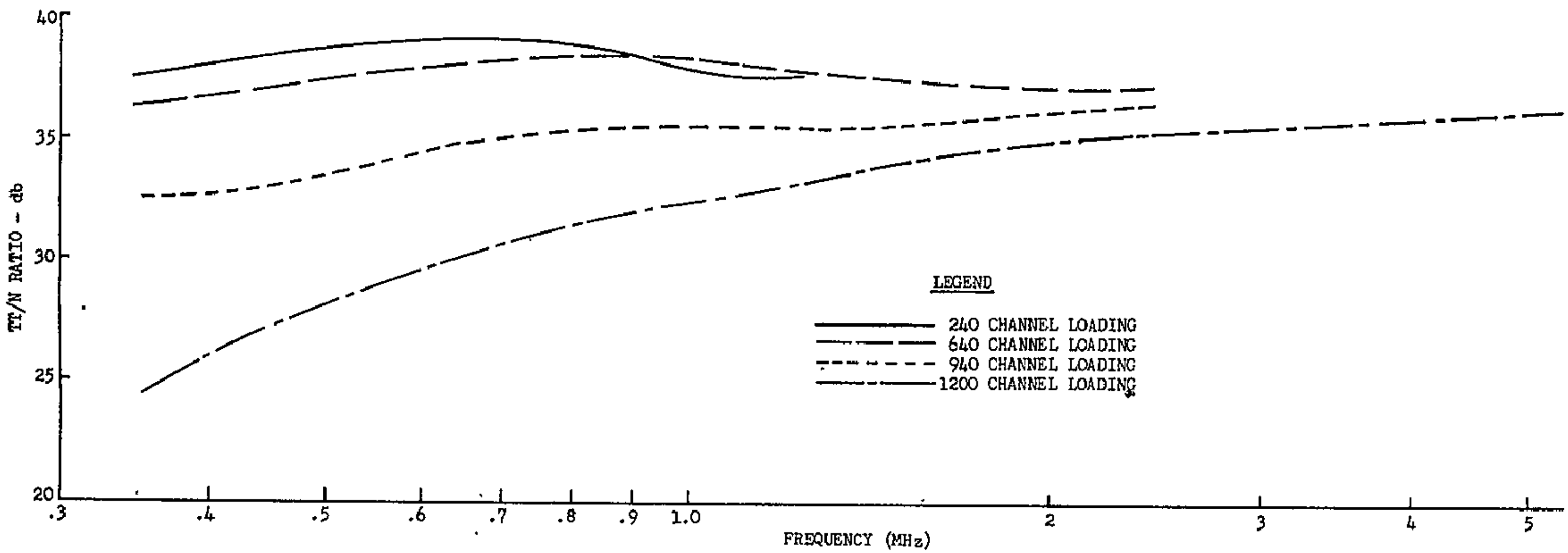


Figure 1.32. Multiplex Channel TT/N Ratio Versus Baseband Frequency, for C/N Ratio Between 7.4 db and 9.1 db (ATS-1)

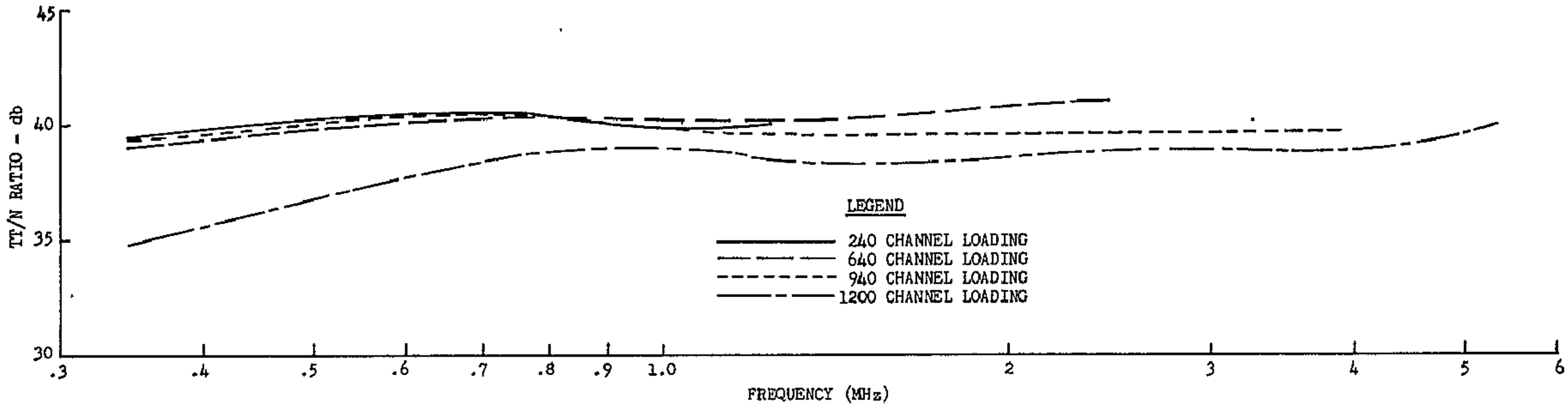


Figure 1.33. Multiplex Channel TT/N Ratio Versus Baseband Frequency, for C/N Ratio Between 11.8 db and 14.3 db (ATS-1)

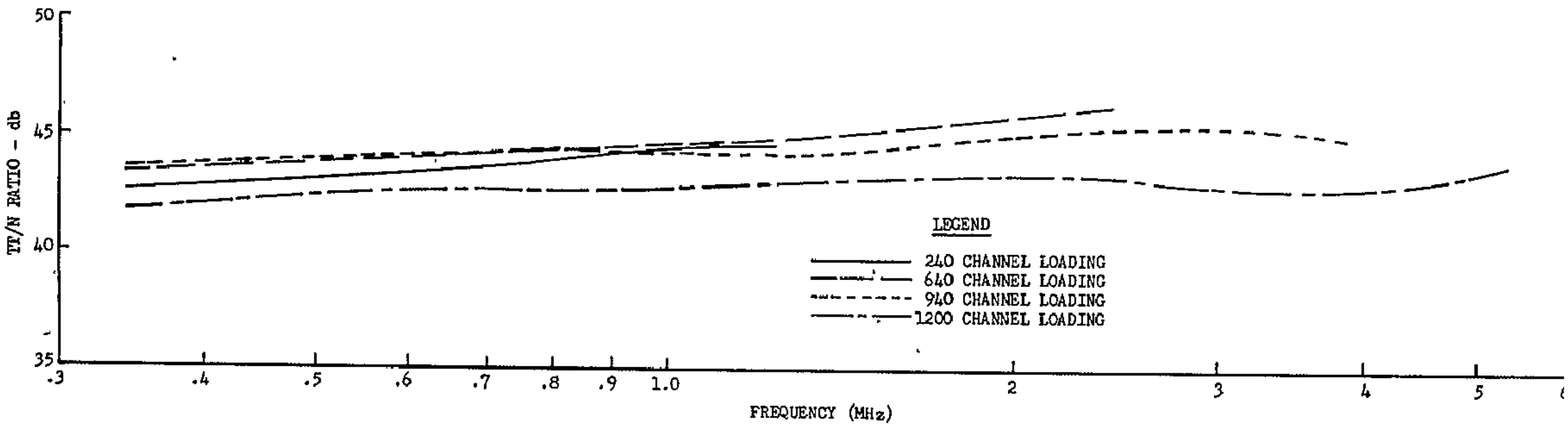


Figure 1.34. Multiplex Channel TT/N Ratio Versus Baseband Frequency for a C/N Ratio of 20.7 db (ATS-3)

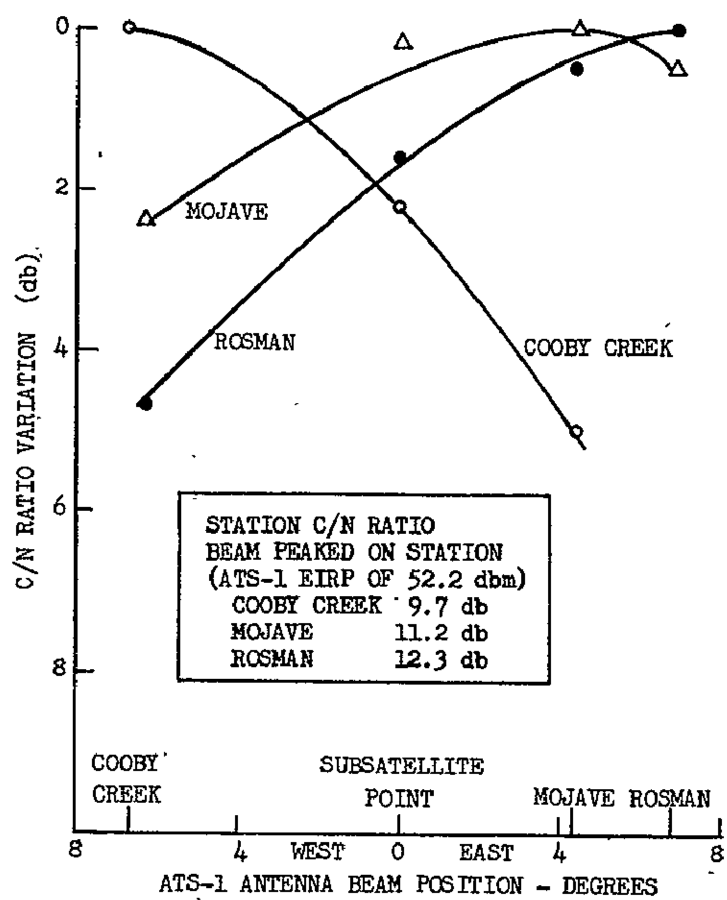


Figure 1.35. Earth Station C/N Ratio Variation Vs. ATS-1 Antenna Beam Position

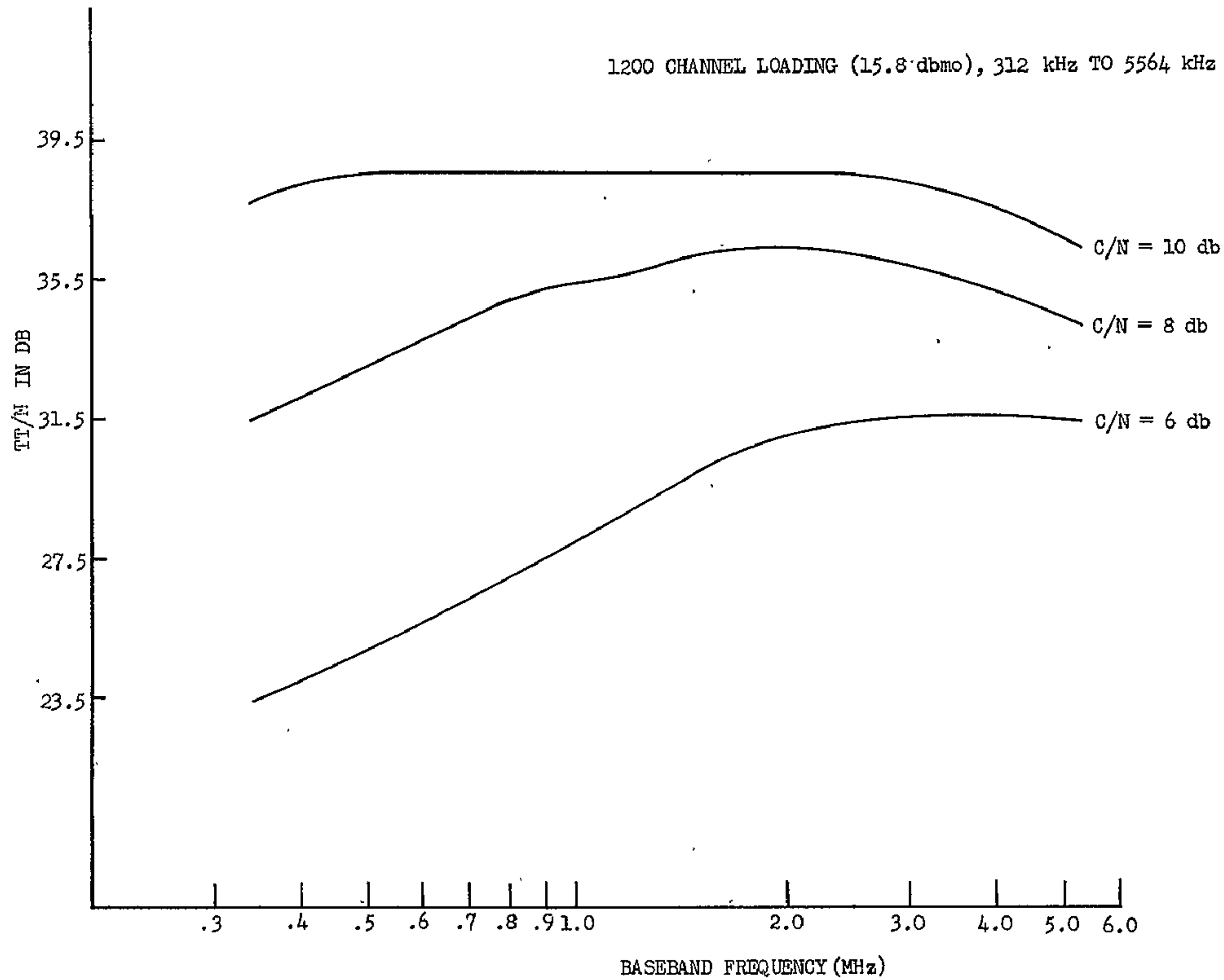


Figure 1.36. Medium Station NPR Versus Baseband Frequency as a Function of C/N Ratio

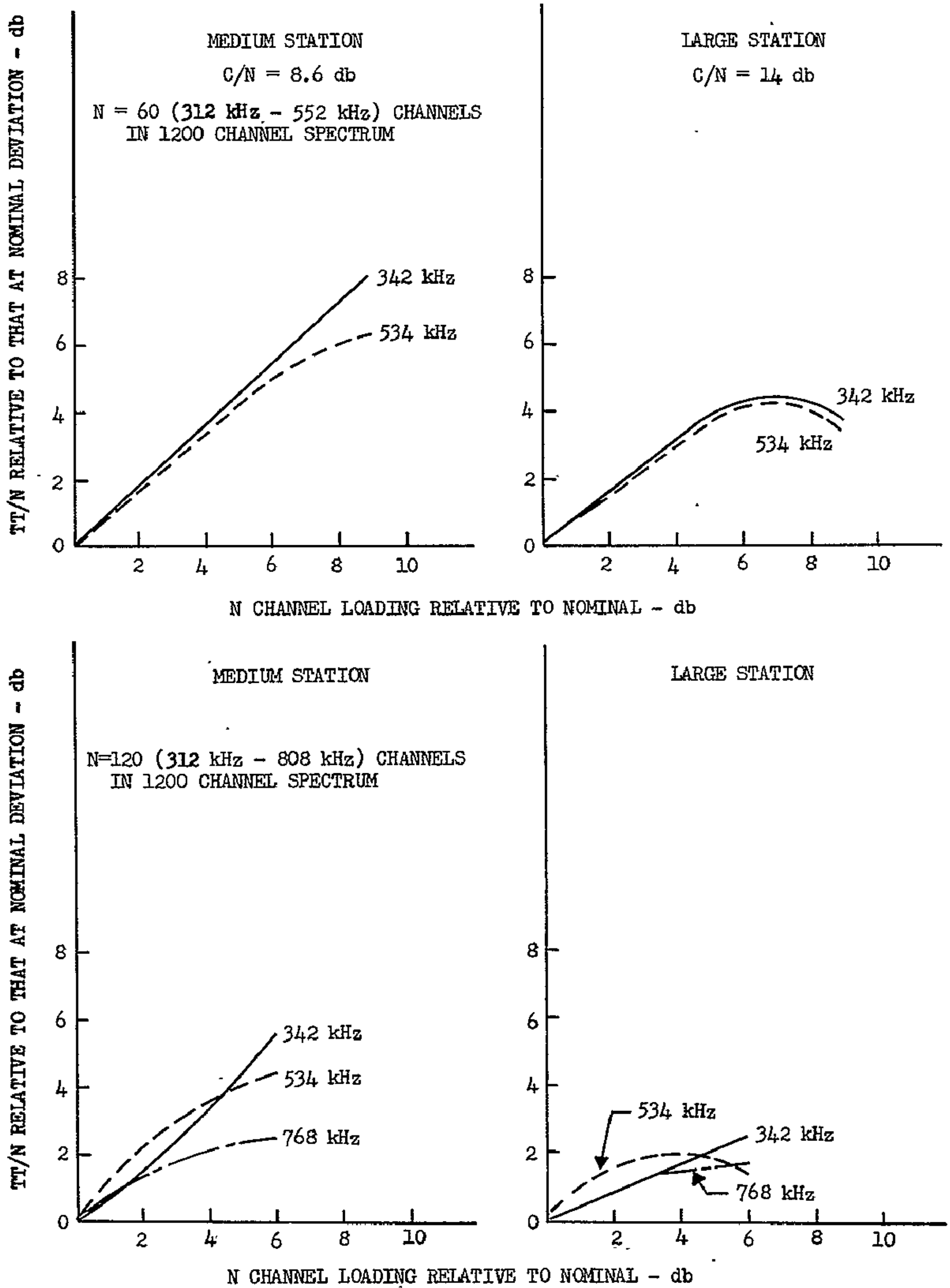


Figure 1.37. Effects of Medium Station Overdeviation at Low Baseband Frequencies

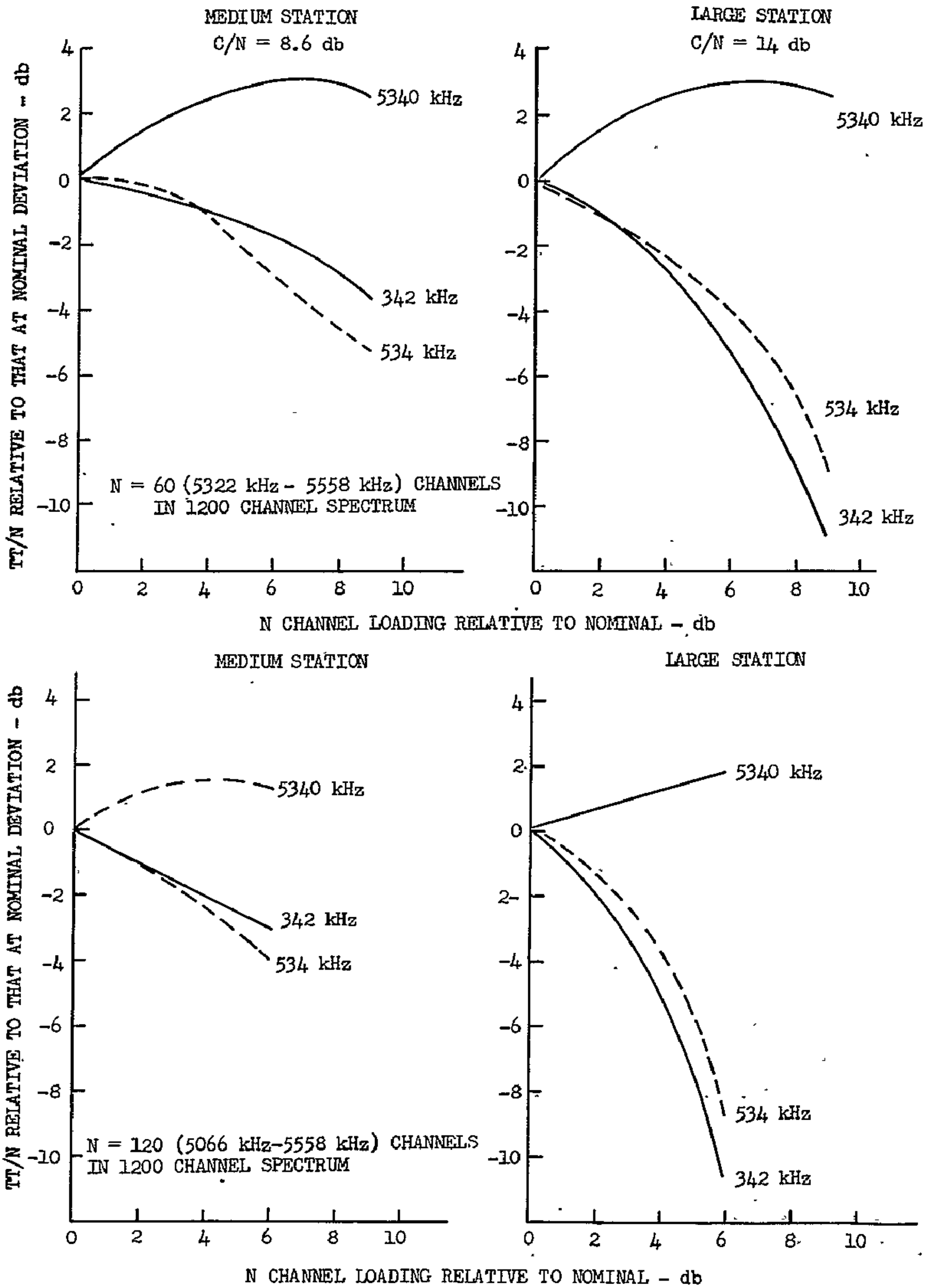


Figure 1.38. Effects of Medium Station Overdeviation at High Baseband Frequencies

1.3 FREQUENCY TRANSLATION MODE-TELEVISION (FM/FM-TV)

1.3.1 INTRODUCTION

Increasing public demands for current news and information from all parts of the world have created a continued need to improve the quality, economy and reliability of television broadcasts from remote transmitting stations, through a satellite, to receiving stations for commercial distribution to the general public. The Applications Technology Satellite Program has responded to the need for improvement of quality and provided a breakthrough in the state-of-the-art by providing sufficient satellite EIRP for high quality monochrome and for full bandwidth color television when using an 85-foot earth station antenna. Several configurations of satellite antenna, transponder, and earth station capabilities are evaluated with the goal of demonstrating improved quality, and supporting this improvement with quantitative data. Although not a formal part of this analysis, economy and reliability have been demonstrated by the continued performance of ATS-1 since December 1966, and of ATS-3 since November 1967.

The TV system utilizes the frequency translation (FT) mode of a dual mode spacecraft transponder to translate FM signals received at 6 GHz from an earth transmitting station to 4 GHz for transmission to an earth receiving station. A description of the FM transmitter, spacecraft transponder and FM receiver subsystems, and a listing of their quantitative performance objectives are found in a subsequent paragraph.

Where applicable, CCIR Recommendations for the performance of links transmitting television signals are utilized for comparison. In particular, CCIR Recommendation 354 (as amended by Working Group IV-A in September 1968), which describes the signal-to-noise performance of a hypothetical reference circuit (described in CCIR Recommendation 352), is used. In addition, other recommendations or documents of the ITU are used in evaluation of the performance of these communications links. These include CCIR Recommendation 421-1, and Study Programme 5A/CMTT (part of Addendum No. 1 to Volume V of the XIth Plenary Assembly of the CCIR). Additional documents which are relevant are CCIR Report 208-1 and Recommendation 352, both as amended in September 1968 by Working Group IV-A. The specific parameters evaluated and the corresponding CCIR/CCITT references are listed in table 1.25. EIA standards are used to evaluate performance where CCIR recommendations are not available.

The analysis of the FM/FM-TV mode is categorized into considerations of video channel performance, waveform distortion, and subjective tests. Audio performance is evaluated from the viewpoint of noise components and waveform distortions, both linear and nonlinear.

The video channel performance evaluation considers four sources of noise (continuous random noise, periodic noise, impulsive noise, and crosstalk) and compares them individually to user requirements. A graphical presentation of thermal signal-to-noise ratio (related to continuous random noise) versus spacecraft EIRP for a given family of earth station G/T values is presented to describe the capabilities and limitations of the ATS system. The effects of linear and non-linear video waveform distortion are evaluated by comparison to CCIR recommendations. Specifically, baseband frequency response, sine-squared pulse tests (T and 2T) line-time and field-time characteristic tests, and baseband envelope delay characteristics are used to evaluate linear distortion. Differential gain and differential phase characteristics are used as indications of non-linear distortion.

A monochrome test pattern analysis and a limited number of representative photographs taken during operational missions subjectively substantiate the findings of the quantitative experiments that the ATS system is a high quality, low-distortion world-wide video relay.

Audio channel noise performance evaluation also considers the four basic sources; i.e., thermal, periodic, impulsive, and crosstalk. The waveform distortion analysis examines amplitude versus frequency response and harmonic distortion components within the channel.

TABLE 1.25. FM/FM-TV TEST PROGRAM

Title	CCIR/CCITT Reference
Video Channel Tests	
Insertion Gain (& Variations)	CCIR Rec. 421-1 Paragraphs 3.1 & 3.2
Continuous Random Noise	CCIR Rec. 421-1 Paragraph 3.3.1
Periodic Noise	CCIR Rec. 421-1 Paragraph 3.3.2
Impulsive Noise	CCIR Rec. 421-1 Paragraph 3.3.3
Line-time Non-linearity Distortion	CCIR Rec. 421-1 Paragraph 3.4.2
Field-time and Line-time Linear Waveform Distortions	CCIR Rec. 421-1 Paragraphs 3.5.1 & 3.5.2
Short-time Linear Waveform Distortion	CCIR Rec. 421-1 Paragraph 3.5.3
Steady-State Characteristics, Envelope-delay and Attenuation Versus Baseband Frequency	CCIR Rec. 421-1 Paragraph 3.6
Color Vector Amplitude & Phase Distortions	CCIR Rep. 407 Paragraph A-1.1.6
Audio Channel Tests	
Noise, all Types and Sources	EIA Standard RS-250A, and CCIR Study Program 5A/CMTT, (Addendum 1 to Vol. V, Oslo 1966).
Waveform Distortions	Same as above, plus CCITT Rec. J21, New Delhi, Dec. 1960
Subjective Tests and Demonstrations	
Monochrome Test Pattern Analysis	Not Applicable
Special Demonstrations	Not Applicable

1.3.2 MODE DESCRIPTION

1.3.2.1 Basic Mode Configuration

The basic FM/FM-TV mode consists of three subsystems. They are an earth FM transmitter Subsystem, a satellite repeater, and an earth FM receiver subsystem. These subsystems make up a television link that is capable of relaying color as well as monochrome television signals. The brief description of these subsystems which follows is intended to familarize the reader with the basic ATS FM/FM-TV mode being evaluated.

The FM television transmitter subsystem shown in figure 1.39 consists of a program channel multiplexer, and FM transmitter, a transmission path including the satellite repeater, an FM receiver, and an FM video output. The output may be located at the same station as the input (for testing convenience) or at other stations (simulating a practical communications link). The input signals consist of the video information and the accompanying audio program signal. The combined baseband signal is used to frequency modulate a microwave oscillator which is then mixed with another microwave oscillator to produce a 70-MHz IF, which in turn is upconverted to the desired RF frequency. A traveling wave tube (TWT) amplifier is used to drive the final klystron power amplifier. The transmitter is capable of operating at either of two microwave frequencies (6212.094 MHz or 6301.050 MHz). A change of frequency is accomplished by changing some of the RF filters and retuning the klystron power amplifier. The output of the power amplifier is applied to the parabolic antenna via the duplexer and cassegrain feed.

As shown in figure 1.39, the spacecraft (S/C) repeater contains circuitry which directs the input signal to the proper transponder. The transponder frequency translates the received 6-GHz signal to 4 GHz for retransmission to the earth stations. The S/C repeater may operate on either or both transponders simultaneously, thus allowing full duplex operation between two earth stations. Each S/C channel contains two TWT amplifiers which may be operated singly or in parallel, thereby providing a choice of two power output levels for each transponder. Each of the TWT's in the ATS-1 S/C has a nominal power output of 4 watts; TWT No. 1 and No. 2 in ATS-3 each has a nominal power output of 4 watts; TWT No. 3 and No. 4 each has a nominal power output of 12 watts. However, TWT No. 3 has been inoperative, thus limiting the maximum ATS-3 power output to 12 watts. The S/C diplexer routes the outputs of the TWT amplifiers to the antenna for transmission to the earth station.

The FM receiver system shown in figure 1.39 contains a low noise parametric amplifier followed by a TWT amplifier. The paramp preamplifier is cooled to a cryogenic temperature of 25°K. After passing through the TWT amplifier, the RF signal is downconverted to 70 MHz where it is amplified and demodulated in an FM discriminator. The baseband output from the discriminator is sent to the FM receive equipment where the video and audio portions of the baseband signal are separated and recovered.

1.3.2.2 Terminal Equipment

A block diagram of the TV baseband signal processing equipment is shown in figure 1.40. At the sending terminal the video signal is filtered through a band stop filter to remove any signal energy contained within the frequency spectrum occupied by the audio subcarrier. The audio portion of the TV program is frequency modulated on to a subcarrier which may be located in the baseband at 4.5, 6.0, or 7.5 MHz with 6.0 MHz being the ATS normal operating mode. The subcarrier is locally demodulated in a discriminator with DC feedback used for subcarrier frequency control, and AC feedback for control over the FM deviation. A standard 75-usec audio pre-emphasis network is included in the feedback loop with provisions for bypassing it, if desired. The frequency-modulated subcarrier and the video signal are then combined and fed to the 70-MHz modulator within the SHF FM transmitter. Previsions are also included for CCIR video pre-emphasis (Rec. 405, Oslo, 1966).

At the receiving terminal the demodulated baseband is fed to the FM Video Unit. The signal is passed through either a CCIR video de-emphasis network, or a 10-db attenuator, and fed to an active video splitter network. The video portion of the signal is fed through a low-pass filter to the video output amplifier. The 4.5-MHz filter is normally employed with a 3.5-MHz video low pass unit available for use with the 4.5-MHz audio subcarrier. The subcarrier is filtered out through the 400-kHz bandpass filter and demodulated by an FM discriminator. A standard 75-usec audio de-emphasis network is available with provision for bypassing it when desired. A 15-kHz low-pass filter (and a 15.75-kHz reject notch filter) forms the final signal shaping component in the audio channel.

1.3.2.3 Summary of System Design Characteristics

Table 1.26 summarizes the primary system characteristics of the FM/FM television mode. Additional details concerning transmitter EIRP levels, receive G/T ratios, design objective carrier-to-noise ratio, and resulting video-audio signal-to-noise (thermal) are found in tables 1.27 to 1.42. The equations used to arrive at these predicted video-audio signal-to-noise ratios are found in Section 7.

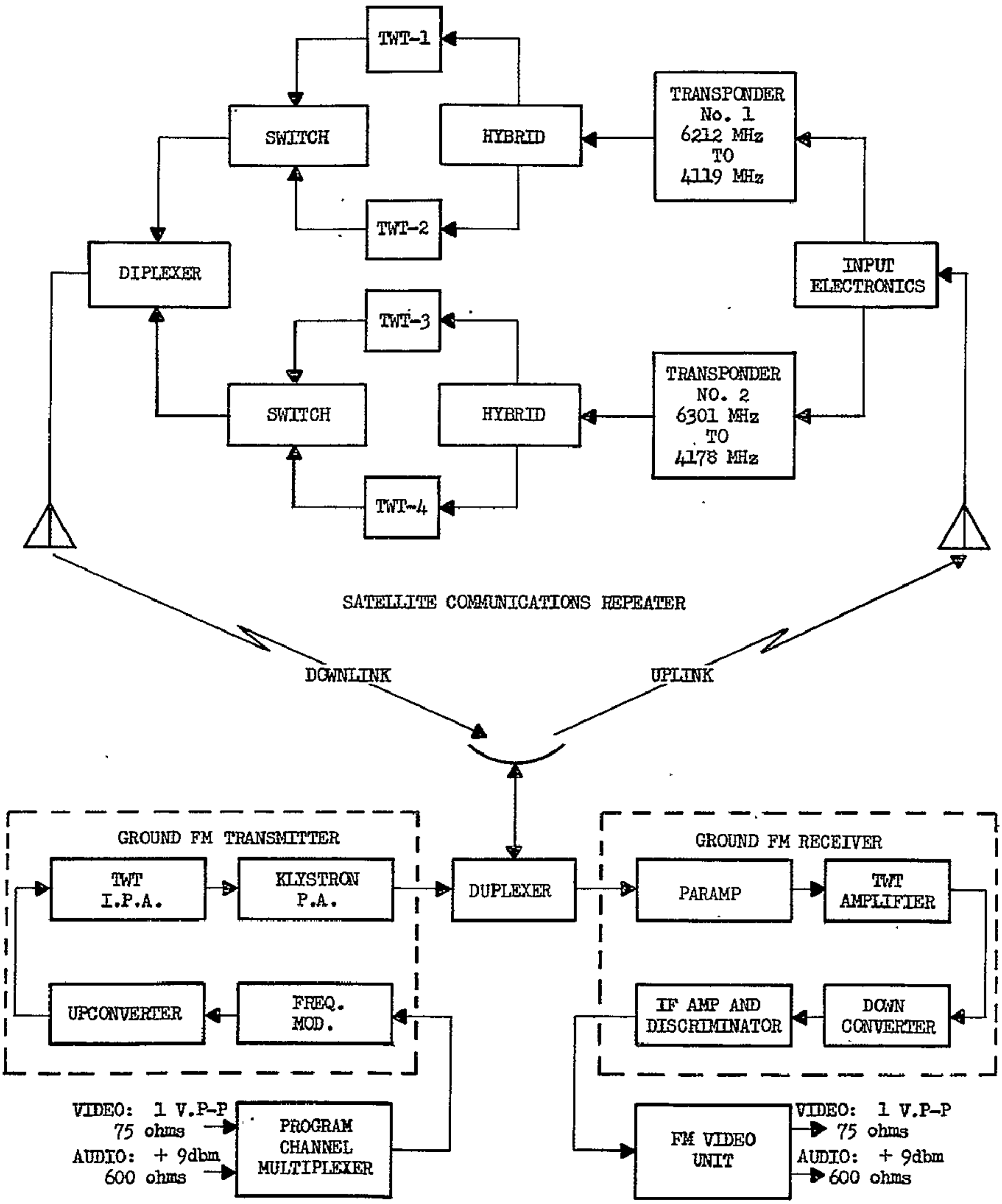


Figure 1.39. Block Diagram ATS FM/FM-TV Mode

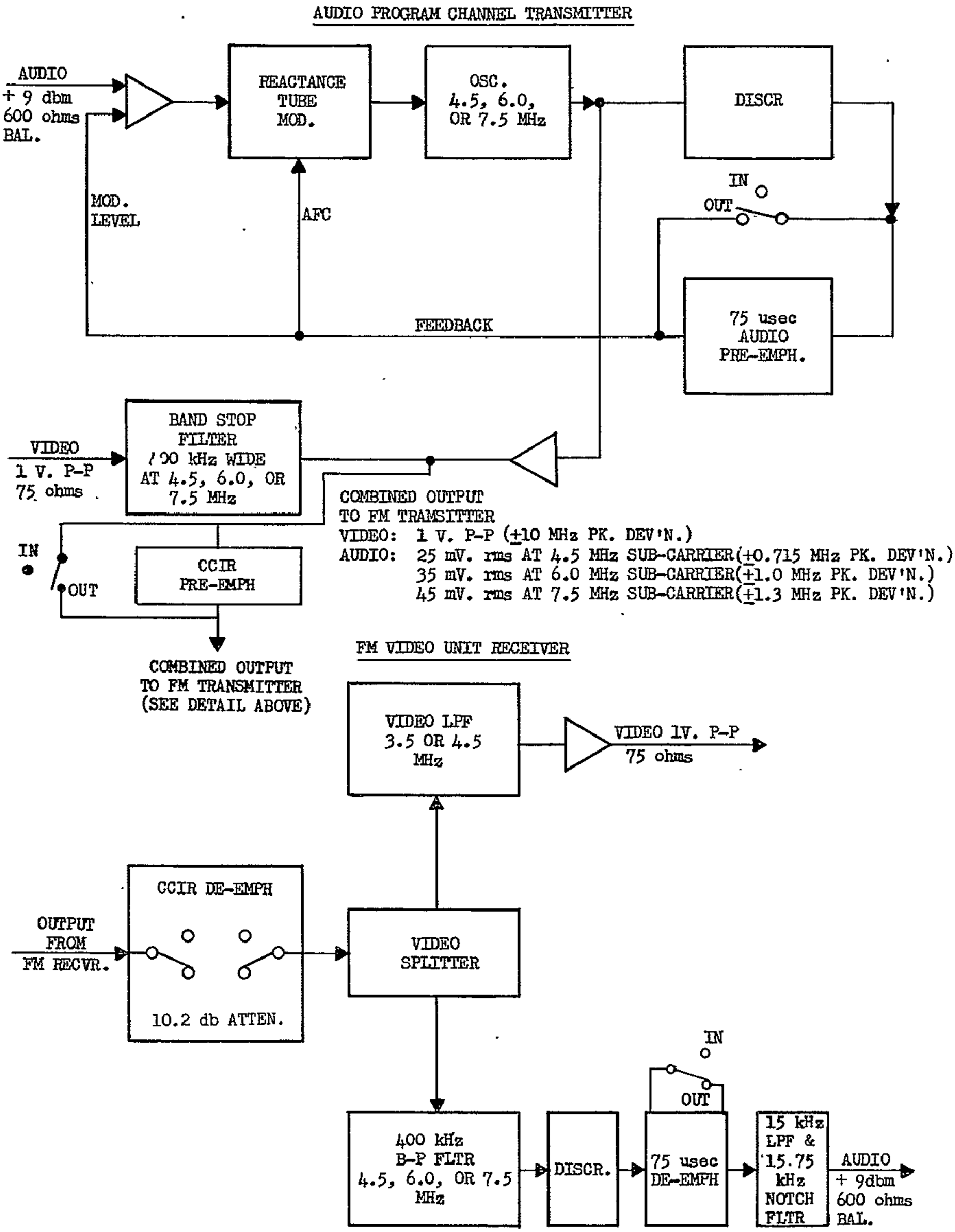


Figure 1.40. Block Diagram, TV Baseband Signal Processing Equipment

TABLE 1.26. FM/FM - TV MODE, DESIGN CHARACTERISTICS

Parameter	Value
RF Freq. (Uplink & Downlink):	
Transponder No. 1 (MHz)	6212.094 up & 4119.599 dn.
Transponder No. 2 (MHz)	6301.050 up & 4178.591 dn.
RF Bandwdiths	
Earth Transmitter	25 MHz
Satellite Transponders	35-40 MHz (Approx.)
Earth Receiver	33 MHz (Approx. 3 db BW)
RF Carrier Deviations:	
By Video Signal	±10 MHz peak
By Subcarrier Signal	±1 MHz peak (at 6 MHz subcarrier)
	±0.715 MHz peak (at 4.5-MHz subcarrier)
	±1.3 MHz peak (at 7.5-MHz subcarrier)
Subcarrier Frequencies	6.0 MHz (4.5 or 7.5 MHz optional)
Subcarrier Deviation (by audio)	±200 kHz peak
Video Section Bandwidth	30 Hz to 4.5 MHz (3.5 MHz optional)
Audio Section Bandwdith	30 Hz to 13 kHz
Video Signal Level & Impedance	1.0 V. Pk-Pk. at 75 ohms
Audio Signal Level & Impedance	+9 dbm at 600 ohms bal.

TABLE 1.27. FM/FM-TV MODE, ATS-1, EARTH TO SATELLITE LINK CALCULATION

(Transponders No. 1 and No. 2)

	85' Antenna	40' Antenna
Transmitter Average Power (dbm)	60.6	67.5
Earth Antenna Gain (net) (db)	61.5	54.6
Earth Station EIRP (dbm)	122.1	122.1
Space Attenuation (db)*	-200.8	-200.8
Satellite Antenna Gain (db)	6.2	6.2
Off Beam Center Allowance (db)	-0.5	-0.5
Received Carrier Power (dbm)	-73.0	-73.0
Receiver Noise Figure (db)	6.2	6.2
Effective Receiver Noise Temperature (db°K)	31.7	31.7
Receiver Noise Power Density (dbm/Hz)	166.9	166.9
Carrier/Noise (in unit BW) (db Hz)	93.9	93.9

*Based on a nominal slant range of 22,000 nmi.

TABLE 1.28. FM/FM-TV MODE, ATS-1, SATELLITE TO EARTH LINK AND OVERALL LINK CALCULATION (ONE TWT)

(Transponders No. 1 and No. 2)

	85' Antenna	40' Antenna
Satellite Transmitter Power Output (dbm)	36.7	36.7
Satellite Antenna Gain (db)	12.7	12.7
Satellite EIRP (dbm)	49.4	49.4
Space Attenuation (db)*	-197.1	-197.1
Off Beam Center Allowance (db)	-0.5	-0.5
Earth Antenna Gain (db)	58.4	51.0
Received Carrier Power (dbm)	-89.8	-97.2
Effective Receiver Noise Temp. (db°K)	20.2	18.8
Receiver Noise Power Density (dbm/Hz)	-178.4	-179.8
Downlink C/N_0 (db)	88.6	82.6
Uplink Contribution (db)	-1.1	-0.3
Total C/N_0 (db)	87.5	82.3

*Based on nominal slant range of 22,000 nmi.

TABLE 1.29. FM/FM-TV MODE, ATS-1, VIDEO CHANNEL S/N CALCULATION (ONE TWT)

(Transponders No. 1 and No. 2)

	85' Antenna	40' Antenna
Total Carrier/Noise (4.85 MHz NBW) (db)	20.7	14.5*
Frequency Deviation (MHz)	±10.0	±10.0
FM Improvement Factor (db) (Measured)	8.4	8.4
Srms/Nrms (db)	29.1	22.9
S_{p-p}/N_{rms} (Excluding sync) (db)	35.2	29.0
Noise Weighting Factor (db) (Measured)	10.6	10.6
Sp-p (Excluding Sync)/Noise (Wgtd) (db)	45.8	39.6

*Includes 1 db degradation due to threshold operation in IF.

TABLE 1.30. FM/FM-TV MODE, ATS-1, AUDIO CHANNEL S/N CALCULATION (ONE TWT)

(Transponders No. 1 and No. 2)

	85' Antenna		40' Antenna	
Subcarrier Frequency (MHz)	6.0	7.5	6.0	7.5
Overall Carrier/Noise (db)	12.3	12.3	6.9	6.9
IF/Subcarrier Filter Noise Bandwidth Ratio (db)	19.0	19.0	19.0	19.0
RMS Deviation of Carrier (kHz)	707	885	707	885
Modulation Improvement Factor (db)	-18.6	-18.6	-18.6	-18.6
Subcarrier-to-Noise Ratio (db)	12.7	12.7	6.3*	6.3*
Subcarrier-to-Audio Filter Noise Bandwidth Ratio (db)	15.0	15.0	15.0	15.0
RMS Deviation of Subcarrier by Audio (kHz)	140	140	140	140
Modulation Improvement Factor (db)	25.4	25.4	25.4	25.4
Audio Signal/Noise Ratio (db)	53.1	53.1	46.7	46.7

*Below Threshold, Calculation allows 1.0 db-degradation.

TABLE 1.31. FM/FM-TV MODE, ATS-1, SATELLITE TO EARTH LINK AND OVERALL LINK CALCULATION (TWO TWT'S)

(Transponders No. 1 and No. 2)

	85' Antenna	40' Antenna
Satellite EIRP (dbm)	52.2	52.2
Space Attenuation (db)*	-197.1	-197.1
Off Beam Center Allowance (db)	-0.5	-0.5
Earth Antenna Gain (db)	58.4	51.0
Received Carrier Power (dbm)	-87.0	-94.4
Effective Receiver Noise Temp. (db°K)	20.2	18.8
Receiver Noise Power Density (dbm/Hz)	-178.4	-179.8
Downlink C/N_0 (db)	91.4	85.4
Uplink Contribution (db)	-1.9	-0.6
Total C/N_0 (db)	89.5	84.8

*Based on a nominal slant range of 22,000 nmi.

TABLE 1.32. FM/FM-TV, ATS-1, VIDEO CHANNEL S/N CALCULATION (TWO TWT'S)

(Transponders No. 1 and No. 2)

	85' Antenna	40' Antenna
Total Carrier/Noise (4.85 MHz NBW) (db)	22.7	18.0
Frequency Deviation (MHz)	±10.0	±10.0
FM Improvement Factor (db) (Measured)	8.4	8.4
Srms/Nrms (db)	31.1	26.4
Sp-p/Nrms (excluding sync) (db)	37.2	32.5
Noise Weighting Factor (db) (Measured)	10.6	10.6
Sp-p (Excluding Sync)/Noise (Wgtd) (db)	47.8	43.1

TABLE 1.33. FM/FM-TV MODE, ATS-1, AUDIO CHANNEL S/N CALCULATION (TWO TWT'S)

(Transponders No. 1 and No. 2)

	85' Antenna		40' Antenna	
Subcarrier Frequency (MHz)	6.0	7.5	6.0	7.5
Overall Carrier/Noise (db)	14.0	14.0	9.3	9.3
IF/Subcarrier Filter Noise Bandwidth Ratio (db)	19.0	19.0	19.0	19.0
RMS Deviation of Carrier (kHz)	707	885	707	885
Modulation Improvement Factor (db)	-18.6	-18.6	-18.6	-18.6
Subcarrier-to-Noise Ratio (db)	14.4	14.4	9.7	9.7
Subcarrier-to-Audio Filter Noise Bandwidth Ratio (db)	15.0	15.0	15.0	15.0
RMS Deviation of Subcarrier by Audio (kHz)	140	140	140	140
Modulation Improvement Factor (db)	25.4	25.4	25.4	25.4
Audio Signal/Noise Ratio (db)	54.8	54.8	50.1	50.1

TABLE 1.34. FM/FM-TV MODE, ATS-3, EARTH TO SATELLITE LINK CALCULATION

	85' Antenna		40' Antenna	
Transponder	No. 1	No. 2	No. 1	No. 2
Transmitter Average Power (dbm)	50.5	50.5	57.4	57.4
Earth Antenna Gain (net) (db)	61.5	6.15	54.6	54.6
Earth Station EIRP (dbm)	112.0	112.0	112.0	112.0
Space Attenuation (db)*	-200.8	-200.8	-200.8	-200.8
Satellite Antenna Gain (db)	16.3	16.3	16.3	16.3
Off Beam Center Allowance (db)	-0.5	-0.5	-0.5	-0.5
Received Carrier Power (dbm)	-73.0	-73.0	-73.0	-73.0
Receiver Noise Figure (db)	6.1	5.6	6.1	5.6
Effective Received Noise Temp (db °K)	31.2	30.7	31.2	30.7
Receiver Noise Power Density (dbm/Hz)	-167.4	-167.9	-167.4	-167.9
C/N_0 (db)	94.4	94.9	94.4	94.9

*Based on a nominal slant range of 22,000 nmi.

TABLE 1.35. FM/FM-TV MODE, ATS-3, SATELLITE TO EARTH LINK AND OVERALL LINK CALCULATION (ONE TWT)

	85' Antenna		40' Antenna	
Transponder	No. 1	No. 2	No. 1	No. 2
Satellite Transmitter Power Output (dbm)	36.0	40.3	36.0	40.3
Satellite Antenna Gain (db)	16.2	16.2	16.2	16.2
Satellite EIRP (dbm)	52.2	56.5	52.2	56.5
Space Attenuation (db)*	-197.1	-197.1	-197.1	-197.1
Off Beam Center Allowance (db)	-0.5	-0.5	-0.5	-0.5
Ground Antenna Gain (db)	58.4	58.4	51.0	51.0
Receiver Carrier Power (db)	-87.0	-82.7	-94.4	-90.1
Effective Received Noise Temp (db°K)	18.8	18.8	18.8	18.8
Receiver Noise Power Density (dbm/Hz)	-179.8	-179.8	-179.8	-179.8
Downlink C/N_0 (db)	92.8	97.1	85.4	89.7
Uplink Contribution (db)	-2.3	-4.2	-0.5	-1.1
Total C/N_0 (db)	90.5	92.9	84.9	88.6

*Based on a nominal slant range of 22,000 nmi.

TABLE 1.36. FM/FM-TV MODE, ATS 3, VIDEO CHANNEL S/N CALCULATION (ONE TWT)

	85' Antenna		40' Antenna	
Transponder	No. 1	No. 2	No. 1	No. 2
Total Carrier/Noise 4.85 MHz NBW. (db)	23.7	26.1	18.1	21.8
Frequency Deviation (MHz)	±10.0	±10.0	±10.0	±10.0
FM Improvement Factor (Measured) (db)	8.4	8.4	8.4	8.4
S_{rms}/N_{rms} (db)	32.1	34.5	26.5	30.2
Sp-p/Nrms (excluding sync) (db)	38.2	40.6	32.6	36.3
Noise Weighting Factor (db) (measured)	10.6	10.6	10.6	10.6
Sp-p (Excluding Sync)/Noise (Wgtd) (db)	48.8	51.2	43.2	46.9

TABLE 1.37. FM/FM-TV MODE, ATS-3, AUDIO CHANNEL S/N CALCULATION (ONE TWT)

(Transponder No. 1)

	85' Antenna		40' Antenna	
Subcarrier Frequency (MHz)	6.0	7.5	6.0	7.5
Overall Carrier/Noise (db)	15.0	15.0	9.4	9.4
IF/Subcarrier Filter Noise Bandwidth Ratio (db)	19.0	19.0	19.0	19.0
RMS Deviation of Carrier (kHz)	707	885	707	885
Modulation Improvement Factor (db)	-19.6	-18.6	-18.6	-18.6
Subcarrier-to-Noise Ratio (db)	15.4	15.4	9.8	9.8
Subcarrier-to-Audio Filter Noise Bandwidth Ratio (db)	15.0	15.0	15.0	15.0
RMS Deviation of Subcarrier by Audio (kHz)	140	140	140	140
Modulation Improvement Factor (db)	25.4	25.4	25.4	25.4
Audio Signal/Noise Ratio (db)	55.8	55.8	50.2	50.2

TABLE 1.38. FM/FM-TV MODE, ATS-3, AUDIO CHANNEL S/N CALCULATION (ONE TWT)

(Transponder No. 2)

	85' Antenna		40' Antenna	
Subcarrier Frequency (MHz)	6.0	7.5	6.0	7.5
Overall Carrier/Noise (db)	17.4	17.4	13.0	13.1
IF/Subcarrier Filter Noise Bandwidth Ratio (db)	19.0	19.0	19.0	19.0
RMS Deviation of Carrier (kHz)	707	885	707	885
Modulation Improvement Factor (db)	-18.6	-18.6	-18.6	-18.6
Subcarrier-to-Noise Ratio (db)	17.8	17.8	13.5	13.5
Subcarrier-to-Audio Filter Noise Bandwidth Ratio (db)	15.0	15.0	15.0	15.0
RMS Deviation of Subcarrier by Audio (kHz)	140	140	140	140
Modulation Improvement Factor (db)	25.4	25.4	25.4	25.4
Audio Signal/Noise Ratio (db)	58.2	58.2	53.9	53.9

TABLE 1.39. FM/FM-TV MODE, ATS-3, SATELLITE TO EARTH LINK AND OVERALL LINK CALCULATION (TWO TWT'S)

	85' Antenna		40' Antenna	
Transponder	No. 1	No. 2	No. 1	No. 2
Satellite Transmitter Power Output (dbm)	38.4	43.1	38.4	43.1
Satellite Antenna Gain (db)	16.2	16.2	16.2	16.2
Satellite EIRP (dbm)	54.6	59.3	54.6	59.3
Space Attenuation (db)*	-197.1	-197.1	-197.1	-197.1
Off Beam Center Allowance (db)	-0.5	-0.5	-0.5	-0.5
Earth Antenna Gain (db)	58.4	58.4	51.0	51.0
Received Carrier Power (db)	-84.6	-79.9	-92.0	-87.3
Effective Receiver Noise Temp (db°K)	18.8	18.8	18.8	18.8
Receiver Noise Power Density (dbm/Hz)	-179.8	-179.8	-179.8	-179.8
Downlink C/N_0 (db)	95.2	99.9	87.8	92.5
Uplink Contribution (db)	-3.4	-6.2	-0.9	-2.0
Overall C/N_0 (db)	91.8	93.7	86.9	90.5

*Based on a nominal slant range of 22,000 nmi.

TABLE 1.40. FM/FM-TV MODE, ATS-3, VIDEO CHANNEL S/N CALCULATION (TWO TWT'S)

	85' Antenna		40' Antenna	
Transponder	No. 1	No. 2	No. 1	No. 2
Total Carrier/Noise 4.85 MHz NBW (db)	25.0	26.9	20.1	23.7
Frequency Deviation (MHz)	±10.0	±10.0	±10.0	±10.0
FM Improvement Factor (Measured) (db)	8.4	8.4	8.4	8.4
S_{rms}/N_{rms} (db)	33.4	35.3	28.5	32.1
Sp-p/Nrms (excluding sync) (db)	39.5	41.4	34.6	38.2
Noise Weighting Factor (db) (measured)	10.6	10.6	10.6	10.6
Sp-p (Excluding Sync)/Noise (Wgtd) (db)	50.1	52.0	45.2	48.8

TABLE 1.41. FM/FM-TV MODE, ATS-3, AUDIO CHANNEL S/N CALCULATION (TWO TWT'S)

(Transponder No. 1)

	85' Antenna		40' Antenna	
Subcarrier Frequency (MHz)	6.0	7.5	6.0	7.5
Overall Carrier/Noise (db)	16.3	16.3	11.4	11.4
IF/Subcarrier Filter Noise Bandwidth Ratio (db)	19.0	19.0	19.0	19.0
RMS Deviation of Carrier (kHz)	707	885	707	885
Modulation Improvement Factor (db)	-18.6	-18.6	-18.6	-18.6
Subcarrier-to-Noise Ratio (db)	16.7	16.7	11.8	11.8
Subcarrier-to-Audio filter Noise Bandwidth Ratio (db)	15.0	15.0	15.0	15.0
RMS Deviation of Subcarrier by Audio (kHz)	140	140	140	140
Modulation Improvement Factor (db)	25.4	25.4	25.4	25.4
Audio Signal/Noise Ratio (db)	57.1	57.1	52.2	52.2

TABLE 1.42. FM/FM-TV MODE, ATS-3, AUDIO CHANNEL S/N CALCULATION (TWO TWT'S)

(Transponder No. 2)

	85' Antenna		40' Antenna	
Subcarrier Frequency (MHz)	6.0	7.5	6.0	7.5
Overall Carrier/Noise (db)	18.2	18.2	15.0	15.0
IF/Subcarrier Filter Noise Bandwidth Ratio (db)	19.0	19.0	19.0	19.0
RMS Deviation of Carrier (kHz)	707	885	707	885
Modulation Improvement Factor (db)	-18.6	-18.6	-18.6	-18.6
Subcarrier-to-Noise Ratio (db)	18.6	18.6	15.4	15.4
Subcarrier-to-Audio filter Noise Bandwidth Ratio (db)	15.0	15.0	15.0	15.0
RMS Deviation of Subcarrier by Audio (kHz)	140	140	140	140
Modulation Improvement Factor (db)	25.4	25.4	25.4	25.4
Audio Signal/Noise Ratio (db)	59.0	59.0	55.8	55.8

1.3.3 SUMMARY OF PERFORMANCE

The basic FM/FM, television mode consists of three subsystems: an earth FM transmitter subsystem, a satellite transponder, and an earth FM receiver subsystem. Sending and receiving terminals are included in the baseband equipment.

Video channel performance may be limited by continuous random noise, periodic noise, impulsive noise, and crosstalk. When the CCIR recommendation pertaining to continuous random noise is applied to this mode the following limits are indicated. A video weighted S/N ratio of 56 db should be attained for 99 percent of the time and a ratio of 48 db should be attained for 99.9 percent of the time. The 8-db difference is an allowance for performance degradation. It is felt that a degradation of 5 db is sufficient for a system such as ATS; thus, a video weighted S/N ratio of 53 db for 99 percent of the time should be acceptable. TV system calculations indicate that the ATS system is within one db of this goal when using ATS-3 with a satellite EIRP of 59.3 db in conjunction with an earth station whose G/T ratio is 39.6 db or better (See table 1.43). The FM/FM mode, according to calculations, is capable of meeting the S/N ratio of 46 db in all cases except one with an 85-ft earth station antenna, or in those cases where a satellite EIRP of 55 dbm or greater is used with an earth station whose G/T ratio is 32 db or better. A graphic presentation of ATS video performance as it relates to other systems is seen in figure 1.41. Application of the CCIR recommended video pre-emphasis is calculated to increase the signal-to-thermal noise ratio by about 2.6 db. Measurements indicate an actual improvement of 2.3 db.

The remaining types of noise appear to cause little degradation in the video channel. Periodic noise, when examined on a "flat" basis (no pre/de-emphasis) is well within the CCIR recommended limit. However, when emphasis is applied the 10-db increase in 60-Hz hum components makes this system noise characteristics marginal. Although impulsive noise has not been measured, no indication of this type of interference reaching an objectionable level has been noted.

Waveform distortion may also cause picture degradation. This type of distortion may be classified as either linear or non-linear waveform distortion. A number of tests are used to determine if distortion exists in either of these classes. It is also necessary to point out that the CCIR recommendations for international links are quite often less stringent than the established U. S. and Canadian operating standards.

There are various linear waveform distortion tests. The baseband amplitude response versus frequency test (figure 1.42) shows the ATS system to be operating within CCIR international limits. The system does not operate within the U. S. and Canadian limits at the high frequency end of the baseband, but this is expected since the ATS video channel must also accommodate a 6.0-MHz audio subcarrier. A short-time linear waveform distortion test was used to further evaluate the high frequency end of the baseband for overshoots. Results from this test which are summarized in table 1.44, show that the ATS system is operating within the CCIR U. S./Canadian recommended limit. When using line-time and field-time linear waveform distortion tests to evaluate the low frequency portion of the baseband, it appears that, although the system is well within the international recommended limits, it is at or near the maximum allowed by the U. S. and Canada. The final test used to evaluate linear waveform was to measure baseband envelope delay. The ATS system remained within both the CCIR international and U. S. /Canadian recommended limits for this test as shown in figure 1.43.

Line time non-linearity distortion and color vector amplitude and phase tests were used to determine the extent of non-linear waveform distortions in the ATS system. Test results indicate that with no emphasis circuits employed, the system exceeds the differential gain limits for the U.S. and Canada, and is near the international limits as recommended by the CCIR. The beneficial effects of using video pre-emphasis and de-emphasis are shown in table 1.44. With emphasis, this distortion parameter is reduced to the point that it is well within the U. S./Canadian tolerances. Test measurements of color vector amplitude and phase responses indicate that the ATS system is well within the CCIR recommendation for this parameter. As above, the benefits derived from the application of pre-emphasis is shown in table 1.44.

Subjective tests and demonstrations were also used to evaluate the ATS system. A monochrome test pattern signal passed through the system was evaluated by site operators. This evaluation consisted of rating a number of parameters. The results indicated the presence of noise in 42 percent of the tests. The remaining parameter ratings indicated no picture degradation from a single parameter for more than 10 percent of the tests. At least 15 demonstrations were performed via the ATS system. Photographs at the end of this section indicate that high picture quality was obtained.

TV audio channel performance was also evaluated from the viewpoint of noise degradations and waveform distortions. Noise studies covered the same aspects as that of the video channel; namely, thermal, periodic, impulsive, and crosstalk. The waveform distortion measurements examined linearity of the amplitude versus frequency and the non-linearity of the harmonic distortion within the channel.

Measurements of signal-to-idle channel thermal noise showed that system performance closely equaled the expectations tabulated in table 1.43. It was also found that seven of the twelve listed ATS system configurations could not be expected to meet the EIA standard of 55 db when operated on a flat, or nonemphasized basis. Adding the CCITT recommended pre-emphasis network to the baseband was found to add about 8.5 db to the expected signal-to-noise performance. Under this condition, all configurations of the ATS system are found to deliver at least 55 db for an audio-channel S/N ratio.

Wave analyzer measurements in the idle audio channel showed that power supply hum components at 60 and 120 Hz were the major items contributing to the periodic noise present in the channel. These components were generally found to be 60 db or more below test tone level, and thus in most cases were insignificant in comparison to the continuous random (thermal) noise. Introduction of the 75 usec, pre-emphasis was seen to have little effect upon the periodic noise components.

Impulsive noise was not examined in detail in the audio channel, but as with the video channel, no indications of problems have been encountered.

Video-to-audio crosstalk from the 15.75-kHz line rate pulses was found to be relatively severe. The addition of a notch filter to the audio channel reduced this source of crosstalk to an acceptable level with only a minor effect upon the amplitude versus frequency response at the high end of the band. Video pre-emphasis was found to eliminate the crosstalk problem. Frequency response at the low end of the band was slightly outside the present limits of the CCIR. (See figure 1.44.) Harmonic distortion measurements also revealed that the earth system equipment was slightly outside of current recommendations.

TABLE 1.43. ATS FM/FM-TV MODE, CALCULATED THERMAL PERFORMANCE (NO PRE-EMPHASIS)

Satellite No.	ATS-1				ATS-3							
Output Tubes in S/C	One TWT		Two TWT's		One TWT				Two TWT's			
Earth Sta. Antenna Size	85'	40'	85'	40'	85'		40'		85'		40'	
Transponder No.	1 or 2	1 or 2	1 or 2	1 or 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2
Earth Station EIRP (dbm)	122.1	122.1	122.1	122.1	112.0	112.0	112.0	112.0	112.0	112.0	112.0	112.0
Satellite G/T (db)	-25.5	-25.5	-25.5	-25.5	-14.9	-14.4	-14.9	-14.4	-14.9	-14.4	-14.9	-14.4
Uplink C/N_o (db)	93.9	93.9	93.9	93.9	94.4	94.9	94.4	94.9	94.4	94.9	94.4	94.9
Satellite EIRP (dbm)	49.4	49.4	52.2	52.2	52.2	56.5	52.2	56.5	54.6	59.3	54.6	59.3
Earth Station G/T (db)	38.2	32.2	38.2	32.2	39.6	39.6	32.2	32.2	39.6	39.6	32.2	32.2
Downlink C/N_o (db)	88.6	82.6	91.4	85.4	92.8	97.1	85.4	89.7	95.2	99.9	87.8	92.5
Total Link C/N (db) (35.5 MHz IF Noise BW)	12.0	*** 6.8	14.0	9.3	15.0	17.4	9.4	13.1	16.3	18.2	11.4	15.0
Video WGTD S/N* (db)	45.8	(1) 39.6	47.8	43.1	48.8	51.2	43.2	46.9	50.1	52.0	45.2	48.8
Audio S/N (Flat)** (db)	52.8	(1) 46.6	54.8	50.1	55.8	58.2	50.2	53.9	57.1	59.0	52.2	55.8

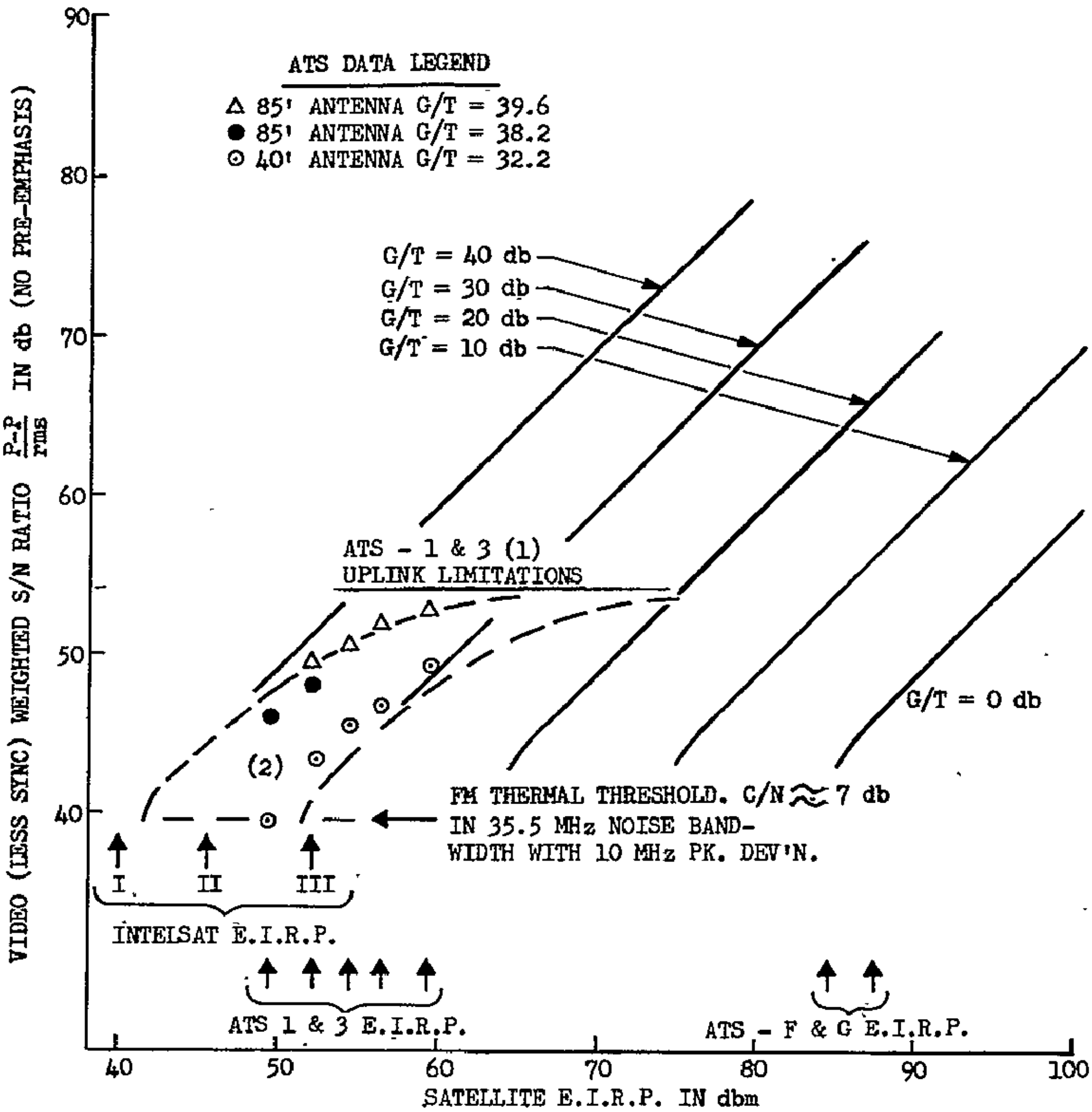
*Based on S/N = Link C/N + (X), where X = 33.8 db (See detail below)
**Based on S/N = Link C/N + (Y), where Y + 40.8 db (See detail below)
***Below threshold
(1) Allows 1.0 db degradation for threshold operation (link C/N = 7.0 db)

X =		
bandwidth factor	=	+ 8.7 db
deviation factor	=	+ 8.4 db
sig. pk-pk (less sync)	=	+ 6.1 db
CCIR wgtg network	=	+ 10.6 db
		+ 33.8 db

Y =		
I. F. bandwidth	=	+ 19.0 db
sub-cxr. bandwidth factor	=	+ 15.0 db
main cxr. deviation factor	=	- 18.6 db
sub-cxr. deviation factor	=	+ 25.4 db
		+ 40.8 db

TABLE 1.44. WAVEFORM CHARACTERISTICS--ATS VIDEO CHANNEL PERFORMANCE VERSUS REQUIREMENTS DATA

Waveform Characteristic	CCIR Recommendation		Measured Performance	
	International Television Circuit	System M (Canada and the U. S. A.)	Flat	With Emphasis
NON-LINEAR WAVEFORM DISTORTION				
Line time non-linearity distortion				
10% average picture level	20%	13%	19.0%	6.5%
50% average picture level	20%	13%	19.5%	7.0%
90% average picture level	20%	13%	18.7%	4.5%
Non-linearity distortion of the synchronizing signal	0.21v to 0.33v	0.26v to 0.31v	Not measured	Not measured
Color vector phase non-linearity	-	±10°	3.5 degrees	<1.5 degrees
Color vector amplitude non-linearity	-	±20%	7 percent	<2.5 percent
LINEAR WAVEFORM DISTORTION				
Field time linear waveform distortion	±10%	5% (signal unclamped) 1% (signal clamped)	3.0% -	<1%
Line time linear waveform distortion	±5%	±1%	1.0%	≈1%
Short time linear waveform distortion	±20%	±13%	5.8%	≈7.4%
Attenuation/frequency characteristic	See fig. 1.42	See fig. 1.42	See fig. 1.42	See. fig. 1.42
Envelope-delay/frequency characteristic	See fig. 1.43	See fig. 1.43	See fig. 1.43	-
Insertion gain	0 ±1.0 db	0 ±0.5 db	0.0 db	N. A.
Variations of insertion gain				
Short period	±0.3 db	±0.2 db	None observed	N. A.
Medium period	±1.0 db	±1.0 db	None observed	N. A.



NOTES:

(1) EARTH TRANSMITTER E.I.R.P. ADJUSTED FOR A S/C RECEIVED CARRIER LEVEL OF -73 dbm.

(2) PERFORMANCE LEVELS INDICATED FOR ATS-1 AND 3 VERIFIED TO BE ACCURATE WITHIN 1 db BY ACTUAL TEST MEASUREMENTS.

Figure 1.41. Video Performance of Several Satellite Systems

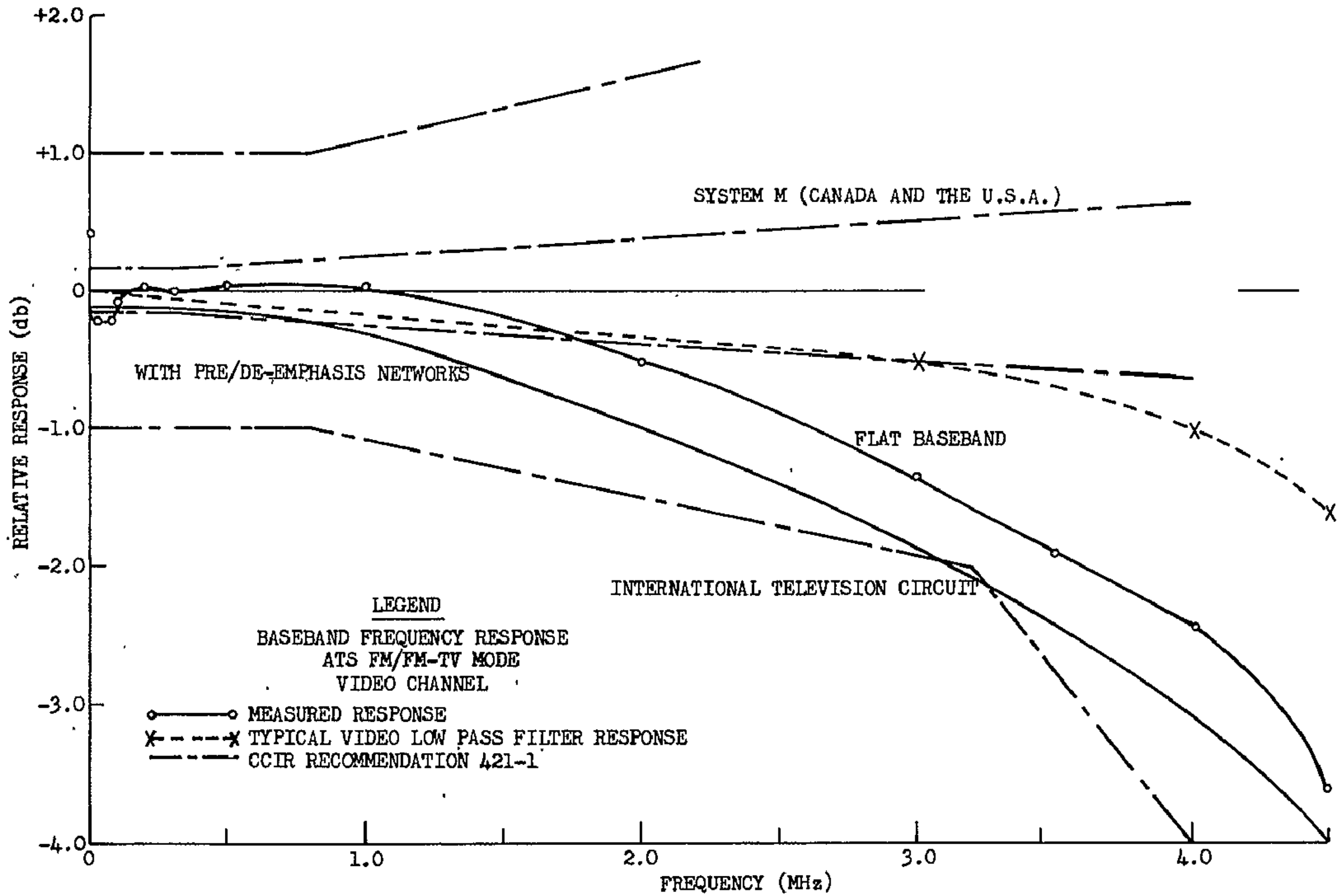


Figure 1.42. Baseband Frequency Response, ATS FM/FM-TV Mode

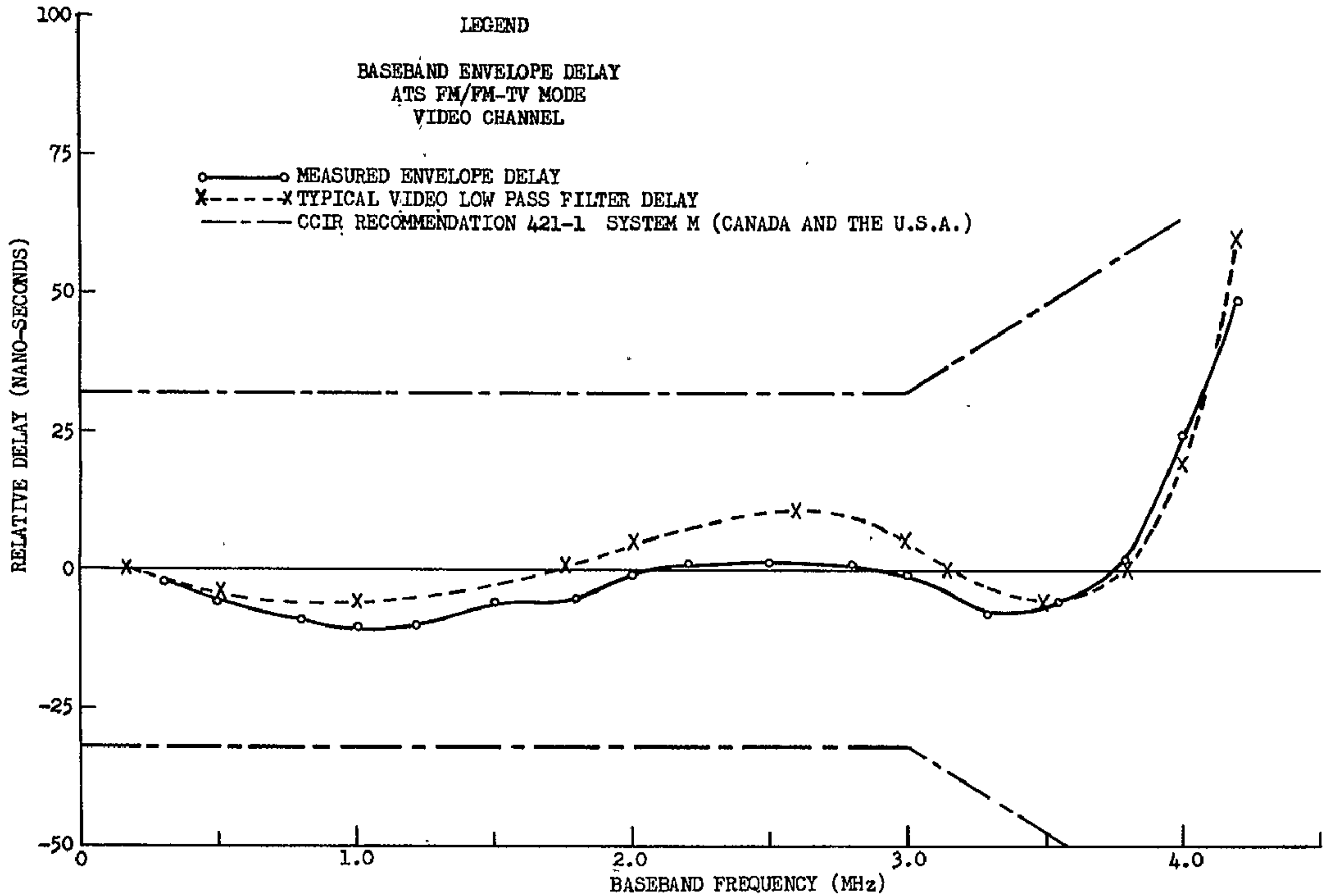


Figure 1.43. Baseband Envelope Delay, ATS FM/FM-TV Mode

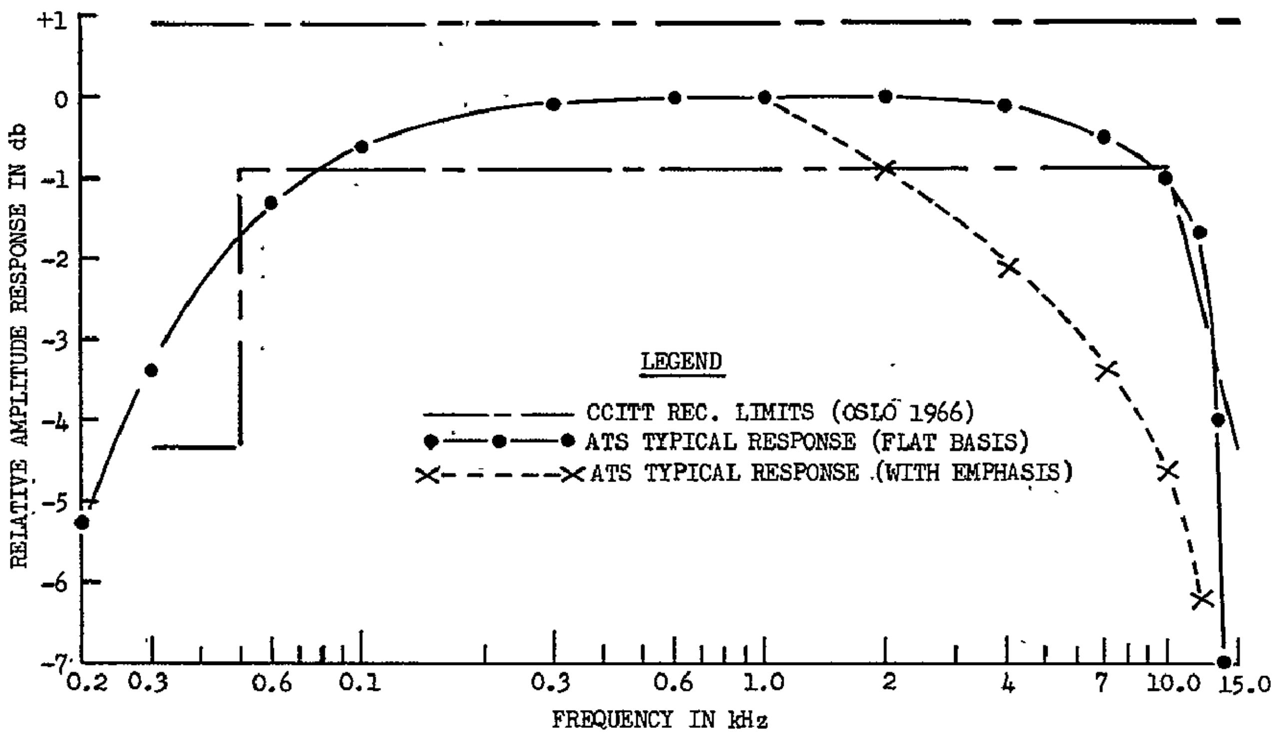


Figure 1.44. TV Audio Channel, Typical Frequency Response with 15.75 kHz Notch Filter

3.4 VIDEO CHANNEL PERFORMANCE

3.4.1 Noise

Video performance as limited by noise is based on four types or sources of noise:

1) Continuous random noise (thermal)
2) Periodic noise (usually power supply hum)
3) Impulsive noise (switching or power transients)
4) Crosstalk.

These noise sources are defined below in terms of the signal-to-noise ratios required to meet certain standards or users requirements.

CONTINUOUS RANDOM NOISE

This parameter is defined by the CCIR as the ratio, in decibels, of the peak-to-peak amplitude of the picture signal (blanking to white level) to the rms amplitude of the noise, between 10 kHz and the nominal upper limit of the video frequency band of the system. The lower frequency limit is to enable power supply hum and microphonic noise to be excluded from these measurements (measured under periodic noise). The measurement is made with a 4.5-MHz low-pass filter and a noise weighting network as specified in CCIR Recommendation 421-1.

The CCIR and other interested agencies are studying the factors and parameters involved in long-distance relaying of television signals via active satellites. Since a single satellite link is capable of spanning very large intercontinental distances, it is felt that the performance for one link (earth station to earth station at baseband) should be at least equal or better than the performance required for long-distance international circuits. Therefore, it is felt that an intercontinental satellite relay system should meet the limits given in CCIR Recommendation 421-1 (Oslo, 1966, Vol. V)*. Applying this recommendation to the ATS system means that a video weighted S/N ratio of 56 db should be attained for 99 percent of the time, while a ratio of 48 db should be attained for not less than 99.9 percent of the time. Experience with synchronous satellite relay systems indicates that an 8-db allowance for performance degradations may not be necessary. Measurements on the ATS systems indicate that at least 2 db should be allowed for atmospheric disturbances (rain, snow, etc). Approximately 3 db is required for earth station equipment degradations between maintenance periods, and for EIRP degradations in the satellite. Satellite EIRP degradations consist of three components; transmitter power output reductions, line losses, and variations of antenna boresight. With despun antenna systems such as used on ATS, the boresight

*CCIR Doc. IV/143-E from Working Group IV-A, Draft Amendment to Rec. 354.

pointing is subject to small variations, especially during periods of eclipse. One must also include the fixed losses for earth stations located off the S/C antenna beam. The ATS test program has held this loss to 1 db or less by optimally pointing the beam at the user site during testing observations. These values indicate a design goal of 53 db for 99 percent of the time should be met by a system similar to the ATS system.

Comparing this suggested design goal against the TV system calculations in table 1.43, it is seen that this objective cannot be achieved. The best S/N is 52 db and is attained only in the case of satellite EIRP of 59.3 db combined with the 85-ft antenna earth station (G/T of 39.6 db). Further examination of the reference table shows that a second case (satellite EIRP of 56.5 dbm combined with the 85-ft antenna) and a third case (satellite EIRP of 54.6 dbm combined with the 85-ft antenna) could obtain a total link S/N of 53 db by increasing the earth station transmitter power by approximately 2.3 db and 10 db, respectively. Combinations of lower satellite EIRP and smaller antennas appear incapable of meeting the recommended thermal noise level.

On the other hand, rather extensive experiments have been conducted (Section 6.1, Reference 21) which show that reasonable video performance is attained at signal-to-weighted noise ratios of about 39 to 41.5 db. The first ratio is the point where the picture quality was rated as either excellent or good by 76 percent of the observers, and as poor or bad by only 0.5 percent. The higher S/N ratio of 41.5 db corresponds to an excellent or good rating by 98 percent of the observers, with less than a 0.1-percent grading of poor or bad. The remaining percentage of observers in each case are those who graded the picture as fair. Thus, it is seen that a satisfactory satellite relay system could be attained with video S/N ratios at least 10 db below that of the CCIR recommendation (i.e., 46 db). This allows a minimum of 7 db for atmospheric loss variations, satellite antenna pointing losses, equipment performance degradations, and the degrading effects of a series of terrestrial links with a worst case end result which is still rated good or excellent by three-quarters of the system viewers and fair by the remaining one-quarter of the viewers. Using this criteria to examine table 1.43, we find that all cases except one with the 85-ft earth station antenna are within limits. The earth stations equipped with the 40-ft antenna can meet this performance level only with satellite EIRP's of 56 dbm or greater (two of the six illustrated conditions).

The above discussion and the system performance calculations listed in table 1.43 are exclusively based upon a flat, or non-emphasized baseband. However, the ATS ground stations are equipped with video pre-emphasis and de-emphasis networks as recommended by the CCIR for terrestrial line-of-sight microwave relay systems. When the de-emphasis network curve is applied to the parabolic spectrum of FM receiver noise, it is found that the calculated improvement in video signal-to-noise is 2.6 db.

Experimental system measurements are very close to this calculation since the average improvement obtained in several measurements was 2.3 db. This relatively small improvement in signal-to-noise ratio is primarily obtained in the upper portion of the video frequency spectrum where the eye is more tolerant to thermal noise components. This accounts for the fact that terrestrial relay systems are frequently operated on a flat basis (i.e., without use of pre-emphasis and de-emphasis networks). However, systems such as the ATS where the audio is carried on a sub-carrier can benefit considerably by the application of video pre-emphasis. This aspect is discussed later in this report section under the heading of Audio Channel Crosstalk.

The above discussed performance predictions are graphically presented in figure 1.41. This figure also presents comparative performance levels for Intelsat I, II, and III as well as for the future satellites ATS-F and G. The video noise relationships among several satellite programs is clearly seen in this graph. For example, Intelsat I is seen to have an effective radiated power which is too low for use with the 35-MHz bandwidth of the ATS system. Figure 1.41 shows the increasing capabilities for TV relay which have been produced by recent satellite programs. As satellite EIRP values reach about 60 dbm, it becomes feasible to transmit color television (and audio) programs with earth receiving stations having G/T ratios as low as 30 db.

On a direct comparison basis, the TV relay capabilities of future satellites ATS-F and G become outstanding if the systems are not uplink limited. It is seen that wide-band TV relay is possible with low cost receiving systems having a G/T ratio as low at 5 db. Although the points indicated in the figure for performance levels of ATS-1 and 3 are calculated from system design parameters, they have been verified to be accurate within 1 db by actual measurement.

PERIODIC NOISE

Periodic noise applies only to single frequency interfering signals as generally caused by power supply hum, including the fundamental frequency and its lower order harmonics. The signal-to-noise ratio for periodic noise is defined as the ratio, in decibels, of the peak-to-peak amplitude of the picture signal (blanking to white level) to the peak-to-peak amplitude of the noise.

CCIR Working Group IV-A has reommended that the requirements of Rec. 421-1 also be applied to satellite relay systems. For system "M"* in Canada and the U.S.A. this

*System "M" is the label assigned by the CCIR to the television system presently in use in the U.S.A. and Canada. This television system has 525 lines per field, interlaced scanning, 2 fields per frame, 15,750 lines per second, a bandwidth of 4.2 MHz, and employs amplitude modulation (negative system) for video modulation. For additional information see CCIR Documents of the XIth Plenary Assembly, Volume V, Report 308-1.

document recommends that the signal-to-noise ratio based on single frequency noise components below 1000 Hz shall equal or exceed 35 db. From 1000 Hz to 2 MHz the signal-to-noise ratio shall equal or exceed 59 db. Above 2 MHz up to the nominal upper frequency limit of the video passband, the signal-to-noise ratio may decrease linearly to a value of 43 db.

Measurements of this parameter in the ATS system indicate that on a "flat", or non-emphasized basis, the 60-Hz hum components are from 43 to 50 db below the peak-to-peak picture signal level. Second, third, and fourth harmonic components of the 60-Hz fundamental are all down 48 to 60 db. The testing program also revealed that there is no significant periodic noise component elsewhere within the limits of the video baseband above 1000 Hz. Thus, it is concluded that the periodic noise components in the "flat" ATS video baseband are 8 db or more below the maximum levels allowed by CCIR Recommendation 421-1.

However, when the CCIR Recommended video emphasis networks are incorporated the 60 Hz hum level increases nearly 10 db. When the receiver de-emphasis network is switched into the circuit, all frequencies below 10 kHz are boosted in level by 10.2 db as compared to their former level. These facts indicate that the major portion of the hum components are introduced into the system between the transmitter pre-emphasis network and the receiver de-emphasis network. Further investigation revealed that the prime offender in the ATS system is the video amplifier immediately following the receiver demodulator, but preceding the de-emphasis network.

It is therefore concluded that when the ATS system is operated with the recommended video pre-emphasis, the periodic noise components will frequently be up to 2 db or so greater than the CCIR Recommended limits. This is no great problem, since a relatively minor circuit redesign should be capable of alleviating the discrepancy.

IMPULSIVE NOISE

The signal-to-noise ratio for impulsive noise is defined as the ratio, in decibels, of the peak-to-peak amplitude of the picture signal (blanking to white level) to the peak-to-peak amplitude of the noise. The CCIR has provisionally suggested that this ratio should not be less than 25 db for impulsive noise of a sporadic or infrequently occurring nature. U.S. and Canadian systems have set their standard at 11 db.

Impulse noise in a video transmission system can be caused by switching transients, primary power line surges, or direct pickup (crosstalk) from outside sources such as gasoline engine ignitions, etc. Because of the wide variety of sources, types, and noise waveform characteristics, no attempt has been made to measure or evaluate this parameter in the ATS system. Each system will be different in its exposure and response to impulsive interference. The above recommended limits are therefore primarily given to serve as a guideline for those systems where impulse noise is a problem.

The ATS system has been in use since January 1967, and as yet there is no indication that interference of an impulsive or sporadic nature has ever reached objectionable proportions. It is concluded that the ATS system as currently configured is not subject to impulse noise degradations.

CROSSTALK

For this discussion, crosstalk is defined as the presence of extraneous signals in the video program channel which are caused by signals in the audio channel. In a system such as ATS, this crosstalk can originate in two ways. First, the crosstalk may consist of an intermodulation product generated in system non-linearities by mixing of the video signal with the modulated audio subcarrier. Secondly, the crosstalk components may be traceable to direct leakage or coupling between the two channels.

Crosstalk is currently under study by the CCIR and other groups, but as of this time no standard or recommendation has been proposed for TV relay systems such as the ATS. EIA (Electronic Industries Association) Standard RS-250A establishes a limit for "Signal-to-Interfering Tone Ratio" which could be construed to apply to audio-to-video crosstalk components. The requirement is based upon the ratio between the peak-to-peak signal voltage and the peak-to-peak interferring tone voltage (excluding power supply hum and its harmonics). The standard specifies a ratio of 60 db for all tones from 1000 Hz to 4.3 MHz, and if two or more non-harmonically related tones are present, the ratio of peak-to-peak signal to combined rms tone voltage is required to be at least 69 db. When two or more harmonically related tones are present, their combined peak-to-peak level shall not exceed the 60-db standard of the fundamental frequency.

A theoretical source of intermodulation induced crosstalk is found to exist between the audio subcarrier and the video signal components in the upper section of the video baseband (i.e., the 3-to 4-MHz region). These signal components are expecially prevalent in color TV transmission. Intermodulation between the 6-MHz audio subcarrier and the modulation sidebands of the 3.58-MHz color subcarrier could produce second and third order components in the vicinity of 2.4 and 1.2 MHz, respectively. Similar intermodulation products at other video frequencies could be generated with the 4.5-or 7.5-MHz audio subcarriers. None of the testing done on the ATS system indicated that this type of intermodulation crosstalk is present. A special experiment conducted using the 6-MHz subcarrier and the 3.6-MHz color carrier for the test signals was inconclusive in that discrete intermodulation components could not be successfully identified above the general noise level.

1.3.4.2 Waveform Distortion

Requirements at the video interconnection points for the transmission of television signals over long distances have been recommended by the CCIR*. These recommendations are given in terms of a hypothetical reference circuit for intercontinental/international television circuits as well as for specific television systems. These recommendations are used to evaluate the video channel waveform distortion in the ATS communications satellite experiment.

Requirements from the CCIR recommendations previously noted, which apply to the waveform characteristics of the transmitted television signal, are summarized in table 1.44 for both International and System M (Canada and the U. S. A) television links. Table 1.44 also summarizes the measured performance of the ATS video channel for these same waveform characteristics.

LINEAR WAVEFORM DISTORTION

Linear waveform distortions are transmission deviations caused by improper compensating gain and phase equalization. Some of the more common symptoms of this type of distortion are streaking, smearing, edge effect, and ringing.

The amplitude-frequency characteristic (baseband frequency response) is one of the steady state characteristics used to evaluate linear waveform distortion. Figure 1.42 presents the measured baseband response of the ATS video channel. In addition, this figure shows the typical response characteristic of the ATS receiver 4.2-MHz video low-pass filter as well as the CCIR recommended design objectives for this characteristic. It is evident that the baseband response is well within the design objectives for the international television circuit. This indicates that linear waveform distortion should also be within CCIR recommended limits for the international television circuit. However, neither the measured response nor filter response meet the more stringent CCIR design objectives for System M(Canada and the U. S. A.) at the high frequency end of the baseband. This is to be expected since the ATS video channel must also accommodate a 6.0 MHz-audio subcarrier.

Linear waveform distortion is further evaluated at the high frequency end of the baseband from the short time waveform distortion characteristic. By transmitting a sine-squared pulse of 0.125-microsecond half-amplitude duration (T-pulse), system performance in the region about 4.0 MHz can be evaluated in terms of amplitude, duration, ringing, and overshoot of the output pulse. Figure 1.45 is typical of the input and output pulses for the ATS video channel. There is a small increase in the half-amplitude width of the received T-pulse but no significant change in pulse amplitude. The first overshoot (negative) trailing is 3.0 percent and the ringing frequency is approximately 4.0 MHz. The mean of numerous measurements indicates the overshoot is nearer 6 percent (part of this distortion is attributed to the S/C). At no time has the overshoot exceeded 13 percent. The gradual roll-off of the baseband frequency response at the high frequencies indicates that overshoot

*XIth Plenary Assembly, Oslo, 1966, Volume V, Recommendation 421-1.

should not be excessive and this is supported by the above data. Thus, the system response to a T-Pulse is within the CCIR recommended limites for both the international television circuit and System M (Canada and the U.S.A.). The line-time waveform characteristic, figure 1.46, also indicates satisfactory high frequency characteristics. There is very little overshoot and no observable ringing following abrupt transitions of the received waveform.

The low frequency portion of the baseband frequency response again does not meet the CCIR design objectives for System M but is well within design objectives for the international television circuit. The effect of the difference, if any, can be evaluated from the line-time and field-time waveform distortion characteristics shown in figures 1.46 and 1.47, respectively. Field-time waveform distortion shows response of the system to a square wave at the field rate of 60 Hz where the slope of the horizontal white level portion of the square wave indicates the amount of distortion. The mean measured line time waveform distortion is 1 percent. The field-time waveform distortion easily meets the CCIR limits for the international television circuit and for System M (Canada and the U.S.A.). The line-time waveform distortion is well within the limits for the international television circuit but is near the limits recommended for System M (Canada and the U.S.A.).

The remaining steady state characteristic used to evaluate linear waveform distortion is the baseband envelope delay. This in effect describes the phase-frequency characteristic of the ATS video channel since delay is the derivative of phase with respect to frequency. Figure 1.43 shows the baseband envelope delay for the ATS video channel as well as the 4.2-MHz video low-pass filter delay characteristic.

Although the actual measurement of envelope delay is somewhat limited in that available test equipment requires a rather high signal-to-noise ratio, the mean of all measured data defining the ATS video channel envelope delay curve falls well within the CCIR design objectives for System M (Canada and the U.S.A.). The design objectives for the international television circuit, although not shown, will also be met since they are considerably less stringent than for System M. The measured delay and 4.2-MHz filter delay characteristics are quite similar indicating that the envelope delay is primarily a function of this filter except for the effects of receiver elements following this filter.

The fact that the ATS video channel baseband phase characteristic does not produce serious linear waveform distortion is also supported by the analysis of the various test waveforms. In particular, the T-pulse used to measure short time waveform distortion shows good symmetry of the main pulse and the ringing lobes. As previously noted, the horizontal bar portion of the transmitted square wave shows negligible distortion.

Some general conclusions can be drawn concerning linear waveform distortion in the "flat, or non-emphasized ATS video channel. The baseband amplitude and phase characteristics as well as linear waveform distortion characteristics are within CCIR recommendations for the international television circuit. The ATS video channel will meet partially the CCIR recommendations for System M (Canada and the U S. A.). It is believed that the poor response occurs principally in the station cabling and baseband equipment, contributions from the satellite repeater being secondary. In particular, the 4.2-MHz video low-pass filter, and circuit elements following this filter determine the phase and frequency response.

LINEAR WAVEFORM DISTORTION (Pre/De-Emphasized Baseband)

A limited number of tests have been performed to determine the effects of the pre-emphasis/de-emphasis networks on the linear waveform characteristics of the ATS video system.

In the baseband frequency response tests, the results indicate that the pre-emphasis/de-emphasis networks have little effect on the baseband low frequency end, but towards the upper frequency end of the baseband, the attenuation increases gradually to approximately 0.5 db, relative to the results obtained when the networks are not used. However, the baseband frequency response is still within the CCIR design objective limits for international television circuits.

The use of pre-emphasis/de-emphasis networks in the short-time linear waveform distortion measurements results in a slight increase in the overshoot of the output pulse, relative to the results obtained with no networks. The increase in overshoot due to the pre/de-emphasis networks, using the ATS-3 S/C, amounts the approximately 1.6 percent. Considering that the aggregate results of tests of the S/C loop with no pre/de-emphasis networks were approximately 5.8 percent, maximum overshoot remains well within the CCIR recommended limit of 13 percent.

The effect of using pre-emphasis/de-emphasis networks in field-time and line-time linear waveform distortion tests is negligible, at best. Results of the field-time tests showed an apparent improvement of about 9 db in the RF loop configuration and about 6 db in the S/C loop configuration when using the pre/de-emphasis networks. This apparent improvement was found to be due to the presence of 60 Hz hum on the displayed waveform. (A discussion of 60-Hz hum when using pre/de-emphasis networks is given in paragraph 3.5.2). Since the de-emphasis networks actually enhance the 60-Hz hum, the results of the field-time linear waveform distortion tests using pre/de-emphasis networks make this parameter marginal, at worst, with respect to the limits recommended by the CCIR for System M (Canada and the U.S.A.) and well within the CCIR recommended limits for international television circuits.

Results of the line-time tests showed no significant change of this parameter by the use of the pre/de-emphasis networks. The line-time linear waveform distortion is still well within the 5-percent limit recommended by the CCIR for international television circuits and slightly exceeds the 1-percent CCIR limit for System M (Canada and the U. S. A.).

In the envelope delay versus baseband frequency tests, the use of pre-emphasis/de-emphasis networks does not significantly change the results, relative to the results obtained with a flat baseband, except at frequencies below 1.5 MHz where these networks cause an increase in the envelope delay variation. Nevertheless, the ATS video system easily meets the delay variation limits recommended by the CCIR for System M (Canada and the U. S. A.).

It is concluded that the use of pre-emphasis/de-emphasis networks, in performing the linear waveform distortion tests, do not significantly change the distortion chaaracteristics relative to the results obtained without these networks. These results are not surprising since the addition of passive pre-emphasis and de-emphasis networks should have minimal impact upon the linear waveform response characteristics provided the two networks are nearly complementary in amplitude and phase versus frequency.

NON-LINEAR WAVEFORM DISTORTION

Non-linearities in the ATS video channel can occur in the baseband, IF, or RF equipment and are referred to as line-time non-linearity distortion. Non-linear transfer functions in the baseband amplifiers or the FM modulator and demodulator produce one form of non-linearity distortion expressed as differential gain. A non-linear phase-frequency characteristic in the RF/IF equipment produces a second form of non-linearity distortion expressed as differential phase. Both of these characteristics require close control in order to transmit color and thus, evaluate the ability of a video channel to transmit color television.

Differential gain in the ATS video channel is evaluated by transmitting a stair-step line pattern with a low level 3.58-MHz subcarrier superimposed on each step. The typical received signal, after passing through a high pass filter, is shown in figure 1.48. Differential gain, determined from the maximum and minimum amplitudes of the 3.58-MHz bursts, varies between 18.7 and 19.5 percent depending on average picture level (10 percent, 50 percent, and 90 percent). This meets the CCIR recommendation for the international television circuit (20 percent) but fails to meet the CCIR recommendation for System M (Canada and the U. S. A.) (13 percent). (Only 10 percent is allowed for color TV (System M) in Japan.)

Differential phase is evaluated by means of a vectorscope presentation. This presentation, figure 1.49, shows the vector angular (phase) displacement with respect to the color subcarrier for the six color vectors: red, green, blue, yellow, cyan, and magenta.

CCIR Report 407* (part A1.1.6) is applicable to this test. The allowable phase displacement and amplitude variation for each color vector is ±10 degrees and ±20 percent, respectively. Measured phase displacement has in general been less than 3.5 degrees and amplitude variations less than 7 percent.

Although this indicates satisfactory linearity in the phase response characteristic, an analysis of the effects of differential doppler shows that a larger phase displacement can be expected twice during the 24-hour synchronous orbit period. Based on a maximum range rate of 6 feet per second, it can be shown that the color vector amplitude variation will be negligible while phase displacement can reach 5.8 degrees, depending on the color. Since each color vector would be displaced in the same direction, compensation is possible with the hue control. A fixed adjustment can be made allowing the phase to vary ±5.8 degrees, or a number of adjustments can be made during the synchronous orbit to maintain in phase variation within smaller limits.

Another factor to be considered is the ATS-1 satellite 1.6-Hz phase modulation due to variations of the satellite phase center. The analysis given in section 7.6 shows that the peak frequency deviation due to this factor slightly exceeds 0.001 Hz. The effect on color vector phase displacement is not considered significant since the resultant phase displacement will be less than one degree for any color vector.

It is concluded that although non-linearities exist, the ATS system is capable of meeting the CCIR recommended international limits for line-time non-linearity distortion, and for color vector phase and amplitude distortion. However, line-time non-linearity distortion is near the maximum allowed on international links and is well above the limits established for U. S. and Canadian TV relay systems. Nevertheless, no degradation in color picture fidelity has been observed during the many subjective tests and demonstrations discussed in paragraph 1.3.6 of this section.

NON-LINEAR WAVEFORM DISTORTION (Pre/De-emphasize Baseband)

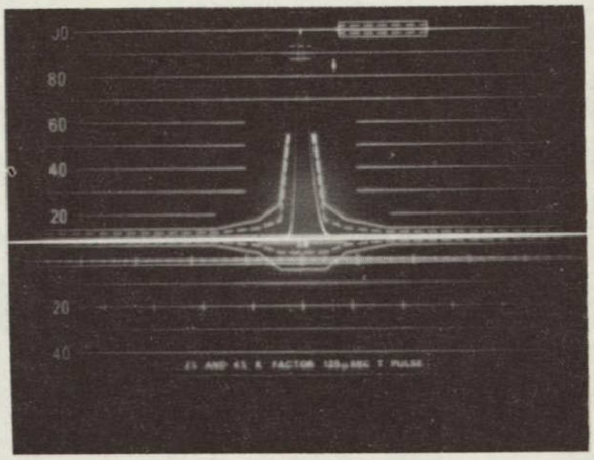
Non-linear waveform distortion tests were also conducted using pre-emphasis/de-emphasis networks. It is expected that the use of these networks should show a significant improvement in the differential gain and phase of the ATS video channel. Since the transmitter pre-emphasis network reduces the deviation of the relatively high energy, low-frequency signal components, the system loading, by the horizontal line sync pulses and the stairstep sawtooth, is considerably reduced and relative system deviation by the color subcarrier is increased. Thus, effective "modulation" of the subcarrier by the low frequency components is reduced and the distortion introduced by RF-IF phase and amplitude non-linearities is diminished. The use of pre/de-emphasis networks in the line-time non-linearity distortion

*XIth Plenary Assembly, Oslo, 1966, Volume V.

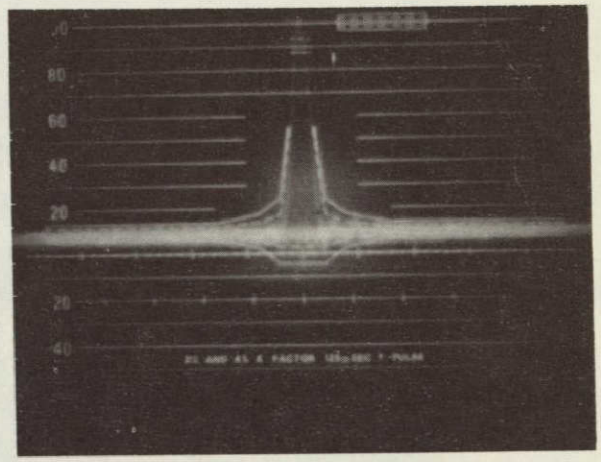
test results in improvements of 12 db or more for 10-percent, 50-percent, and 90-percent average picture levels over the results obtained with non pre/de-emphasis networks. Therefore, with the use of these networks, the ATS video system differential gain easily meet the more stringent 13 percent CCIR limit for System M (Canada and the U.S.A.).

In the color vector amplitude and phase distortion tests, the use of pre/de-emphasi networks results in greatly improved phase and amplitude variations relative to the same tests performed with non emphasis networks. The CCIR recommended limits of ±10 degree phase variation and ±20 percent amplitude variations are easily met by the ATS video channel even without the use of pre-emphasis/de-emphasis networks, but their use is effective in response improvement as seen from table 1.44.

In summary, the use of pre-emphasis/de-emphasis networks is found to be very effective in holding system non-linear waveform distortions to minimum values. This result indicates that the major portion of this distortion occurs in the RF/IF or modulator/demodulator portions of the system.



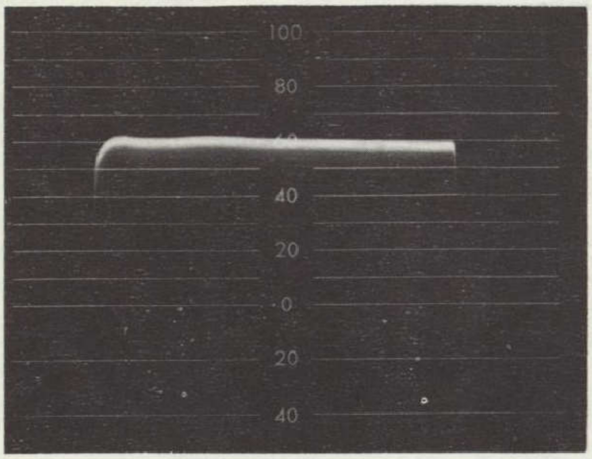
TRANSMITTED T-PULSE



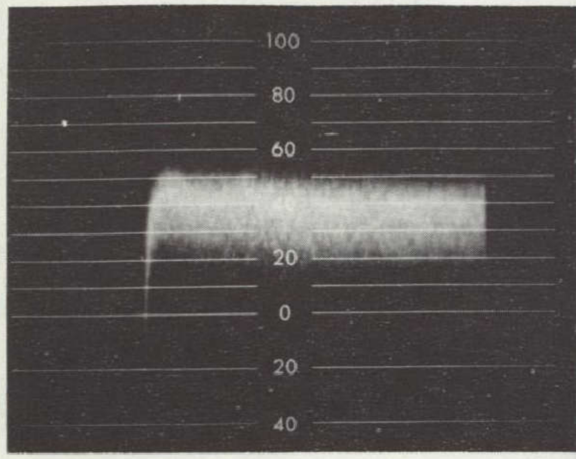
RECEIVED T-PULSE

MOJAVE 8 NOV. 1968

Figure 1.45. Video Channel Short-Time Linear Waveform Distortion (T-Pulse)



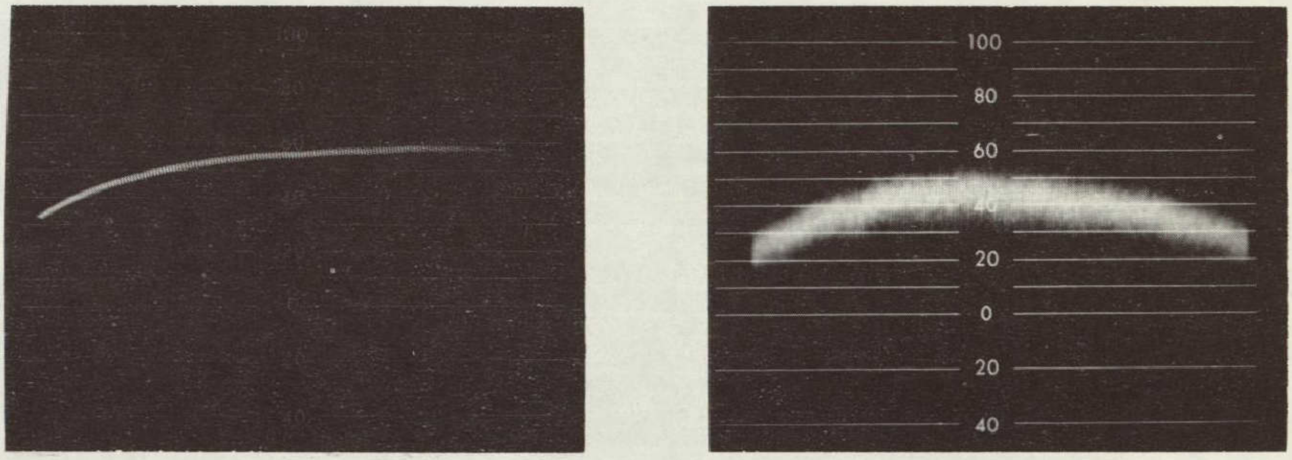
TRANSMITTED WINDOW PATTERN



RECEIVED WINDOW PATTERN

COOBY CREEK 2 NOV. 1968

Figure 1.46. Video Channel Line-Time Linear Waveform Distortion

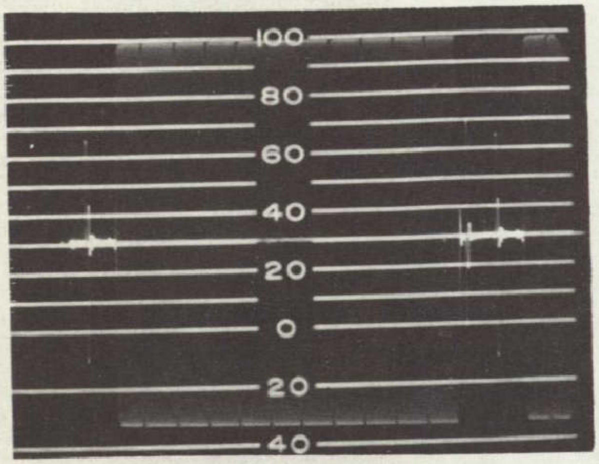


TRANSMITTED WHITE LEVEL
PORTION OF WINDOW PATTERN

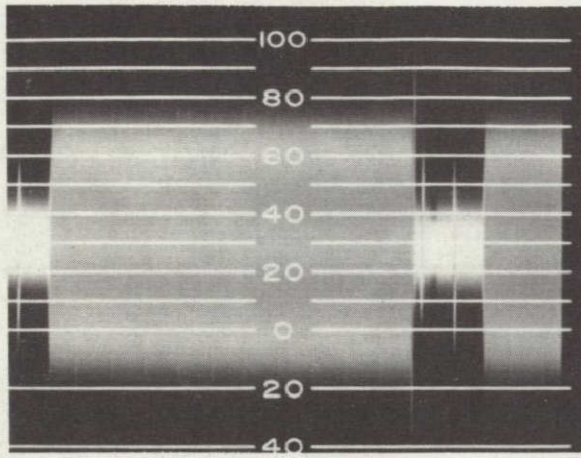
RECEIVED WHITE LEVEL
PORTION OF WINDOW PATTERN

COOBY CREEK 2 NOV. 1968

Figure 1.47. Video Channel Field-Time Linear Waveform Distortion



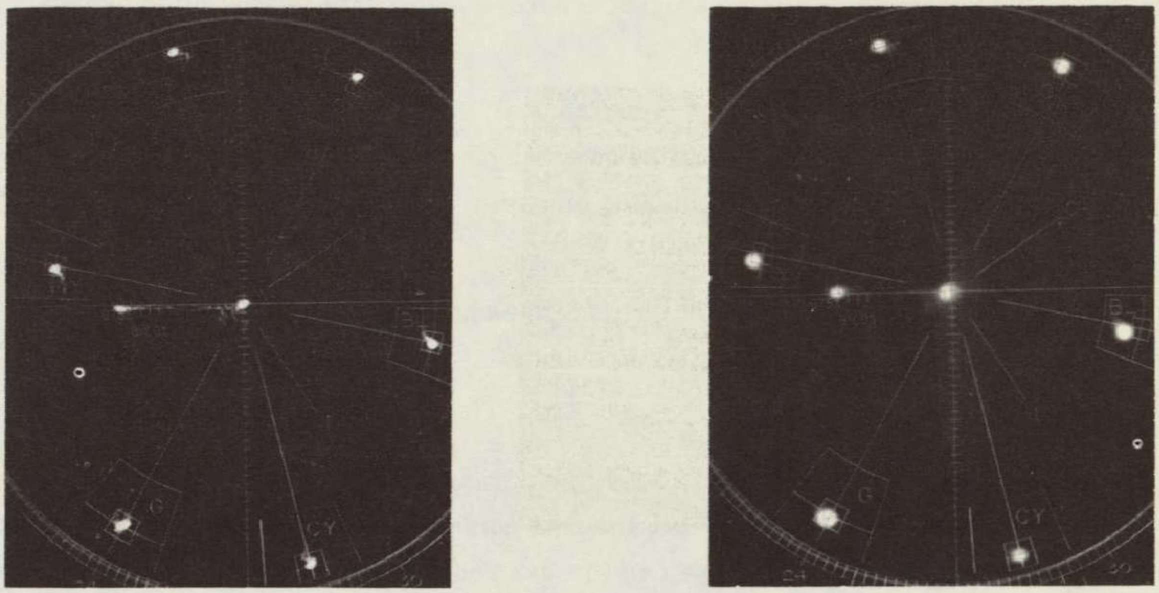
TRANSMITTED STAIRSTEP
PATTERN DISPLAYED
THROUGH HIGH PASS FILTER



RECEIVED STAIRSTEP
PATTERN DISPLAYED
THROUGH HIGH PASS FILTER

COOBY CREEK 1 NOV. 1968

Figure 1.48. Video Channel Line-Time Non-Linearity Distortion



TRANSMITTED RECEIVED

ROSMAN 31 OCTOBER 1968

Figure 1.49. Video Channel Color Vector Phase and Amplitude Variations

1.3.5 AUDIO CHANNEL PERFORMANCE

1.3.5.1 Noise

Television audio, or program channel, performance as limited by noise, is based on four types of sources of noise:

1) Continuous random noise (thermal)
2) Periodic noise (usually power supply hum)
3) Impulsive noise (switching or power transients)
4) Crosstalk

These sources are defined below in terms of the signal-to-noise ratios required or suggested to meet certain standards or user requirements.

CONTINUOUS RANDOM NOISE

The signal-to-noise ratio for this parameter is defined as the ratio, expressed in decibels, of the rms test tone level to the rms noise level measured on a flat or unweighted basis in the program channel. The CCITT* has recommended that the absolute rms noise voltage level, when referred to a point of zero relative level, should not exceed -52 db. The circuit noise referred to in this document is all types of sources except crosstalk. The Electronic Industries Association standard RS-250A recommends that the audio channel signal-to-noise ratio should be at least 55 db for a multi-hop relay system, and 58 db for a single hop system. This latter document is primarily intended for studio to transmitter links, and it defines noise as any extraneous output voltage in the frequency band from 50 Hz to 15 kHz. These references, while not directly applicable to a system such as the ATS, are nevertheless useful for comparison purposes and as a guide for establishing system requirements.

The ATS system design is illustrated in block diagram form in figure 1.40. This diagram shows that the audio is inserted directly onto the baseband (as a modulated subcarrier) along with the video signal. The system deviations and bandwidths were chosen such that the expected signal-to-thermal noise ratio would be as shown in the last line of table 1.43. This table is computed on a flat system basis with no pre-emphasis or de-emphasis.

Comparison of the system performance expectations from the Tabel to the above reference CCIR recommendation of 52 db indicates nine of the twelve ATS configurations reach this level. If a comparison is made with the 55-db allowance for multi-hop systems of the EIA, we find that five of the 12 variations reach this level. Obviously, variations in system design influence this parameter. For example, changes in subcarrier and main

*Addendum No. 1 to Volume V of the CCIR, Oslo 1966 - Study Program 5A/CMTT carrier deviation and uplink transmitter power levels can be implemented which would act to increase the signal-to-thermal noise ratio. However, the lengths to which this can be practiced is limited by the compromising influence of other factors such as crosstalk and intermodulation noise.

Therefore, it may logically be concluded that an adequate satellite relay system for television video and its accompanying audio channel is provided by the ATS. This statement is based on the assumption that other sources of noise in the audio channel are relatively insignificant compared to the thermal noise level. The system adequacy is especially proven for the ATS-3 and equivalent spacecraft whose EIRP's are 54 dbm or greater, since in these cases a 40-foot earth station antenna will suffice. Numerous measurements of audio channel signal-to-idle noise have been made on the various earth station-satellite configuration. This parameter has been checked on both a flat and pre-emphasized basis. The actual measured value was found to agree within 1.5 db with the theoretical value listed in table 1.43. Furthermore, concurrent measurements of carrier-to-noise in the 70-MHz IF were found to verify the accuracy of the bandwidth and deviation factors listed in table 1.43.

PERIODIC NOISE

This noise source applies only to single frequency interfering signals as most generally caused by power supply hum at its fundamental frequency and its lower order harmonics. The signal-to-noise ratio for this parameter is defined as the ratio in decibels of the rms audio test tone level to the rms level of the interfering periodic noise signal.

There is no standard which specifically applies to periodic noise in a program channel. This aspect of the overall noise problem is covered in the suggested limits referenced in the Continuous Random Noise paragraph above. The system measurements referenced above also obviously included the 60-Hz fundamental and its harmonics in the idle channel measurement. However, in order to verify that the idle channel noise is primarily caused by thermal limitations, a wave analyzer search was made in the program channel looking for periodic noise components. These measurements were conducted several times at all three ATS stations, and with a few exceptions, the signal-to-periodic noise ratio was found to be greater than 55 db. It was also found that periodic signals other than 60 to 120 Hz were practically non-existent Most of the test measurements did not list a numeric value but merely stated that the 60-and 120-Hz components were each greater than 55-db below-audio test-tone level. In a few cases, where actual quantitative values were given, the power supply hum components were seen to be from 60 to 70 db down. Further verification of these orders of magnitude is seen in the paragraphs above on Continuous Random Noise where the measured S/N was found to compare closely to the caluclated value. Since the measured values included the effects of periodic noise, and since the measured values included the effects of periodic noise, and since the measured values frequently ran well over 50 db, the actual level of power supply hum components must be approaching 60 db or more, below audio test tone.

IMPULSIVE NOISE

This type of interference can be caused by switching transients, primary power line surges, or by direct pickup from outside sources. Because of the more limited bandwidth, the audio channel is not as susceptible to impulsive interference from external sources such as the video channel. Also, because of the wide variety of sources, types, and noise waveform characteristics, no attempt has been made to measure or evaluate this parameter in the ATS system. Each relay system will be different in its exposure and response to impulsive interference. There is no evidence that impulsive noise is a problem in the TV audio channel. It is concluded that the configuration of the ATS system is not subject to impulsive noise degradations.

CROSSTALK

For the purposes of this discussion, crosstalk is defined as the presence of extraneous signals in the audio program channel which are caused by signals of the video channel. In a television relay system such as the ATS, this crosstalk can originate in two ways. First, it may originate as an intermodulation, or cross-modulation, product between the audio channel subcarrier and a periodic component in the video signal such as the 60 Hz field sync pulses or the 15.75-kHz line sync pulses. Secondly, it may be the result of direct leakage or coupling between the circuits and cables of the two channels.

There is no directly applicable standard from which to judge this parameter. The previously referenced Study Program 5A/CMTT of the CCIR requires that the "near-end or far-end crosstalk attenuation for speech between two high-quality wideband circuits for program transmissions, or between a circuit of this type and any other circuit used to relay program transmissions, or between such a circuit and a telephone circuit, should be at least 78 db on cable lines and at least 61 db on open wire lines". This recommendation obviously covers program channels in the telephone network and does not apply to the video/audio transmission system under study and discussion. Nevertheless, the recommended values are useful for comparison purposes. However, the aforementioned EIA standard RS-250A is a more appropriate reference since it deals with radio relay equipment for an application similar to the ATS and specifically notes that it applies to circuits that are "common to the audio and video signals". It also sets a requirement of 55 db S/N ratio for multi-hop systems where the noise is " any extraneous output voltage in the frequency band from 50 Hz to 15 kHz". In addition, the document requires that the S/N measurements be made while relaying a standard composite picture signal under standard input and output conditions.

The above discussed measurements of random (thermal) and periodic noise were made on an idle system basis; i.e., with no video signal present in the system. It was seen that thermal noise alone could frequently cause the audio-channel S/N ratio to be less than 55 db. It was also found that periodic noise in the idle channel (principally power supply hum components) could generally be expected to the 60 db or more below test tone level. Thus, if crosstalk noise (video into audio) is not to be a significant factor, it too will have to be at least 60 db or more, below test-tone level. Wave analyzer searches in the audio channel have shown that 60-Hz crosstalk components from the video field rate sync pulses are from 40 db up to 55 db or more, below test-tone level. However, line-rate crosstalk at 15.75 kHz was quite frequently found to be only 35 to 40 db down. Since this interfering signal was outside of the required audio passband. A notch filter tuned to the 15.75 kHz interfering frequency was installed in the receiving side of the system and subsequent measurements showed this crosstalk signal to be down at least 70 db.

Nothing could be done about the 60-Hz component as it was within the channel passband. When the video channel was energized with a test pattern or other video waveform, there was a general increase in interference induced into the audio channel. A voltmeter connected to the idle audio channel showed an increase of 6 to 8 db over the idle system noise level, but a wave analyzer search of the channel failed to locate discrete components whose sum equals the level required to account for this increase. When video pre-emphasis was applied to the system the crosstalk problem disappeared. The former 6-to 8-db increase in noise level under the influence of a video signal dropped to 0.5 db or less. This means that the video-to-audio crosstalk components must decrease to a level at least 10 db or more below idle channel (primarily thermal) noise. This indicates a total improvement approaching 20 db, and since adding video pre-emphasis reduces the low frequency deviation of the transmitter by 10 db, the predominate crosstalk problem is caused by the parabolic component of the differential phase which introduces intermodulation distortion into the system. It is concluded that the incorporation of video pre-emphasis techniques is effective in eliminating crosstalk problems, and thus the primary limitation to achieving the desired channel S/N ratio of at least 52 db is the system thermal noise level.

1.3.5.2 Waveform Distortion

The waveform distortion characteristic of the television audio channel is determined by its linear and non-linear responses. The first of these is primarily a function of its amplitude versus frequency response characteristic, while the second is a measure of the harmonic distortion present in the channel.

LINEAR WAVEFORM DISTORTION

This distortion characteristic of an audio program channel is the result of improper gain and phase equalization across the channel bandpass. The human ear is largely insentive to phase variations, and since data signals are not expected to be relayed via this channel, no measurements of the phase delay characteristics have been made. The amplitude versus frequency response is an important characteristic of a program channel. The CCITT has recommended that the frequency band effectively transmitted should extend from 30 Hz to 15 kHz. The suggested limits within this band are as shown in figure 1.44. This figure also shows the typical response obtained in the audio channel after the addition of the 15.75-kHz notch filter referenced in the above section. The sharp roll-off in the response above 12 kHz is primarily caused by this notch filter. The 3 db down point is now approximately 13 kHz instead of the former 15 kHz. This change is considered to be relatively insignificant, and the channel high frequency response is adequate for program transmission purposes. The channel low frequency response is seen to be about 1 db or less out of the referenced CCITT limits (Oslo 1966) at 50 Hz. However, the response is well within the earlier recommendations in effect at the time of equipment procurement. This latter document allowed a response of -2.6 db at 50 Hz and -4.35 db at 30 Hz, both referenced to the test tone level at 800 Hz. In any event, the low-frequency response is judged to be satisfactory for its purpose; and since the deficiency is entirely within the ground equipment, a relatively small-circuit modification could easily be incorporated which would boost the bass response if desired.

NON-LINEAR WAVEFORM DISTORTION

A recent CCITT suggestion from study program 5A/CMTT of Oslo 1966 has recommended a THD of 3 percent for fundamentals from 50 to 100 Hz, one percent from 100 to 7500 Hz, and 3 percent again for fundamentals between 7500 to 15000 Hz. This parameter has been measured several times via both ATS-1 and ATS-3. The average values obtained were 3.3 percent at 100 Hz, 3.1 percent at 1 kHz, and 2.3 percent at 5 kHz. Many of the measurements were made with an analyzer-type instrument which notches out the fundamental and reads all undesired signals remaining in the passband. As such, the resulting reading is more a loaded channel signal-to-noise ratio than a total harmonic-distortion reading. However, as previously seen, thermal noise and power supply hum are generally at least 40 db (1%) or more, below test tone level. Thus the harmonic distortion readings obtained, although somewhat higher than desired, are nevertheless considered to be representative of typical audio-system performance.

1.3.6 SUBJECTIVE TESTS AND DEMONSTRATIONS

The previous paragraphs of this section have evaluated the video picture quality by quantitative measure, related to established standards. However, the purpose of these tests, and that of the ATS TV system is to transmit audio and video information from one point to another with a reception quality that is acceptable to a high percentage of the viewers. Therefore, it is reasonable to consider the ATS TV performance by means of subjective evaluations.

Following the subjective test analysis is a summary of some of the more important demonstrations relayed over ATS.

A monochrome test pattern analysis experiment has been used to evaluate subjectively the monochrome television picture quality of the ATS system. In this experiment an EIA test pattern signal was used to drive the FM transmitter. The transmitted signal, after passing through the satellite, was received and displayed on a television monitor. This displayed image of the EIA test pattern was then examined by the site operators to rate the following parameters: resolution, streaking, smearing, ringing, ghosts, noise, and interference. Picture quality is high when resolution is high, and the effects of the other listed parameters are negligible.

Since this test was subjective in nature, different operators may have graded, or rated, parameters of the same display differently. Even the same operator may on different occasions have assigned different parameter values to the same quality presentation. It should be understood that test patterns of this type are used because of their ability to indicate system deficiencies which the observer may not be aware of while observing a normal picture. Also, trained technicians and engineers would, in all probability, be somewhat more critical than the average viewer. Resolution ratings will not be examined since many of the ratings obtained in the past were inconclusive. Based on subjective tests, ATS resolution is considered adequate and comparable to commercial television systems. The parameter rated poorest by the site operators was "noise". No noise was reported in 58 percent of the tests; severe noise was reported in 12 percent of the tests; and the remaining tests were reported to have moderate noise. All of the remaining picture parameters were rated as "NONE" in at least 90 percent of the tests.

Although there are occasional inconsistencies, it is felt that the parameter ratings for nearly all of the monochrome picture analysis tests indicate a high quality picture. It would appear that picture deterioration is caused by noise more often than any other parameter.

Numerous television demonstrations have been relayed over the ATS system and all have been judged subjectively to be of excellent quality. A partial list of these demonstrations includes:

Event	Link
1) Expo 67-Australian Day	U.S. to Australia
2) Our World	U.S. and Japan to Australia
3) America's Cup Race	U.S. to Australia
4) Italian President's Visit	Australia to U.S.
5) Japanese Prime Minister's Visit	Australia to Japan
6) President Johnson's Visit	Australia to U.S.
7) Davis Cup Tennis	Australia to U.S.
8) 1968 Olympics	U.S. to Japan
9) Apollo 8	Pacific Ocean to U.S./Japan/Australia
10) Pope Paul's Visit	Colombia to Europe
11) 1968 World Series	U.S. to Puerto Rico
12) Apollo 7	Atlantic Ocean to U.S.
13) 1968 Olympics	Mexico to Europe
14) 1968 Election Returns	U.S. to Europe
15) Apollo 10	Pacific Ocean to U.S.

These demonstrations represent the video portion of the programs only. The networks involved usually arrange several options for the audio and choose the one which gives the best results at program time. The audio may be transmitted via the 6-MHz audio subcarrier in the ATS system, land line, VHF link, or another satellite such as Intelsat For some demonstrations, the 6-MHz audio subcarrier carried the background program while the commentary was transmitted independently of the ATS system.

Figures 1.50, 1.51, and 1.52 are representative photographs of picture monitor presentations which demonstrate the high picture quality obtainable with the ATS system. Figure 1.52 shows a live broadcast presentation. The other photos were obtained from video recordings of received broadcasts. Although some deterioration occurs in the recording and photographic processes, high resolution remains apparent in all of the photographs. Figure 1.51 also shows excellent flesh tone characteristics as well as vivid colors.

Subjective tests and numerous international demonstrations substantiate that the ATS system is capable of producing high quality, low distortion video pictures.

Figure 1.50. Prime Minister Sato's Visit to Australia, October 12, 1967 (ATS-1)

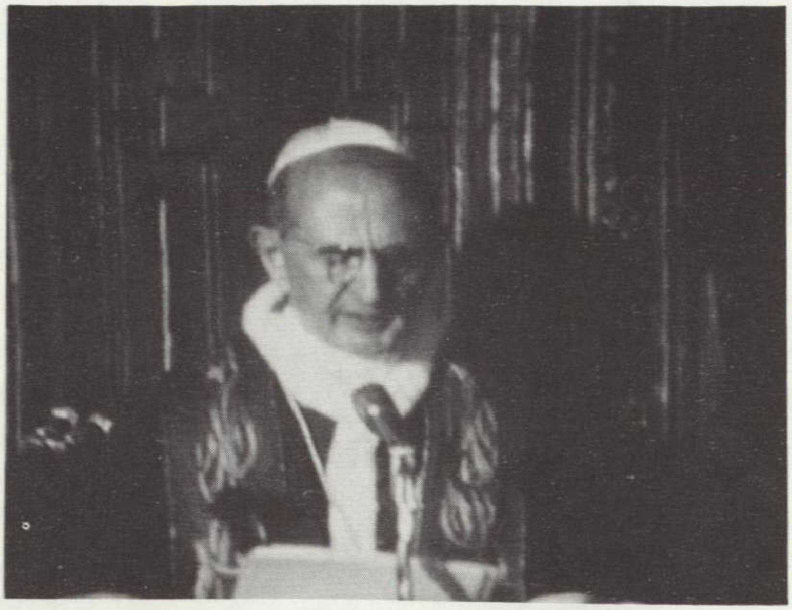


Figure 1.51. Pope's Visit to Colombia, 24 August 1968

Figure 1.52. Test For Apollo 9 Recovery, March 1969

1.4 FREQUENCY TRANSLATION MODE (FM/FM-FDM) MULTIPLEX

1.4.1 INTRODUCTION

The objective of the FM/FM-FDM Mode experiment is to evaluate the performance characteristics and usefulness of SHF as a medium for wideband FDM telephony transmission for selected combinations of earth stations and satellite EIRP values. The performance characteristics of test tone-to-noise ratio (TT/N) and intermodulation distortion are evaluated under loaded and idle conditions in order to simulate actual operational conditions. The test data is then used to determine the loaded and idle noise characteristics. Data error rate and multiplex channel frequency stability are also analyzed.

The technique used is single access in that the spacecraft (S/C) transponder is available to only one earth station at a time; all earth stations may receive, but only one may transmit. Since there are two transponders on the S/C, full duplex operation between two earth stations is possible; however, this evaluation is concerned with single access only.

The results of single station tests (one station receiving its own transmission via the S/C) are sufficient to determine the single access channel characteristics. The data is used to determine the characteristics of the FM/FM-FDM mode satellite communication system, and thus provide a valuable input for the design of future systems. This data is especially pertinent when it is considered that most existing and proposed operational satellite communications systems use the FM/FM transmission technique.

The FM/FM-FDM mode performance is evaluated where applicable by comparison of actual performance with CCIR recommended user requirements. In particular, CCIR recommendation 353-1 (Oslo, 1966) is used to define the recommended user TT/N in an FDM satellite communication system (as described in the hypothetical reference circuit defined in CCIR recommendation 352).

The idle TT/N and the loaded TT/N are especially important parameters since these define the operational limits of the system. The idle TT/N defines the limitation in TT/N which exists in an FCM channel when the noise is due solely to thermal and threshold effects (i.e., the carrier is unmodulated).

The idle TT/N measured for various conditions of spacecraft EIRP and earth station G/T are shown plotted with a family of theoretical earth station G/T curves. The theoretical G/T curves represent earth station performance when all of the idle noise is due to thermal effects (no threshold noise or other components are considered), and thus provides a basis of comparison between the ATS system and other state of the art systems which may utilize different types of demodulators.

The loaded TT/N measurements are compared with predicted values for various system configurations. Also, the idle and loaded TT/N ratios are compared with each other for each particular system configuration in order to determine the effects of modulation on the channel performance.

The effect of pre/de-emphasis is shown graphically for one particular station (both CCIR recommended pre/de-emphasis, and 6 db/octave).

The noise characteristics of the FM/FM-FDM baseband spectrum are presented in terms of thermal, threshold, and modulation noise. The relationship of the various components to the receiver IF C/N is developed. It is shown that at a C/N greater than 10 db, the thermal noise in the baseband increases as the square of the baseband frequency, and is completely determined from idle channel measurements (either TT/N or TPR). At C/N ratios of 10 db and less, the threshold noise components become predominant (especially at the low end of the baseband spectrum). The threshold noise is divided into two components, one relating to idle channel conditions (carrier unmodulated) and one relating to loaded channel conditions. The modulation noise is also composed of two components; one due to system nonlinearities which are independent of receiver C/N ratio, and a threshold effect which bears a nonlinear relationship to receiver C/N ratio. A technique is developed for determining the non-linear noise characteristic from basic system tests (i.e., NPR/TPR, and multitone tests). A further technique relating intermodulation distortion to basic system parameters (IF/RF amplitude and phase response) is developed in section 7.7.

Multiplex channel frequency stability is analyzed and compared with CCITT requirements. The maximum frequency excursion in a multiplex channel due to satellite doppler is developed.

Finally, data is presented, evaluating the quality of frequency shift keyed (FSK) digital transmission obtained in a standard FDM voice channel.

1.4.2 MODE DESCRIPTION

1.4.2.1 General

FDM terminals are installed in each of the three ATS earth stations which are located at Rosman, North Carolina; Mojave, California; and Cooby Creek, Australia. The system utilizes the ATS satellites to conduct single station tests. Two satellites (ATS-1 and ATS-3) are used for the FDM system experiments. The satellites are in synchronous orbit with their subtrack points located in the Pacific and Atlantic Oceans, respectively. The ATS-1 satellite is within mutual visibility of all three earth stations; however, only Rosman and Mojave are visible to the ATS-3 satellite.

The Mojave and Cooby Creek stations each use a 40-foot-diameter antenna for transmit and receive, while the Rosman station uses an 85 foot diameter antenna. The satellite communications repeaters are essentially identical; however, they have different receiving antenna gains and EIRP's (effective radiated power output relative to an isotropic antenna, see tables 1.59 and 1.60 presented in paragraph 1.4.4). As indicated above, many combinations of earth station and satellite are available, each with unique link characteristics Several of the possible combinations were used to determine the performance characteristics and usefulness of SHF for wide band FDM telephony transmission. The operating conditions of each of the particular links are presented in subsequent paragraphs.

The measurements were taken with the system noise loaded to simulate an actual FDM operational condition, as well as unloaded to determine the system loaded and idle characteristics. Tests were conducted with simulated loading of up to 1200 one-way voice channels at the Rosman station, and up to 240 one-way channels at Mojave and Cooby Creek. Tests were also conducted at the latter stations using a bandwidth corresponding to 1200 one-way channels; however, these tests may only be run using the higher satellite EIRP's so that the received signal power level is maintained above the FM threshold point (except where tests are specifically intended to determine below threshold operation).

1.4.2.2 Basic Mode Configuration

The basic FM/FM-FDM mode configuration, shown in figure 1.53, consists of a multiplex input terminal, a radio transmitting terminal, a transmission path (which includes the spacecraft), a radio receiver terminal, and a multiplex output terminal. The input signal consists of one or more voice channels (300 Hz to 3400 Hz BW each) and these are translated to the proper baseband frequency by the multiplex send equipment (as discussed more fully in paragraph 1.4.2.3). The multiplex output is combined with wideband noise to simulate the loading effect desired. The baseband signal is used to frequency modulate a microwave oscillator which is then mixed with another fixed frequency microwave oscillator to produce a 70-MHz IF which in turn is upconverted to the desired RF frequency. A traveling wave tube (TWT) amplifier is used to drive the final klystron power amplifier which provides up to 10-KW power output. The transmitter is capable of operating at either of two microwave frequencies (6212.094 MHz or 6301.050 MHz). Changeover from one to the other frequency is accomplished by changing some of the RF filters and retuning the klystron power amplifier. The output of the power amplifier is directed to the parabolic antenna via the duplexer and cassegrain feed.

As shown in figure 1.53, the spacecraft (S/C) repeater contains input circuitry which separates the input signal channels and directs them to the proper transponder. The transponder frequency-translates the received 6-GHz signal to 4-GHz for retransmission to the earth stations. The S/C repeater may operate on either channel or both channels simultaneously, thus allowing full duplex operation between two earth stations (each earth station receiving the other's transmission). Each S/C channel contains two TWT amplifiers which may be operated singly or in parallel, thereby providing a choice of two power output levels for each transponder. Each of the TWT's in the ATS-1 S/C has a nominal power output of 4 watts; TWT Nos. 1 and 2 in ATS-3 each has a nominal power output of four watts; TWT Nos. 3 and 4 each has a nominal power output of 12 watts; however TWT No. 3 has been inoperative, thus limiting the maximum S/C power output to 12 watts. The S/C diplexer routes the outputs of the TWT amplifiers to the antenna for transmission to the earth station. The FM/FM-FDM subsystem characteristics are shown in table 1.59. The S/C transmit and receive parameters are summarized in table 1.61 and detailed in paragraph in 1.4.2.3, which presents the system path calculations.

The FM receiver shown in figure 1.53 contains a low noise parametric amplifier followed by a Tunnel Diode Amplifier (TDA), except at Rosman which uses a TWT amplifier. The paramp preamplifier is cooled to a cryogenic temperature of 25°K. After passing through the TDA (or TWT) amplifier, the RF signal is downconverted to 70 MHz where it is amplified and demodulated in an FM discriminator. The baseband output from the discriminator is sent to the multiplex receive equipment where each multiplexed channel is translated to the required frequency.

A 6-GHz converter is provided to enable ground loop testing of the RF circuitry (RF loop). Figure 1.54 shows a block diagram of the RF loop. As shown, the RF signal may be sampled either before or after the power amplifier (which is terminated into a dummy load during RF loop tests). The 6 GHz FM signal is converted without demodulation to a 4-GHz FM signal for injection into the receiver preamp.

1.4.2.3 Link Calculations

ink performance calculations are presented in tables 1.45 through 1.56 for all system configurations. These include all combinations of spacecraft EIRP and earth stations (stations with 40 foot as well as 85 foot diameter antennas).

Antenna gains and free spaces losses are calculated for a ground-to-satellite carrier frequency of 6.3 GHz and a satellite-to-ground carrier frequency of 4.17 GHz and a nominal slant range of 22,000 nmi. The actual range is dependent upon the relative positions of the satellite and the tracking station and may differ as much as 2000 nmi between a ground station operating with two synchronous satellites (causing up to 0.8-db difference in path loss). Detailed procedures employed to compute factors for the FM/FM-FDM mode link calculation are contained in paragraph 7.1.

1.4.2.4 Multiplex Equipment

Figures 1.55 and 1.56 show the multiplex arrangement for stations with 1200-channel and 240-channel capability, respectively. Each station utilizes two channel banks, each consisting of twelve 3.1-kHz voice channels. Provisions are made to locate each channel bank at any point within the baseband frequency range. The channel arrangement is in accordance with CCITT rec. G211, with super groups (60-channel capability), master groups (300-channel capability), and super-master groups (900-channel capability) available to position each channel bank (12-channel capability).

The FDM equipment utilizes single sideband, suppressed carrier techniques to "stack" the voice channels in groups of twelve channels each. Referring to figures 1.55 and 1.56, the audio signal for channel 1 is used to amplitude modulate a 108 kHz subcarrier. The lower modulation sideband is filtered to provide a signal spectrum from 104.6 kHz to 107.7 kHz. In a similar manner, the channel 2 signal spectrum is limited to frequencies from 100.6 kHz to 103.7 kHz. The process is continued until all twelve channels are spaced in frequency from 60 kHz to 108 kHz (this spectrum constitutes a group). The various group signals are then used to modulate a group carrier. The process is extended to build up supergroups, mastergroups, and supermaster groups until all of the voice channels have been placed in their proper frequency location. In the FDM equipment block diagrams, a triangle is used to symbolize the filter which separates the desired sideband energy from the carrier and unwanted sideband (triangle with a positive slope indicates that the upper sideband is selected; conversely, a downward or negative slope indicates that the lower sideband has been used). It should be noted that the Rosman station (figure 1.55) uses two identical mastergroups (designated MG3) which carry information at 11156 kHz to 12388 kHz. The mastergroups form part of two separate supermaster groups which are combined to provide the total baseband. Each of the supermaster groups is a standard 900 channel system (although in the ATS system one of the supermaster groups carries only the upper frequency spectrum).

Since the ATS system is not intended to be an operational system, there is no need to be able to use the total channel capacity (1200 at Rosman and 240 at Mojave and Cooby Creek); consequently only two 12-channel groups have been provided at each terminal. Each group may be placed anywhere within the baseband as shown in the mux equipment block diagrams.

It should be pointed out that the channel subcarrier frequencies are derived from separate master oscillators for the transmit and receive terminal. This allows shifting of each unit if required for frequency corrections when operating with other stations.

The frequency response, envelope delay, and linearity of a typical multiplex voice channel are shown in figures 1.57 through 1.59, respectively. The measured responses are compared with the manufacturer's equipment specifications. The curves are presented for both the RF and S/C loops.

TABLE 1.45. FM/FM-FDM MODE, ATS-1, EARTH TO SATELLITE LINK CALCULATION

(Transponders No. 1 and No. 2)

	85' Antenna	40' Antenna
Transmitter Average Power (dbm)	60.6	67.5
Earth Antenna Gain (net) (db)	61.5	54.6
Earth Station EIRP (dbm)	122.1	122.1
Space Attenuation (db) *	-200.8	-200.8
Satellite Antenna Gain (db)	6.2	6.2
Off Beam Center Allowance (db)	-0.5	-0.5
Received Carrier Power (dbm)	-73.0	-73.0
Receiver Noise Figure (db)	6.2	6.2
Effective Receiver Noise Temperature (db°K)	31.7	31.7
Receiver Noise Power Density (dbm/Hz)	-166.9	-166.9
Carrier/Noise (in unit BW) (db Hz)	93.9	93.9

* Based on a nominal slant range of 22,000 nmi.

TABLE 1.46. FM/FM-FDM MODE, ATS-1, SATELLITE TO EARTH LINK AND OVERALL LINK CALCULATION (ONE TWT)

(Transponders No. 1 and No. 2)

	85' Antenna	40' Antenna
Satellite Transmitter Power Output (dbm)	36.7	36.7
Satellite Antenna Gain (db)	12.7	12.7
Satellite EIRP (dbm)	49.4	49.4
Space Attenuation (db) *	-197.1	-197.1
Off Beam Center Allowance (db)	-0.5	-0.5
Earth Antenna Gain (db)	58.4	51.0
Received Carrier Power (dbm)	-89.8	-97.2
Effective Receiver Noise Temp. (db°K)	20.2	18.8
Receiver Noise Power Density (dbm/Hz)	-178.4	-179.8
Receiver IF Noise Bandwidth (dbHz) **	75.5	75.5
Receiver Noise Level (dbm)	-102.9	-104.3
Carrier/Noise (in 35.5 MHz NBW) (db)	13.1	7.1 †
Receiver Bandwidth (dbHz) ***	71.9	71.9
Receiver Noise Level (dbm)	-106.5	-107.9
Carrier/Noise (in 15.5 MHz NBW) (db)	16.7	10.7
Downlink C/N_o (db)	88.6	82.6
Uplink Contribution (db)	-1.1	-0.3
Total C/N_o (db)	87.5	82.3

* Based on a nominal slant range of 22,000 nmi.
** For 1200 channel spectrum (35.5-MHz IF Noise BW)
*** For 240 channel spectrum (15.5-MHz IF Noise BW)
† Below Threshold

TABLE 1.47. FM/FM-FDM MODE, ATS-1, SATELLITE TO EARTH LINK AND OVERALL LINK CALCULATION (TWO TWT'S)

(Transponders No. 1 and No. 2)

	85' Antenna	40' Antenna
Satellite EIRP (dbm)	52.2	52.2
Space Attenuation (db) *	-197.1	-197.1
Off Beam Center Allowance (db)	-0.5	-0.5
Earth Antenna Gain (db)	58.4	51.0
Received Carrier Power (dbm)	-87.0	-94.4
Effective Receiver Noise Temp. (db°K)	20.2	18.8
Receiver Noise Power Density (dbm/Hz)	-178.4	-179.8
Receiver IF Noise Bandwidth (db Hz) **	75.5	75.5
Receiver Noise Level (dbm)	-102.9	-104.3
Carrier/Noise (in 35.5 MHz NBW) (db)	15.9	9.9
Receiver Bandwidth (db Hz) ***	71.9	71.9
Receiver Noise Level (dbm)	-106.5	-107.9
Carrier/Noise (in 15.5 MHz NBW) (db)	19.5	13.5
Downlink C/N_o (db)	91.4	85.4
Uplink Contribution (db)	-1.9	-0.6
Total C/N_o (db)	89.5	84.8

* Based on a nominal slant range of 22,000 nmi.
** 1200 channel spectrum (35.5-MHz IF Noise BW)
*** 240 channel spectrum (15.5-MHz IF Noise BW)

TABLE 1.48 FM/FM-FDM MODE, ATS-1, MULTIPLEX CHANNEL S/N CALCULATION (ONE TWT)

(Transponders No. 1 and No. 2)

	85' Antenna		40' Antenna	
Multiplex Channel	Low Chan.	High Chan.	Low Chan.	High Chan.
Total C/N_o (db)	87.5	87.5	82.3	82.3
Receiver IF Noise Bandwidth (dbHz)	75.5	75.5	71.9	71.9
Total C/N (db)	12.0	12.0	10.4	10.4
Channel Bandwidth (3.1 KHz) (dbHz)	34.9	34.9	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0	3.0	3.0
RMS Deviation of Carrier (kHz)	490	490	870	870
Modulation Improvement Factor (db)	3.1	-20.7	8.1	-3.1
Test Tone/Thermal Noise (Wgtd) (db)	58.7	34.9	58.5	47.3
K_{OV} (TT/Overall Intermodulation Noise) (Wgtd) (db)	61.5	41.2	61.5	51.7
Total TT/N (Wgtd) (db)	56.9	34.0	56.7	46.0

TABLE 1.49. FM/FM-FDM MODE, ATS-1, MULTIPLEX CHANNEL S/N CALCULATION (TWO TWT'S)

(Transponders No. 1 and No. 2)

	85' Antenna		40' Antenna	
Multiplex Channel	Low Chan.	High Chan.	Low Chan.	High Chan.
Total C/N_o (db)	89.5	89.5	84.8	84.8
Receiver IF Noise Bandwidth (db Hz)	75.5	75.5	71.9	71.9
Total C/N (db)	14.0	14.0	12.9	12.9
Channel Bandwidth (3.1 KHz) (dbHz)	34.9	34.9	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0	3.0	3.0
RMS Deviation of Carrier (kHz)	490	490	870	870
Modulation Improvement Factor (db)	3.1	-20.7	8.1	-3.1
Test Tone/Thermal Noise (Wgtd) (db)	60.7	36.9	61.0	49.5
K_{OV} (TT/Overall Intermodulation Noise) (Wgtd) (db)	61.5	41.2	61.5	51.7
Total TT/N (Wgtd) (db)	58.1	35.5	58.2	47.6

TABLE 1.50. FM/FM-FDM MODE, ATS-3, EARTH TO SATELLITE LINK CALCULATION

	85' Antenna		40' Antenna	
Transponder	No. 1	No. 2	No. 1	No. 2
Transmitter Average Power (dbm)	50.5	50.5	57.4	57.4
Earth Antenna Gain (net) (db)	61.5	61.5	54.6	54.6
Earth Station EIRP (dbm)	112.0	112.0	112.0	112.0
Space Attenuation (db) *	-200.8	-200.8	-200.8	-200.8
Satellite Antenna Gain (db)	16.3	16.3	16.3	16.3
Off Beam Center Allowance (db)	-0.5	-0.5	-0.5	-0.5
Received Carrier Power (dbm)	-73.0	-73.0	-73.0	-73.0
Receiver Noise Figure (db)	6.1	5.6	6.1	5.6
Effective Received Noise Temp (db°K)	31.2	30.7	31.2	30.7
Receiver Noise Power Density (dbm/Hz)	-167.4	-167.9	-167.4	-167.9
C/N_o (db)	94.4	94.9	94.4	94.9

*Based on a nominal slant range of 22,000 nmi.

TABLE 1.51. FM/FM-FDM MODE, ATS-3, SATELLITE TO EARTH LINK AND OVERALL LINK CALCULATION (ONE TWT)

	85' Antenna		40' Antenna	
Transponder	No. 1	No. 2	No. 1	No. 2
Satellite Transmitter Power Output (dbm)	36.0	40.3	36.0	40.3
Satellite Antenna Gain (db)	16.2	16.2	16.2	16.2
Satellite EIRP (dbm)	52.2	56.5	52.2	56.5
Space Attenuation (db) *	-197.1	-197.1	-197.1	-197.1
Off Beam Center Allowance (db)	-0.5	-0.5	-0.5	-0.5
Earth Antenna Gain (db)	58.4	58.4	51.0	51.0
Receiver Carrier Power (db)	-87.0	-82.7	-94.4	-90.1
Effective Received Noise Temp (db°K)	18.8	18.8	18.8	18.8
Receiver Noise Power Density (dbm/Hz)	-179.8	-179.8	-179.8	-179.8
Receiver IF Noise Bandwidth (dbHz)**	75.5	75.5	75.5	75.5
Receiver Noise Level (dbm)	-104.3	-104.3	-104.3	-104.3
Carrier/Noise (downlink)(db)(in 35.5 MHz NBW)	17.3	21.6	9.9	14.2
Receiver Bandwidth (dbHz)***	71.9	71.9	71.9	71.9
Receiver Noise Level (dbm)	-107.9	-107.9	-107.9	-107.9
Carrier/Noise (db)(in 15.5 MHz NBW)	20.9	25.2	13.5	17.5
Downlink C/N_0 (db)	92.8	97.1	85.4	89.7
Uplink Contribution (db)	-2.3	-4.2	-0.5	-1.1
Total C/N_0 (db)	90.5	92.9	84.9	88.6

*Based on a nominal slant range of 22,000 nmi.
**1200 channel spectrum (35.5-MHz IF Noise BW)
***240 channel spectrum (15.5-MHz IF Noise BW)

TABLE 1.52. FM/FM-FDM MODE, ATS-3, SATELLITE TO EARTH LINK AND OVERALL LINK CALCULATION (TWO TWT'S)

	85' Antenna		40' Antenna	
Transponder	No.1	No. 2	No. 1	No. 2
Satellite Transmitter Power Output (dbm)	38.4	43.1	38.4	43.1
Satellite Antenna Gain (db)	16.2	16.2	16.2	16.2
Satellite EIRP (dbm)	54.6	59.3	54.6	59.3
Space Attenuation (db)*	-197.1	-197.1	-197.1	-197.1
Off Beam Center Allowance (db)	-0.5	-0.5	-0.5	-0.5
Earth Antenna Gain (db)	58.4	58.4	51.0	51.0
Received Carrier Power (db)	-84.6	-79.9	-92.0	-87.3
Effective Receiver Noise Temp (db °K)	18.8	18.8	18.8	18.8
Receiver Noise Power Density (dbm/Hz)	-179.8	-179.8	-179.8	-179.8
Receiver IF Noise Bandwidth (dbHz)**	75.5	75.5	75.5	75.5
Receiver Noise Level (dbm)	-104.3	-104.3	-104.3	-104.3
Carrier/Noise (downlink) (in 35.5 MHz NBW) (db)	19.7	24.4	12.3	17.0
Receiver Bandwidth (dbHz)***	71.9	71.9	71.9	71.9
Receiver Noise Level (dbm)	-107.9	-107.9	-107.9	-107.9
Carrier/Noise (in 15.5 MHz NBW) (db)	23.3	28.0	15.9	20.6
Downlink C/N_o (db)	95.2	99.9	87.8	92.5
Uplink Contribution (db)	-3.4	-6.2	-0.9	-2.0
Overall C/N_o (db)	91.8	93.7	86.9	90.5

* Based on a nominal slant range of 22,000 nmi.
** 1200 channel spectrum (35.5-MHz IF Noise BW)
*** 240 channel spectrum (15.5-MHz IF Noise BW)

TABLE 1.53. FM/FM-FDM MODE, ATS-3, MULTIPLEX CHANNEL S/N CALCULATION (ONE TWT)

(Transponder No. 1)

	85' Antenna		40' Antenna	
Multiplex Channel	Low Chan	High Chan	Low Chan	High Chan
Total C/N_o (db)	90.5	90.5	84.9	84.9
Receiver IF Noise Bandwidth (dbHz)	75.5	75.5	71.9	71.9
Total C/N (db)	15.0	15.0	13.0	13.0
Channel Bandwidth (3.1 kHz) (dbHz)	34.9	34.9	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0	3.0	3.0
RMS Deviation of Carrier (kHz)	490	490	870	870
Modulation Improvement Factor (db)	3.1	-20.7	8.1	-3.1
Test Tone/Thermal Noise (Wgtd) (db)	61.7	37.9	61.1	49.9
K_{ov} (TT/Overall Intermodulation Noise) (Wgtd) (db)	65.2	43.7	65.2	54.8
Total TT/N (Wgtd) (db)	60.1	36.9	59.7	48.7

TABLE 1.54. FM/FM-FDM MODE, ATS-3, MULTIPLEX CHANNEL S/N CALCULATION (ONE TWT)

(Transponder No. 2)

	85' Antenna		40' Antenna	
Multiplex Channel	Low Chan	High Chan	Low Chan	High Chan
Total C/N_o (db)	92.9	92.0	88.3	88.3
Receiver IF Noise Bandwidth (dbHz)	75.5	75.5	71.9	71.9
Total C/N (db)	17.4	17.4	16.4	16.4
Channel Bandwidth (3.1 kHz) (dbHz)	34.9	34.9	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0	3.0	3.0
RMS Deviation of Carrier (kHz)	490	490	870	870
Modulation Improvement Factor (db)	3.1	-20.7	8.1	-3.1
Test Tone/Thermal Noise (Wgtd) (db)	64.1	40.3	64.5	53.3
K_{ov} (TT/Overall Intermodulation Noise) (Wgtd) (db)	65.2	43.7	65.2	54.8
Total TT/N (Wgtd) (db)	61.6	38.8	61.8	51.0

TABLE 1.55. FM/FM-FDM MODE, ATS-3, MULTIPLEX CHANNEL S/N CALCULATION (TWO TWT'S)

(Transponder No. 1)

	85' Antenna		40' Antenna	
Multiplex Channel	Low Chan	High Chan	Low Chan	High Chan
Total C/N_0 (db)	91.8	91.8	86.9	86.9
Receiver IF Noise Bandwidth (dbHz)	75.5	75.5	71.9	71.9
Total C/N (db)	16.3	16.3	15.0	15.0
Channel Bandwidth (3.1 kHz) (dbHz)	34.9	34.9	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0	3.0	3.0
RMS Deviation of Carrier (kHz)	490	490	870	870
Modulation Improvement Factor (db)	3.1	-20.7	8.1	-3.1
Test Tone/Thermal Noise (Wgtd) (db)	63.0	39.2	63.1	51.9
K_{ov} (TT/Overall Intermodulation Noise) (Wgtd) (db)	65.2	43.7	65.2	54.8
Total TT/N (Wgtd) (db)	61.0	37.9	61.0	50.1

TABLE 1.56. FM/FM-FDM MODE, ATS-3, MULTIPLEX CHANNEL S/N CALCULATION (TWO TWT'S)

(Transponder No. 2)

	85' Antenna		40' Antenna	
Multiplex Channel	Low Chan	High Chan	Low Chan	High Chan
Total C/N_0 (db)	93.7	93.7	90.5	90.5
Receiver IF Noise Bandwidth (dbHz)	75.5	75.5	71.9	71.9
Total C/N (db)	18.2	18.2	18.6	18.6
Channel Bandwidth (3.1 kHz) (dbHz)	34.9	34.9	34.9	34.9
F1A Noise Weighting Factor (db)	3.0	3.0	3.0	3.0
RMS Deviation of Carrier (kHz)	490	490	870	870
Modulation Improvement Factor (db)	3.1	-20.7	8.1	-3.1
Test Tone/Thermal Noise (Wgtd) (db)	64.9	41.1	66.7	55.5
K_{ov} (TT/Overall Intermodulation Noise) (Wgtd) (db)	65.2	43.7	65.2	54.8
Total TT/N (Wgtd) (db)	62.0	39.2	62.9	52.2

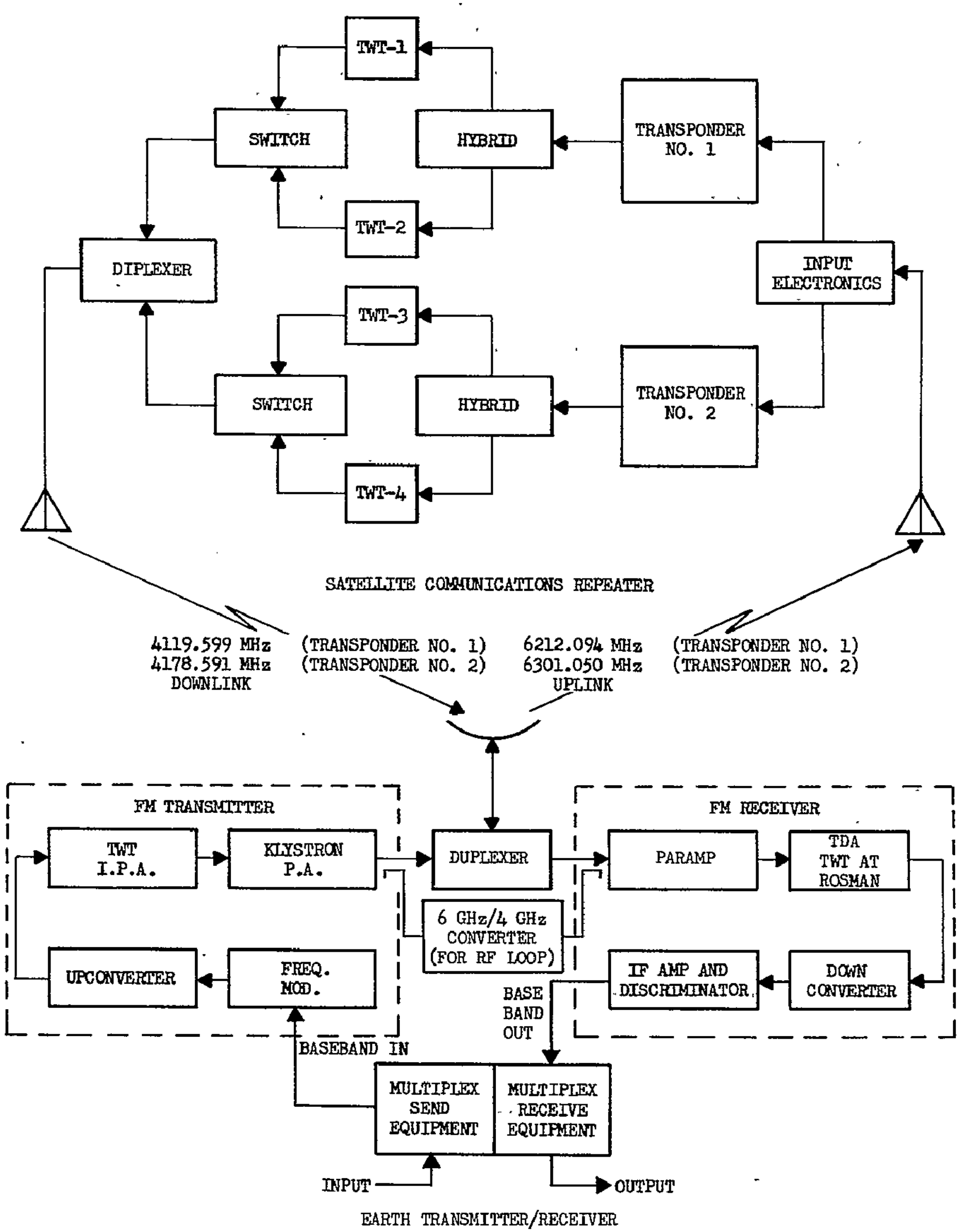


Figure 1.53. ATS FM/FM-FDM Mode Block Diagram

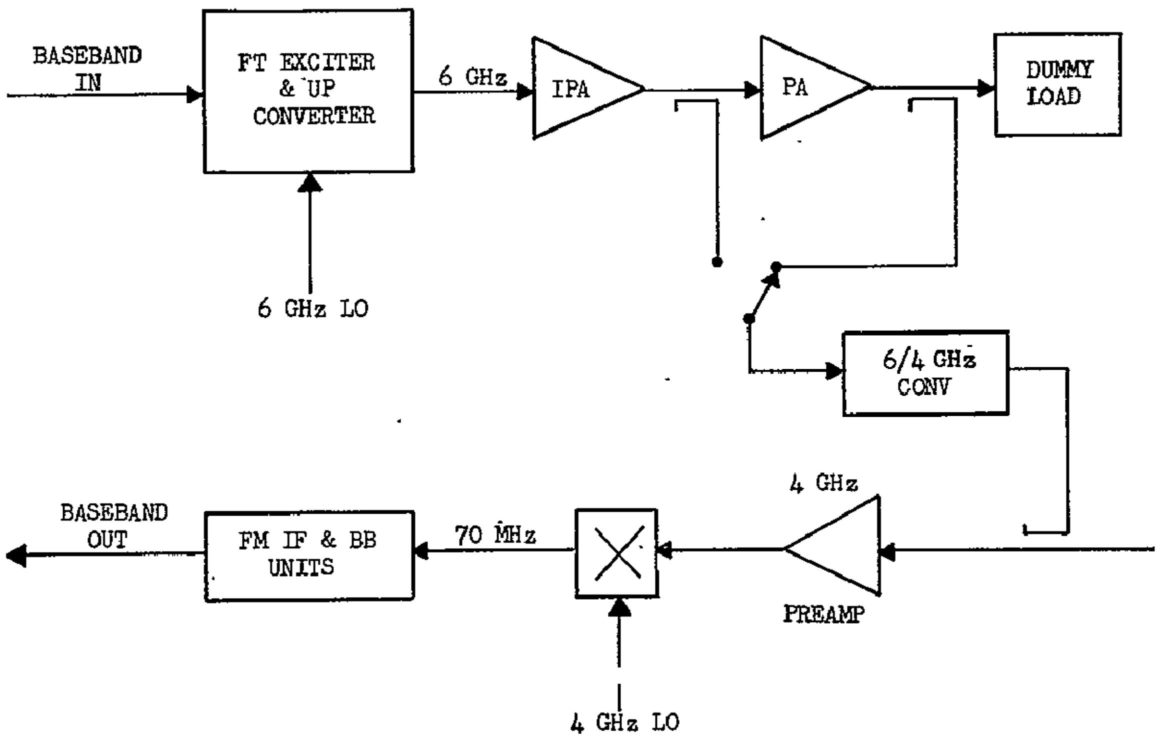


Figure 1.54. RF Loop Block Diagram (FM/FM-FDM Mode)

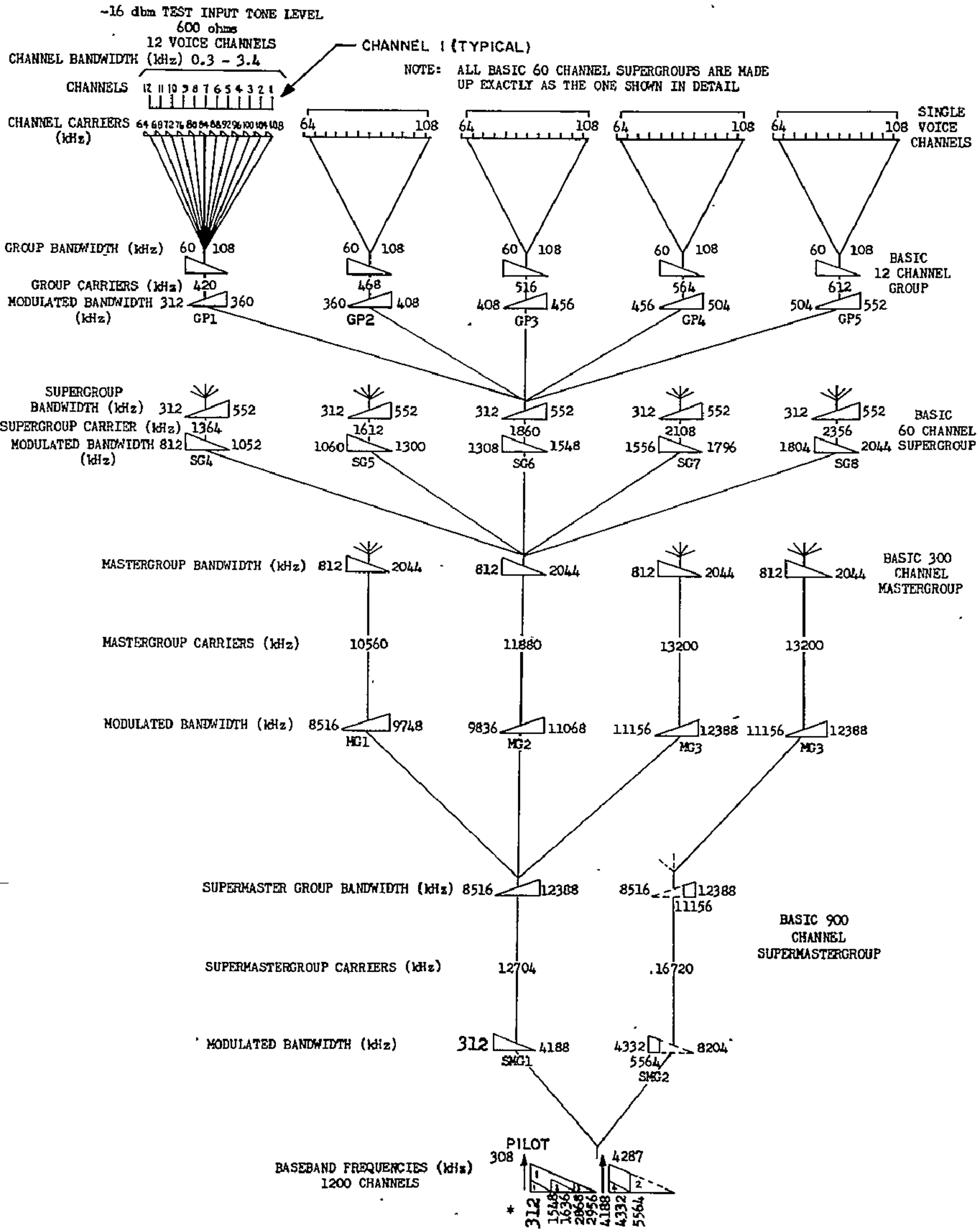


Figure 1.55. Frequency and Modulation Plan (1200 Channels)

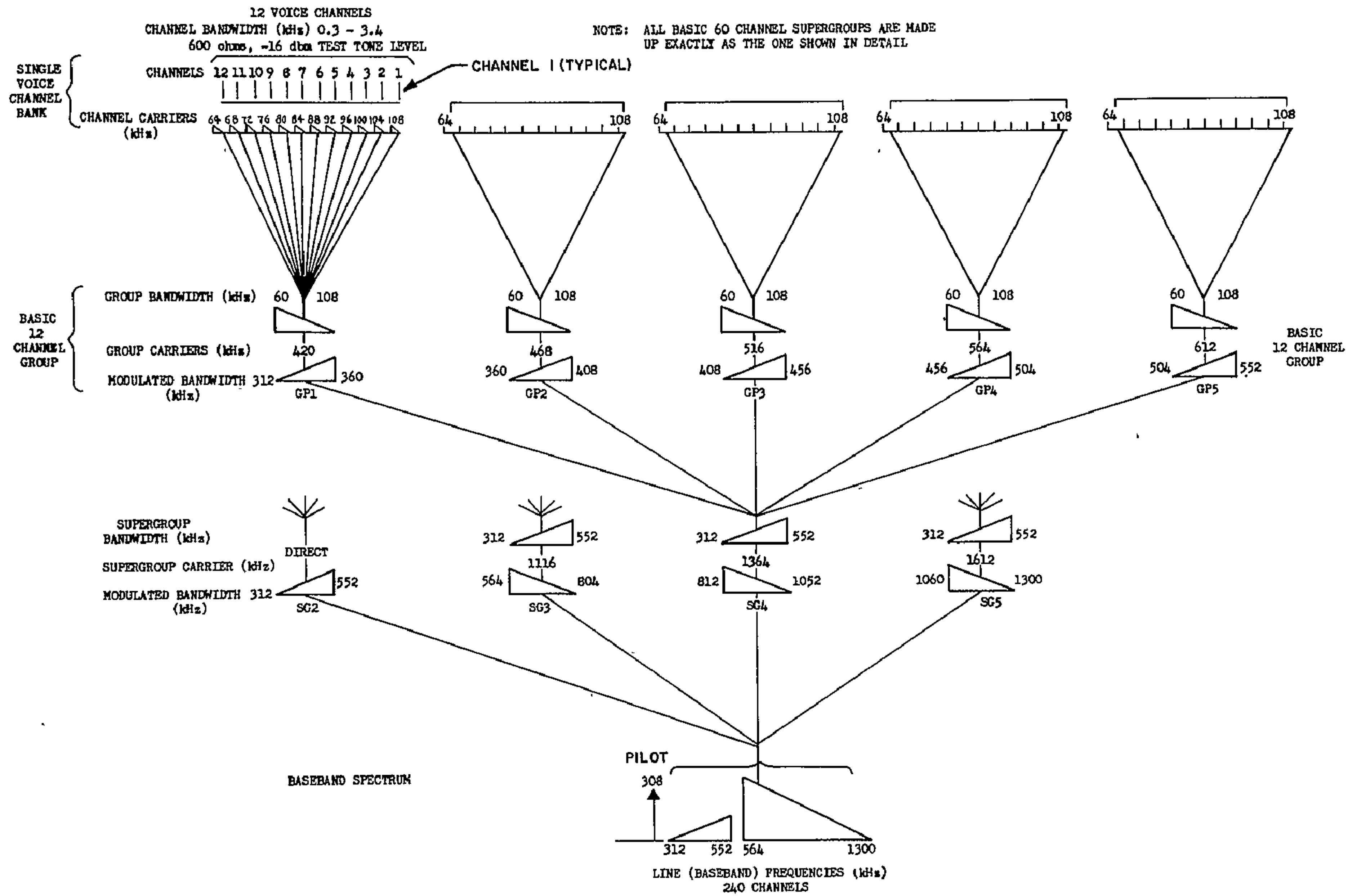


Figure 1.56. Frequency and Modulation Plan (240 Channels)

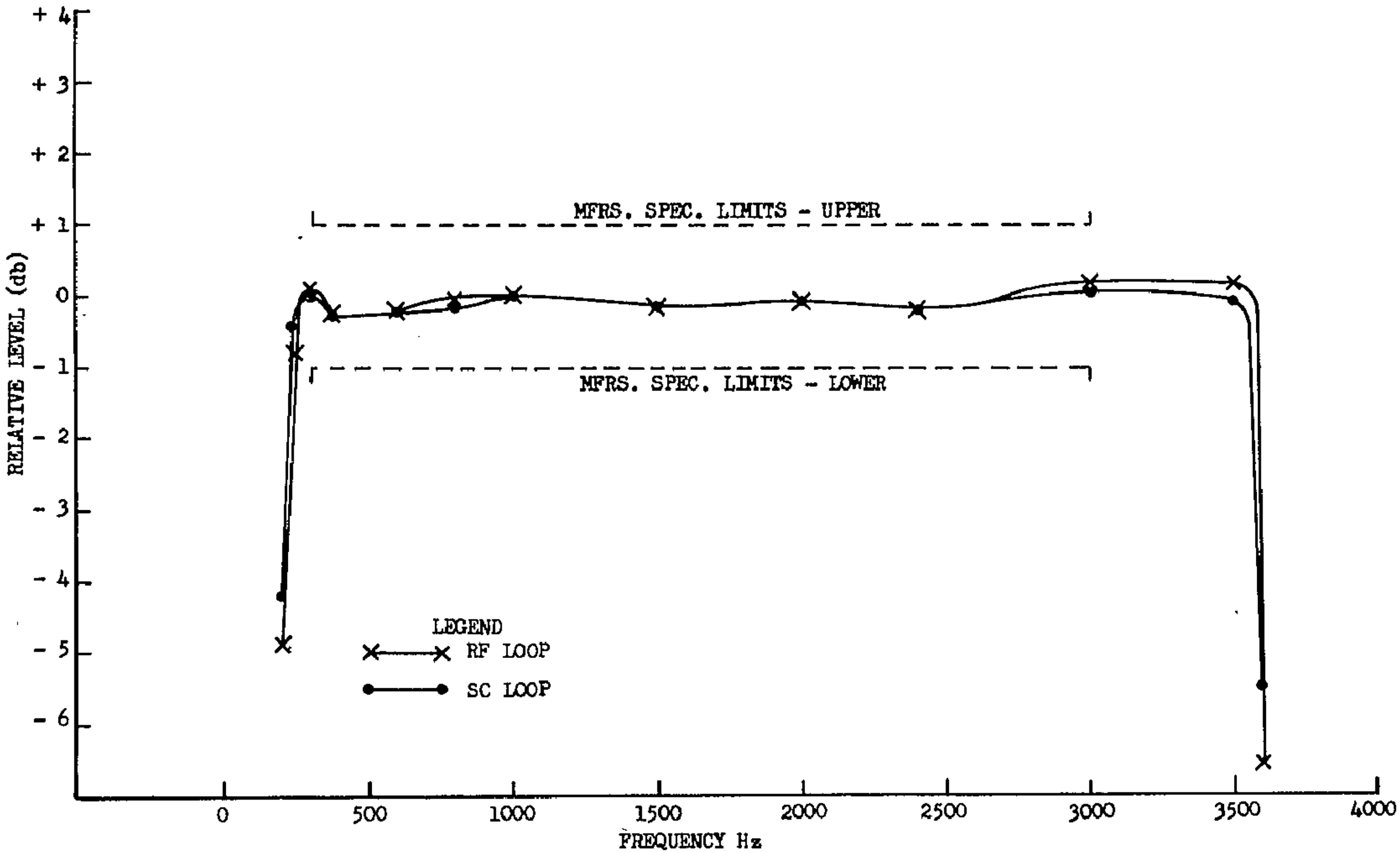


Figure 1.57. Typical Multiplex Channel Frequency Response

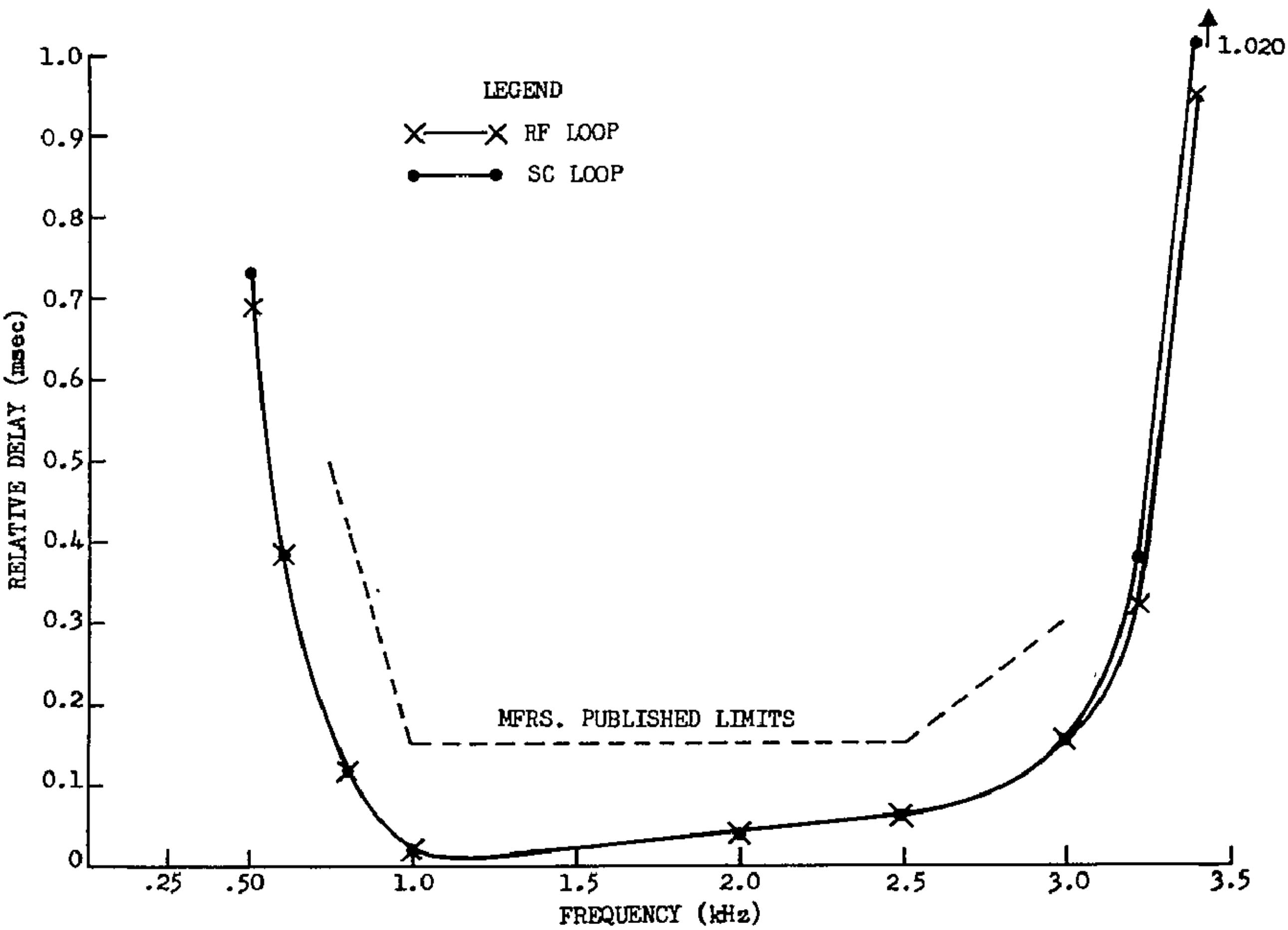


Figure 1.58. Typical Multiplex Channel Audio Envelope Delay

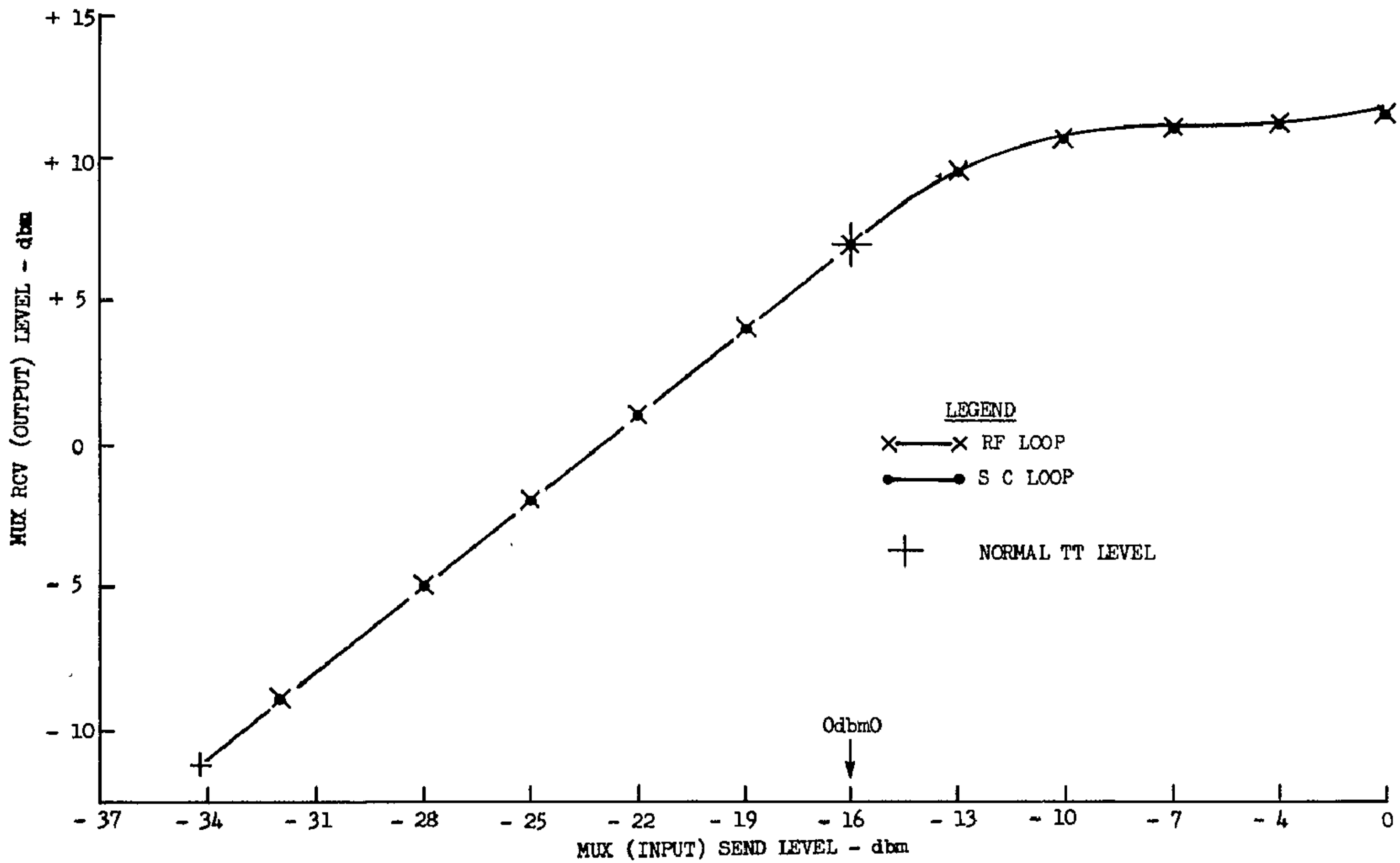


Figure 1.59. Typical Multiplex Channel Linearity

1.4.3 SUMMARY OF PERFORMANCE

The FM/FM-FDM channel performance is dependent upon a number of factors; of which the following are paramount:

a) Spacecraft EIRP, which ranges from 52.5 dbm to 56.5 dbm (an additional EIRP of 49.4 dbm is available, however, it is seldom used in the FM/FM configuration)

b) Earth station G/T of 32.2 db and 39.6 db

c) Channel loading which is 1200 channels at Rosman and 240 channels at Mojave and Cooby Creek

d) FDM channel baseband location (the channel performance varies over the baseband with the low channels having higher values of TT/N). All stations make low-channel measurements at 342 kHz; 240 channel capacity stations make high-channel measurements at 1248 kHz; and 1200 channel capacity stations make high-channel measurements at 5340 kHz.

The measured test tone-to-noise ratio (TT/N) in the low channel for 240 and 1200 channel loading varies from 54.4 db to 58.4 db for the various system configurations, while the TT/N ratio for the high channel (240 channel system) varies from 46.0 db to 49.6 db. The variation in TT/N ratio for the high channel of a 1200 channel system is 34.2 db to 38.1 db. Using CCIR recommended pre/de-emphasis, the corresponding TT/N ratio variations are 50.2 db to 55.6 db, 50.7 db to 53.7 db, and 38.7 db to 42.5 db, respectively. Consideration of the foregoing shows that, with CCIR pre/de-emphasis, nearly all of the system configurations will allow FDM channel operation which meets or exceeds the CCIR recommended TT/N of 50 db. The only exceptions are those system configurations which use a 1200 channel spectrum; in which cases the TT/N ratios at the low end of the baseband exceeds the recommended value, but the TT/N ratios at the high end are from 11.3 db to 7.5 db below the recommended value (all values were measured using F1A weighting).

The noise characteristics of the FM/FM-FDM channel may be characterized by four components: intermodulation noise (I), thermal noise (R), threshold noise (N_1) and threshold noise (Δ).

At low C/N ratios (7 to 10 db), the threshold components (N_1) and (Δ) are predomina in the lower portion of the baseband. In the intermediate range of C/N ratios, which for the ATS system is 11 to 15 db, thermal noise (R) predominates. At high C/N ratios (20 db), intermodulation noise (I) predominates since the other noise components, which are a function of the C/N ratio, become insignificant.

The non-linear noise characteristics of the system are determined by two techniques; multitone tests and noise loading tests, the results of which are in close agreement (the relationship between the two methods is developed in subsection 7.7). The multitone tests yield information concerning the limiting factor in the channel performance, i.e.,at Rosman, using a 1200-channel spectrum, linear group delay is the limiting factor.

By comparing measured loaded and idle channel characteristics, it is possible to determine whether a channel is limited by thermal or intermodulation effects. It is shown that, at nominal loading, all system configurations are thermal noise limited.

The FDM channel frequency stability is largely dependent upon doppler effects in the system (the effect of oscillator instabilities is minimal due to the fact that they appear on the RF carrier and sidebands alike). The effects of doppler are separated into the factors; a) spin modulation produced by misalignment of the S/C receiving and transmitting antenna phase centers and b) doppler produced by the change in range between the spacecraft and the earth station. These effects have not been observed through the ATS system in the FM/FM mode, however, tests have been conducted from which a quantitative evaluation of their impact on FDM channel performance was made. It was found that the effect of spin modulation is about 0.0005 Hz. The effect of differential doppler due to the maximum change in range observed to date (10 ft/sec) causes a frequency shift of approximately 0.5 Hz between the carrier and a 5-MHz baseband tone. This is well within the CCITT recommendation of 2-Hz maximum.

1.4.4 TEST TONE-TO-NOISE RATIO

Predicted and measured values of test tone-to-noise ratio (TT/N) are shown in tables 1.57 and 1.58 for various combinations of earth station and spacecraft EIRP. Both the loaded and idle conditions are shown. The loaded condition is based on 1200 channel loading at Rosman, and 240 channel loading at Mojave and at Cooby Creek (CCIR recommended loading). The measurements were performed for one channel at each end of the baseband spectrum. Table 1.57 shows the results of measured (and predicted values) for the system operating without pre-emphasis/de-emphasis, while table 1.58 presents similar data with CCIR recommended pre-emphasis/de-emphasis.

Figure 1.64 shows the result of using pre/de-emphasis for the 1200 channel loading configuration. As shown in figure 1.64, the use of pre/de-emphasis tends to equalize the TT/N ratio in all channels across the baseband by decreasing the TT/N ratio in the channels in the low end and increasing the TT/N ratios in the high end. The PhM/PhM configuration is essentially an FM/FM system with pre/de-emphasis of 6 db per octave (the PhM/PhM configuration TT/N is nearly flat across the baseband).

1.4.4.1 Idle Test Tone-To-Noise Ratio

The idle test tone-to-noise ratio, TT/N, is determined from idle noise measurements of the system. The idle TT/N is a measurement of the ratio of the nominal test tone power in an FDM channel to the noise power in the channel with no modulation applied to the carrier. The idle noise power is due primarily to the thermal noise (R) generated in the earth station pre-amplifier and the earth station antenna sky noise as well as noise transmitted by the spacecraft due to thermal noise in the spacecraft receiver. A second component of the idle noise is due to threshold effects of the earth station receiver. The threshold noise (N_i) is due to impulse noise which is a nonlinear function of the receiver IF C/N. The threshold noise is significant only at low C/N ratios and is consequently omitted from the link calculations when the IF C/N ratio exceeds 10 db. Refer to paragraph 3.2.1 for a detailed discussion of threshold noise effects.

The earth station receivers used in the ATS systems all utilize low-noise front ends, thus thermal noise due to sky noise appears as the major contributor to the receiver system noise temperature (T_s). Both the receiver noise and the sky noise are variables, the former being dependent primarily upon equipment tuning and physical temperature, while the latter is a function of the propagation medium and background (galactic) noise as well as thermal noise due to side lobe illumination from the earth. Consideration of the foregoing factors indicates that T_s cannot be predicted with absolute certainty, however, approximate values can be anticipated for specific system conditions. This was done in the link calculations (paragraph 1.4.2.3) where 76°K is used for T_s for all system configurations except Rosman using ATS-1, where T_s is 105°K. This difference (amounting to 1.4 db) is due to the low elevation angle which Rosman has while operating with ATS-1.

Figures 3.48 and 3.49 in section 3.2.1 show plots of T_s versus time for each ATS system configuration. Each point plotted represents the average of several measurements taken over a period of one week. The T_s is also measured for each test run, thus it is possible to consider the effect of T_s when analyzing the test data.

The idle TT/N ratio is measured when the system is unloaded (operating in the idle condition). At this time essentially no information is being transmitted, thus no modulation is applied to the carrier frequency and the received noise power does not contain any intermodulation noise (refer to paragraph 1.4.5 for a complete discussion of intermodulation effects). Noise contributions due to the multiplex equipment are specified by the manufacturer to be at least 70 db below test tone level (70 db TT/N), and are therefore considered to be negligible with regard to the ATS system analysis. The klystron power amplifier has been measured during integration tests to have a thermal noise power ratio of about 55 db (equivalent to TT/N in excess of 70 db), thereby producing a negligible effect on the overall TT/N; thus, earth station T_s is the main contributor to the idle channel noise level. The multiplex channel output is filtered using an F1A weighting filter, causing the measured TT/N to include a 3.0 db improvement over the unweighted condition. CCIR recommended psophometric weighting is not utilized; however, the improvement in TT/N is essentially the same for either type of weighting, the main difference between the two being the center frequency of the two weighting networks (the TT/N improvement due to psophometric weighting is approximately 2.5 db).

Figure 1.60 through 1.63 show plots of caluclated idle TT/N versus spacecraft EIRP for constant values of G/T. G/T is the ratio of the receiving antenna gain to the system noise temperature, expressed in db, and provides a figure of merit indicative of the quality of the receiving system. Values of G/T equal to 30 db, 35 db, and 40 db are chosen to bracket the G/T ratios representative of the ATS earth stations employed in the test program. The abscissa values of EIRP are chosen to bracket those employed in the ATS-1 and ATS-3 satellites. The TT/N calculations are based upon the system operating parameters shown in table 1.59 (with T_s normalized to 76°K). Since the baseband noise density in an FM system is parabolic in nature (proportional to the square of the baseband frequency), the TT/N varies across the baseband, thus requiring separate TT/N plots for the high and low voice channels. Separate plots are also required for the different channel capacities (1200 and 240) because different modulation indexes are used to make maximum use of the IF spectrum; thus, the test tone signal strength is different, causing changes in TT/N, even for the same baseband frequency. It should also be noted that, while the low channels are both at 342 kHz, the high channels are measured at different baseband frequencies for the 1200-

channel and 240-channel systems (5340 kHz and 1248 kHz, respectively). The predicted value of idle TT/N may be determined for any spacecraft EIRP from the station G/T curve (32.2 db for a 40' earth station and 39.6 db for an 85' earth station). As shown in figures 1.60 through 1.63, the uplink C/N_0 (carrier to noise ratio per unit bandwidth) limits the multiplex channel idle TT/N at high values of spacecraft EIRP (for a fixed earth station G/T). The uplink C/N_0 used to calculate G/T for all configurations was chosen to be 94.4 db, which is the mean of the theoretical values of 93.9, 94.4, and 94.9 db calculated respectively for ATS-1 (transponders No. 1 and 2), ATS-3 (transponder No. 1), and ATS-3 (transponder No. 2). The use of one value of uplink C/N_0 greatly reduces the complexity of the data presentation, and does not add appreciable error to the G/T curves (especially at the levels of EIRP that the ATS system operates).

The measured values of idle TT/N have been included in figures 1.60 through 1.63 in order to illustrate how closely the predicted and measured values agree (the measured values have been normalized for an uplink C/N_0 of 94.4 db to establish a common basis for comparison). As shown in figures 1.60 and 1.61, (40' station, high and low channels) the measured and predicted values agree within 0.5 db. Likewise, close agreement (within 0.5 db) is also seen between predicted and measured values for the 85' station when operating with the ATS-3 spacecraft (high channel, figure 1.62). The remaining measured values for the 85' station agree with the predicted values within 2 db (except for one system condition with ATS-1 which shows a difference of approximately 4 db).

Table 1.60 contains the calculated values of idle channel test tone-to-noise ratios (TT/N) for each system configuration. It is of interest to note that an increase in S/C EIRP does not necessarily produce a corresponding increase in TT/N (refer to ATS-3, 85' antenna, transponders 1 and 2). This is because an increase in S/C EIRP improves only the downlink CNR, and does not affect the uplink. It may be seen from table 1.60 that the 1200-channel system configuration using ATS-3, transponder No. 2, one or two TWT's, is uplink limited when operating with the 85' earth station antenna (transponder No. 1, two TWT's, is also slightly uplink limited). The uplink limitation could be avoided by reducing the number of channels transmitted and changing the system configuration accordingly.

The threshold noise, N_i, is negligible at the C/N ratios shown in table 1.60, thus the idle noise is due primarily to thermal noise and the loaded noise (noise present when the system is loaded) is the result of thermal and intermodulation noise. The intermodulation and thermal effects are equal whenever the idle TT/N exceeds the loaded TT/N by exactly 3 db. Consequently, the link is determined to be intermodulation noise limited whenever the idle TT/N exceeds the loaded TT/N by more than 3 db (the link is thermal noise limited whenever the difference between the unloaded and loaded TT/N is less than 3 db). As seen from table 1.60, all system configurations are thermal noise limited except for 240 channel operation using ATS-3, transponder no. 2, two TWT's, with a 40' earth station antenna. In this configuration the intermodulation noise is only slightly greater than the thermal noise as evidenced by the fact that the calculated unloaded and loaded TT/N values differ by only 3.3 db in the high channel, and 3.8 db in the low channel. Although not shown, the thermal noise limitation will not apply to the 85-foot earth station antenna at some reduced level of loading (less than 1200 channels).

1.4.4.2 Loaded Test Tone-to-Noise Ratio

The loaded test tone-to-noise ratio, TT/N, is determined from loaded noise measurements of the system (the loading is performed in accordance with CCIR recommendation 353-1). The loaded TT/N is a measurement of the ratio of the nominal test tone power in an FDM channel to the noise power in the channel with no test tone applied to the multiplex channel input, but with noise loading applied to the entire baseband (a slot filter in the noise generator keeps the applied noise loading out of the channel under test).

The loaded TT/N for various combinations of earth station and spacecraft EIRP are presented in tables 1.57, 1.58 and 1.60. Figure 1.64 shows the results of using pre/de-emphasis for the 1200 channel loading configurations.

The loaded TT/N, when compared to the idle TT/N, provides a means of determining the impact that intermodulation effects have on channel performance (refer to paragraph 1.4.5). Also, the link may be determined to be either thermal noise limited or intermodulation noise limited by comparing the idle and loaded TT/N (as discussed in paragraph 1.4.3).

Table 1.61 presents a summary of the link performance limitation based upon the link calculations (tables 1.45 through 1.56, paragraph 1.4.2.3). For each system configuration, table 1.61 indicates whether the system is uplink limited, downlink limited, or optimum (by definition, the system is optimized when the absolute value of the difference between the uplink C/N_0 and the downlink C/N_0 (in db) is equal to or less than 2 db). Table 1.61 also shows whether thermal or intermodulation effects are most prominent in the FDM channel under test (one channel at each end of the baseband).

A comparison between predicted and measured FDM channel performance (refer to table 1.57) shows that in all cases the measured channel performance without pre/de-emphasis was less than that which had been predicted. The discrepancy in the low channel (342 kHz) ranged between 1.4 db to 3.8 db, while the variation in the high channel (5340 kHz at Rosman, and 1248 kHz at Mojave and Cooby Creek) was 0.1 db to 1.6 db (six of the eight configurations showed variations of one db or less). The foregoing comparison indicates that the noise characteristics of the high channel are known to a greater precision than are those of the low channel. This is understandable when considered in light of the following facts:

a) The thermal noise follows a well known parabolic distribution (proportional to the square of the baseband frequency) and thus predominates at the high end of the baseband spectrum, while less defined effects may be the determining factors at the low end of the baseband spectrum.

b) Threshold effects (not considered in the predicted calculations) are more prominent at the low end of the baseband spectrum.

A similar comparison using CCIR pre/de-emphasis for terrestrial line-of-sight radio-relay systems (table 1.58) shows somewhat better correlation between measured and predicted values for the high channels (ranging from 0.1 db to 0.8 db) except for Mojave using ATS-3 with EIRP of 52.2 dbm where the correlation is worse (1.0 db without pre/de-emphasis and 2.0 db with pre/de-emphasis). Also, closer correlation exists in the low channels for all system conditions using the Rosman station (differences between measured and predicted values ranges from 1.3 db to 2.6 db with pre/de-emphasis as compared with corresponding differences of 1.7 db to 3.2 db without pre/de-emphasis). The difference between predicted and measured values for the low channel at Mojave is considerably greater (ranging from 4.9 db to 6.4 db) then the corresponding difference measured without pre/de-emphasis (1.4 db to 3.6 db).

Consideration of the foregoing test results shows that the use of CCIR recommended pre/de-emphasis affects the FDM channels in the expected manner except for the low channels in a 240 channel baseband spectrum. The large variation between predicted and measured values in this case is due to the fact that the predicted values did not account for the following factors:

a) Truncation of the IF signal spectrum due to the pre-emphasis network "emphasizing" the high baseband frequency components. When the deviation is much greater than the highest modulating frequency, then the truncation effect is a function of $B_{IF}/\Delta f$ (the ratio of the IF bandwidth to the peak deviation of the carrier). For Rosman (1200 channel system) this ratio is equal to 3.74 while at Mojave (240 channel system) the ratio is 2.04, thus the truncation effect may be expected to be greater at Mojave than at Rosman. The truncation effect causes a uniform noise distribution to appear across the baseband. This uniform distribution adds to the essentially parabolic distortion caused by the IF group delay so that the effects of truncation are first observed in the lower frequency channels.

b) The intermodulation baseband noise spectrum at the output of the demodulator is changed. This may be seen from a consideration of the Wiener-Khintchine Theorem (refer to paragraph 7.7 for a development of this theorem as applied to intermodulation distortion in an FM/FM system) which leads to the development of the output noise spectrum as a function of the convolution of the input spectrum (double-sided) with itself. Since the input spectrum has the high-frequency channels emphasized, the convolution of the input spectrum with itself produces an intermodulation spectrum which is increased at the low frequency end. Thus, the effects of emphasis will be more prominent in the low end of the baseband spectrum. In the case of 240 channel pre/de-emphasis, the characteristics of the pre-emphasis network causes this intermodulation to be greater at the low frequency end than that for 1200 channel pre/de-emphasis.

The foregoing discussion indicates why the difference between measured and predicted values is large in the low channels for the 240 channel system compared to the low channels for the 1200 channel system.

As shown in figure 1.64, the use of pre/de-emphasis depresses the TT/N performance in the lower 400 channels, while improving the performance in the upper 800 channels. The use of 6 db/octave pre/de-emphasis effectively converts the system from FM/FM to PhM/PhM and tends to equalize the channel TT/N across the entire baseband spectrum.

In an operational system, the optimum emphasis circuit will be the one which maximizes the number of channels which meet or exceed a predetermined TT/N ratio (e.g., CCIR recommendation of 50 db). It is thus apparent that the optimum emphasis circuit will be a function of the number of channels as well as the baseband noise characteristics.

TABLE 1.57. TT/N SUMMARY, FM/FM-FDM MODE WITHOUT PRE-EMPHASIS/DE-EMPHASIS (SINGLE STATION ACCESS)

Station	Satellite	EIRP dbm	Measured Ratios				Predicted Ratios			
			Loaded TT/N (db)		Idle TT/N (db)		Loaded TT/N (db)		Idle TT/N (db)	
			Low Ch:	High Ch:	Low Ch:	High Ch:	Low Ch:	High Ch:	Low Ch:	High Ch:
Rosman	ATS-1	52.2	56.4	34.2	56.4	34.2	58.1	35.5	60.7	36.9
(85' Ant.)	ATS-3	52.2	56.8	36.4	58.6	36.7	60.1	36.9	61.7	37.9
		54.6	57.6	37.8	60.2	38.1	61.0	37.9	63.0	39.2
		56.5	58.4	38.1	62.3	39.9	61.6	38.8	64.1	40.3
Mojave	ATS-1	52.2	56.8	47.3	60.6	49.1	58.2	47.6	61.0	49.8
(40' Ant.)	ATS-3	52.2	56.1	47.7	59.6	49.4	59.7	48.7	61.1	49.9
		54.6	57.7	49.6	62.5	51.3	61.0	50.1	63.1	51.9
Cooby Creek	ATS-1	52.2	54.4	46.0	58.9	47.4	58.2	47.6	61.0	49.8
(40' Ant.)										

NOTE: TT/N ratios based on 1200 channel loading at Rosman and 240 channel loading at Mojave and Cooby Creek. Low channel is 342 kHz at all earth stations. High channels are 5340 kHz at Rosman and 1248 kHz at Mojave and Cooby Creek.

TABLE 1.58. TT/N SUMMARY, FM/FM-FDM MODE WITH PRE-EMPHASIS/DE-EMPHASIS
(SINGLE STATION ACCESS)

Station	Satellite	EIRP dbm	Measured Ratios				Predicted Ratios			
			Loaded TT/N (db)		Idle TT/N (db)		Loaded TT/N (db)		Idle TT/N (db)	
			Low Ch:	High Ch:	Low Ch:	High Ch:	Low Ch:	High Ch:	Low Ch:	High Ch:
Rosman	ATS-1	52.2	52.8	38.7	53.2	39.6	54.1	39.5	56.7	40.9
(85' Ant.)	ATS-3	52.2	54.2	40.5	55.2	41.6	56.1	40.9	57.7	41.9
		54.6	55.3	41.5	56.5	41.9	57.0	41.9	59.0	43.2
		56.5	55.6	42.5	58.5	43.5	57.8	42.8	60.1	44.3
Mojave	ATS-1	52.2	50.3	51.5	56.6	51.6	55.2	51.6	58.0	53.8
(40' Ant.)	ATS-3	52.2	50.2	50.7	57.5	52.0	56.7	52.7	58.1	53.9
		54.6	51.6	53.7	59.6	55.6	58.0	54.1	60.1	55.9

NOTE: TT/N ratios based on 1200 channel loading at Rosman and 240 channel loading at Mojave. Low channel is 342 kHz at both earth stations. High channels are 5340 kHz at Rosman and 1248 kHz at Mojave.

TABLE 1.59. FM/FM-FDM SUBSYSTEM CHARACTERISTICS (EARTH STATIONS)

Parameters	Rosman 85-ft Antenna	Mojave and Cooby Creek 40-ft Antenna	
Channel Spectrum (No. of Channels)	1200	1200	240
RF Frequency (Uplink)			
Transponder No. 1 (MHz)	6212.094	6212.094	6212.094
Transponder No. 2 (MHz)	6301.050	6301.050	6301.050
RF Frequency (Downlink)			
Transponder No. 1 (MHz)	4119.599	4119.599	4119.599
Transponder No. 2 (MHz)	4178.591	4178.591	4178.591
Earth Station Receiver IF BW (Nominal) (MHz)	30	30	12
FDM Channel Bandwidth (Unweighted) (kHz)	3.1	3.1	3.1
FDM Channel Spacing (kHz)	4.0	4.0	4.0
FDM Baseband Channel Spectrum (kHz)	312 to 5564	312 to 5564*	312 to 1300
Weighting Improvement (F1A) (db)	3.0	3.0	3.0
Peak Deviation of Carrier			
per Channel (MHz)	0.69	0.69	1.22
total baseband** (MHz)	9.5	9.5	7.6
Nominal Channel Loading ** (db)	15.8	15.8	8.8

* The Multiplex equipment at Mojave and Cooby Creek is limited to 240 channel operation.

**The CCITT recommended noise loading for N channels (G-222). Refer to paragraph 7.6 of Section 7.1.1 for a complete discussion of the FDM-FM system loading - Calculation assumes a peak to rms factor of 10 db.

TABLE 1.60. FM/FM-FDM SYSTEM PARAMETERS AND THEORETICAL PERFORMANCE

		ATS-1				ATS-3							
		1 TWT		2 TWT'S		1 TWT				2 TWT'S			
Earth Station Antenna (ft)		85'	40'	85'	40'	85'		40'		85'		40'	
Satellite Transponder No.		1 or 2	1 or 2	1 or 2	1 or 2	1	2	1	2	1	2	1	2
Earth Station EIRP	(dbm)	122.1	122.1	122.1	122.1	112.0	112.0	112.0	112.0	112.0	112.0	112.0	112.0
Satellite G/T	(db)	-26.7	-26.7	-26.7	-26.7	-14.9	-14.4	-14.9	-14.4	-14.9	-14.4	-14.9	-14.4
Uplink C/N_o	(db)	93.9	93.9	93.9	93.9	94.4	94.9	94.4	94.9	94.4	94.9	94.4	94.9
Satellite EIRP	(dbm)	49.4	49.4	52.2	52.2	52.2	56.5	52.2	56.5	54.6	59.3	54.6	59.3
Earth Station G/T	(db)	38.2	32.2	38.2	32.2	39.6	39.6	32.2	32.2	39.6	39.6	32.2	32.2
Downlink C/N_o	(db)	88.6	82.6	91.4	85.4	92.8	97.1	85.4	89.7	95.2	99.9	87.8	92.5
Total Link C/N_o	(db)	87.5	82.3	89.5	84.8	90.5	92.9	84.9	88.6	91.8	93.7	86.9	90.5
MULTIPLEX CHANNEL PERFORMANCE* Test Tone-to-Idle Noise													
High Channel TT/N (wgtd)	(db)	34.9	47.3	36.9	49.8	37.9	40.3	49.9	53.3	39.2	41.1	51.9	55.5
Low Channel TT/N (wgtd)	(db)	58.7	58.5	60.7	61.0	61.7	64.1	61.1	64.5	63.0	64.9	63.1	66.7
Test Tone-to-Loaded Noise**													
High Channel TT/N (wgtd)	(db)	34.0	46.0	35.5	47.6	36.9	38.8	48.7	51.0	37.9	39.2	50.1	52.2
Low Channel TT/N (wgtd)	(db)	56.9	56.7	58.1	58.2	60.1	61.6	59.7	61.8	61.0	62.0	61.0	62.9

*Performance calculations are based on a 1200-channel spectrum at Rosman (85' antenna), and 240 channel spectrum at Mojave and Cooby Creek (40' antenna). The High-channel base-band frequency is 5340 kHz at Rosman and 1248 kHz at Mojave and Cooby Creek. The low channel baseband frequency is 342 kHz at all stations.

**CCIR Recommended loading for 1200 channels at Rosman, and 240 channels at Mojave and Cooby Creek (15.8 dbm0 and 8.8 dbm0, respectively).

TABLE 1.61. SUMMARY OF THEORETICAL LINK PERFORMANCE LIMITATION, FM/FM-FDM MODE

Station	Satellite	Satellite EIRP (dbm)	$\left(C/N_o\right)^*_{up} - \left(C/N_o\right)_{down}$ (Based on System Calculations)	① Limiting Link D = Downlink U = Uplink O = Optimum	② Channel Noise Limitation R + N_i = Thermal Noise I + Δ = Intermodulation Noise O = Optimum: Low Channel	② Channel Noise Limitation: High Channel
Rosman	ATS-1	49.4	5.3	D	R + N_i	R + N_i
		52.2	2.5	D	O	R + N_i
	ATS-3	52.2	1.6	O	R + N_i	R + N_i
		54.6	-0.8	O	R + N_i	R + N_i
		56.5	-2.2	U	O	R + N_i
Mojave	ATS-1	49.4	11.3	D	R + N_i	R + N_i
		52.2	8.5	D	O	O
	ATS-3	52.2	9.0	D	R + N_i	R + N_i
		54.6	6.6	D	R + N_i	R + N_i
		56.5	5.2	D	O	O
Cooby Creek	ATS-1	52.2	8.5	D	O	O

*N_o = noise per unit bandwidth

① By definition, the system performance is downlink limited when $\left(C/N_o\right)_{up} - \left(C/N_o\right)_{down} > 2$ db

Uplink limited when $\left(C/N_o\right)_{down} - \left(C/N_o\right)_{up} > 2$ db, and optimum when $\left|\left(C/N_o\right)_{up} - \left(C/N_o\right)_{down}\right| \leq 2$ db

② The channel is R + N_i limited when $(R + N_i) - (I + \Delta) > 2$ db, I limited when $(I + \Delta) - (R + N_i) > 2$ db, and optimum when

$\left|(R + N_i) - (I + \Delta)\right| \leq 2$ db

Low Channel = 316 to 342 kHz
High Channel = 5340 or 5560 at Rosman and 1248 or 1296 at Mojave and Cooby Creek
CCIR Loading (15.8 dbm0 at Rosman and 8.8 dbm0 at Cooby Creek and Mojave)

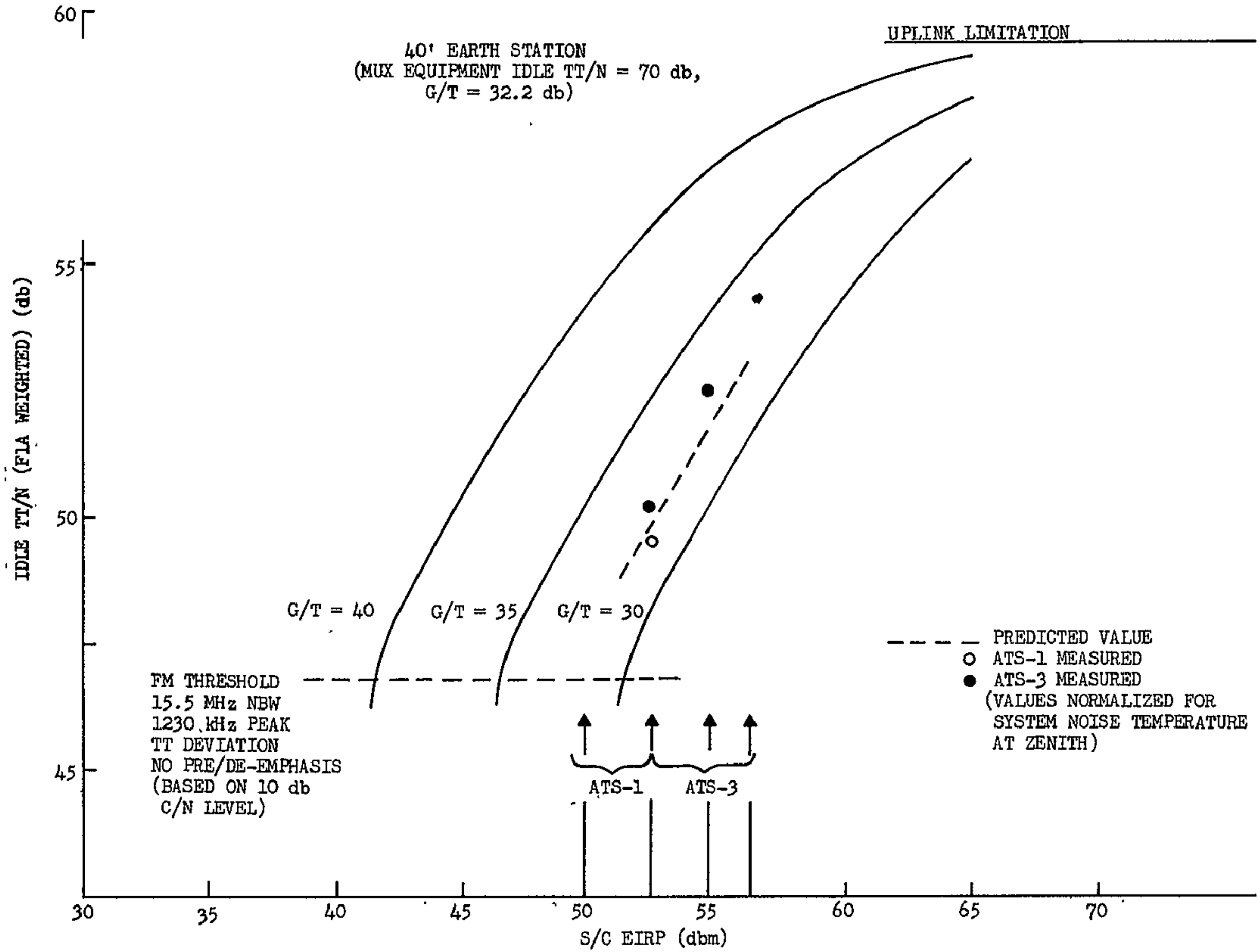


Figure 1.60. FDM Channel Mean Idle TT/N (240 Channels 1296 kHz) vs S/C EIRP

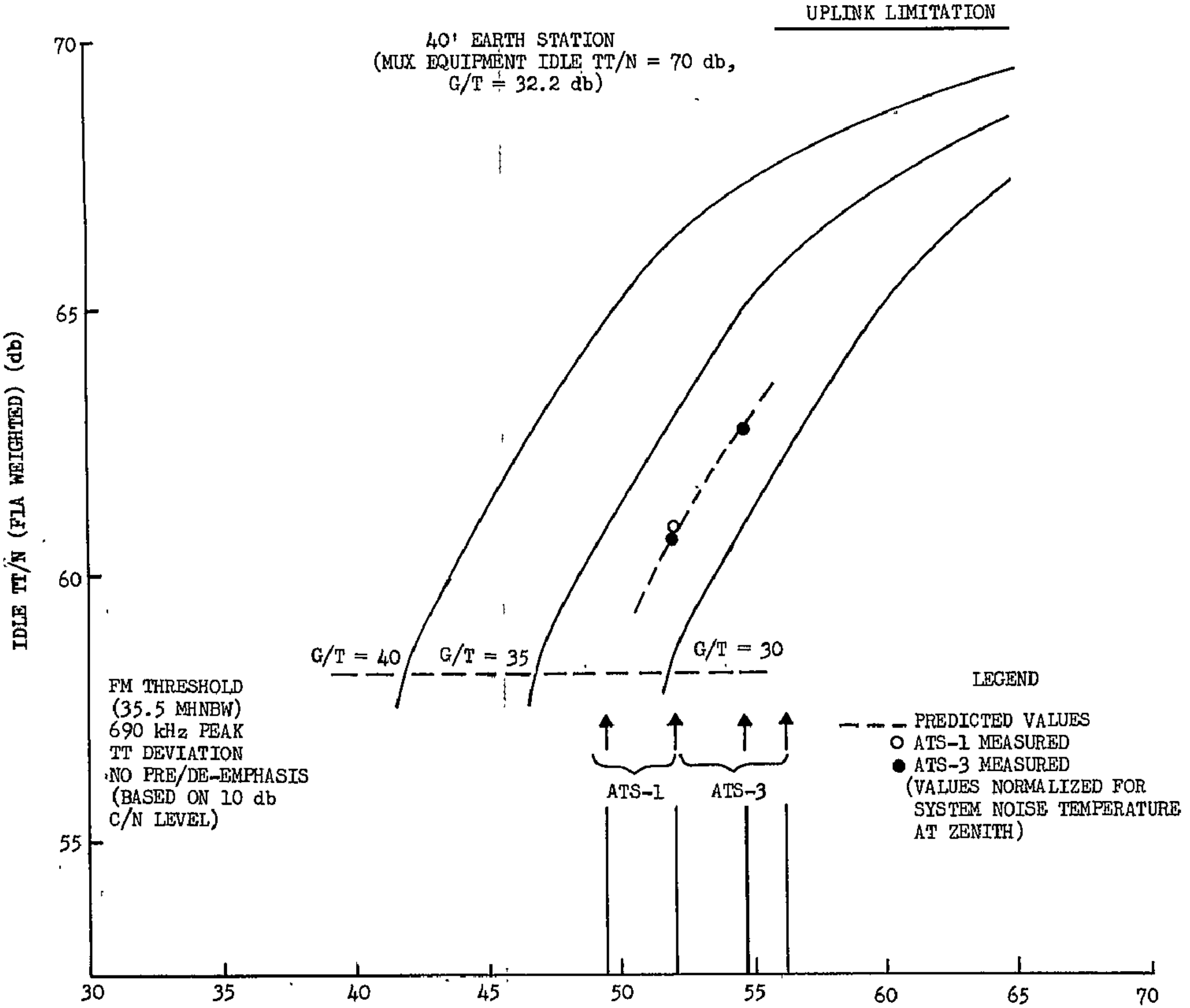


Figure 1.61. FDM Channel Mean Idle TT/N (240 Channels, 328 kHz) vs S/C EIRP

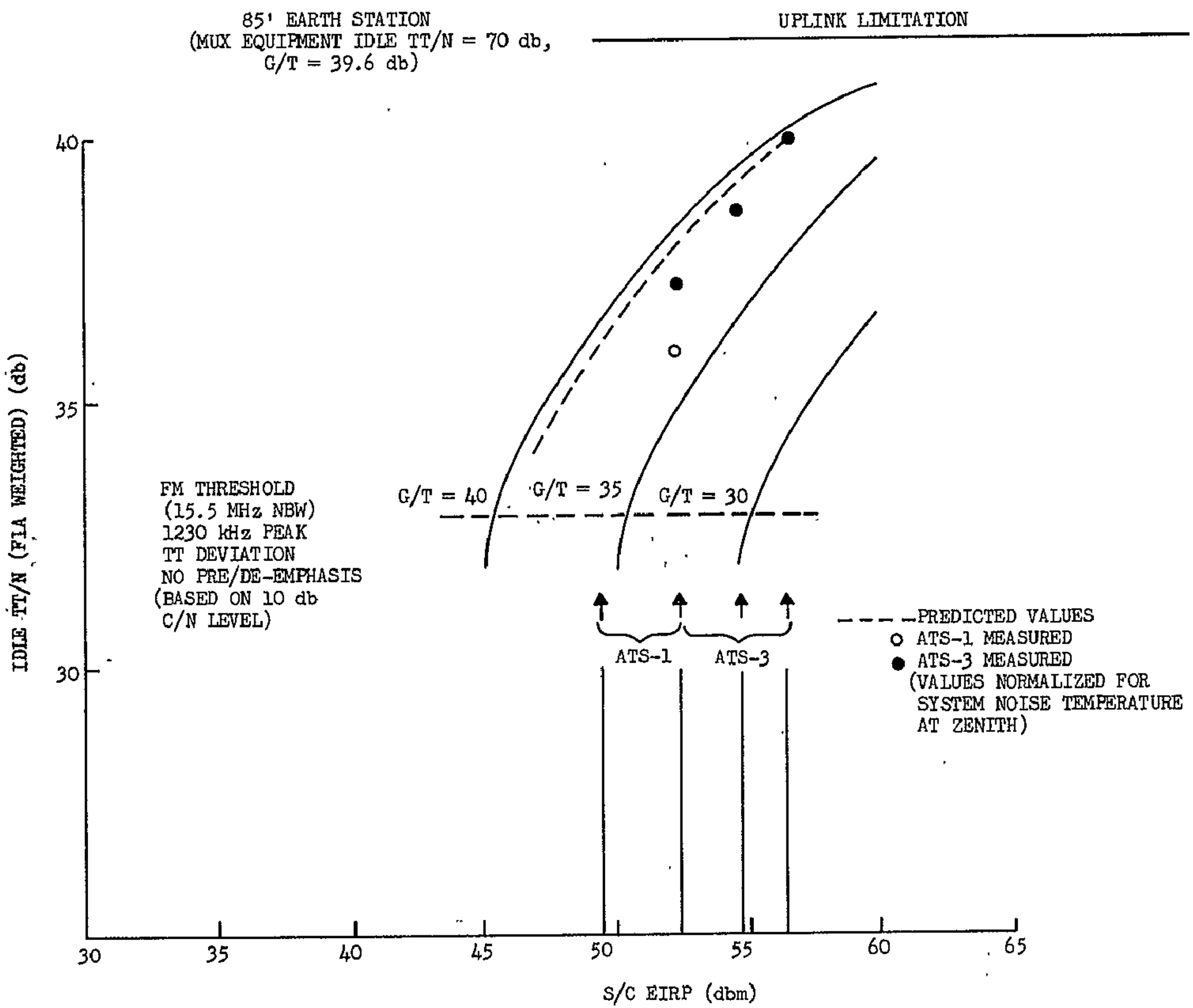


Figure 1.62. FDM Channel Mean Idle TT/N (1200 Channels, 5560 kHz) vs S/C EIRP

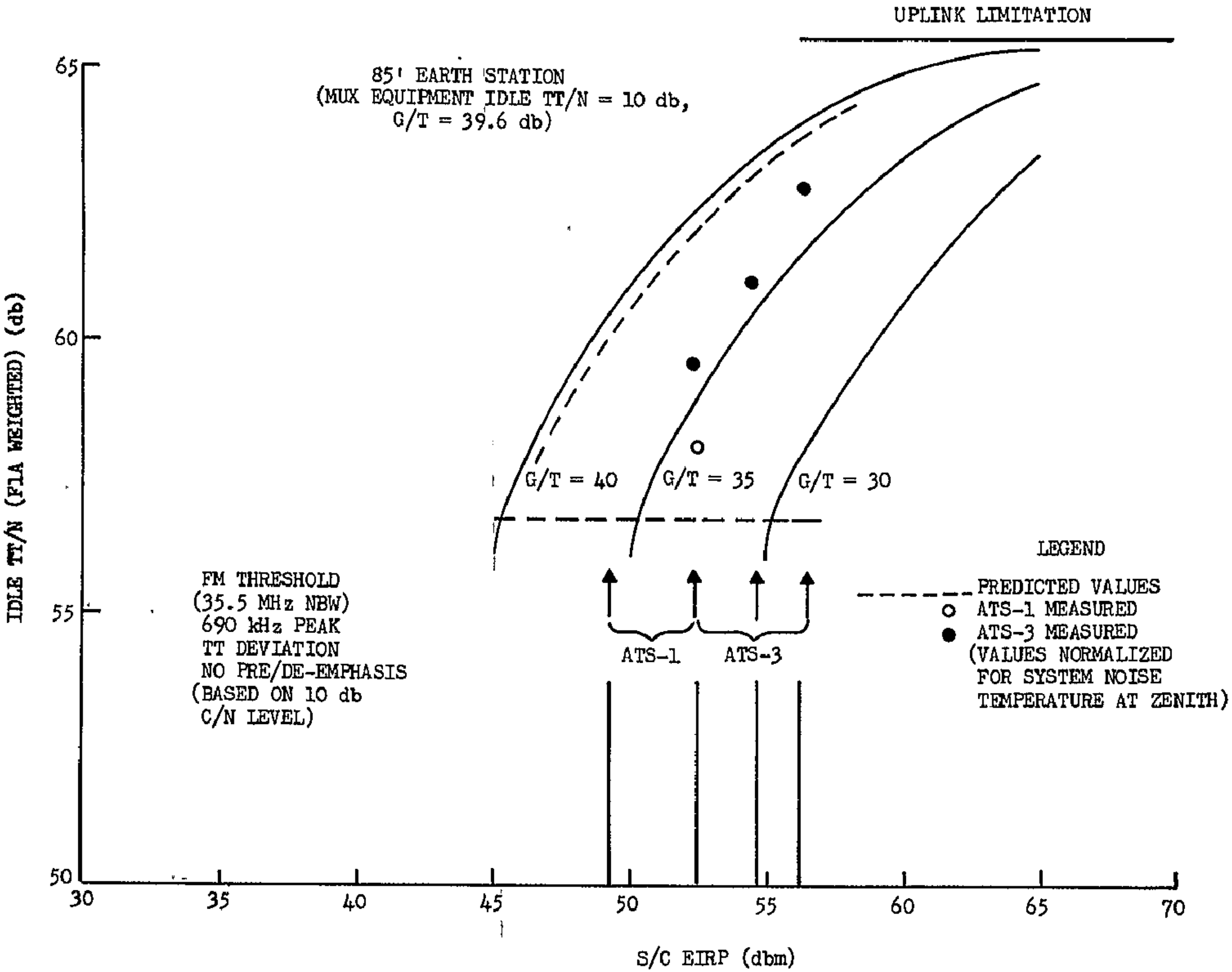


Figure 1.63. FDM Channel Mean Idle TT/N (1200 Channels, 328 kHz) vs S/C EIRP

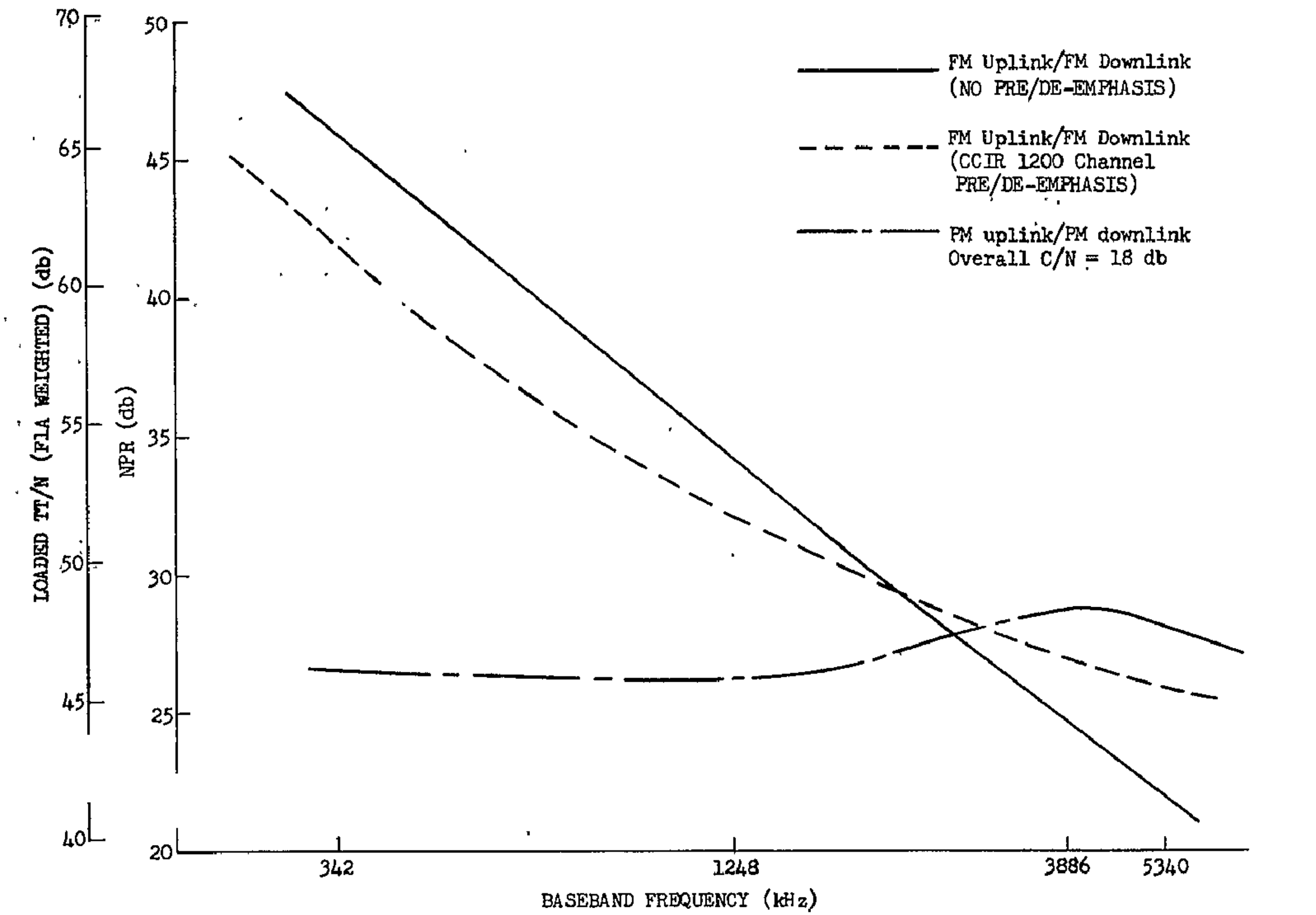


Figure 1.64. Comparison of Pre/De-emphasis in the FM/FM-FDM Mode (ATS-3, 1200 Channel Loading)

1.4.5 NOISE CHARACTERISTICS OF THE FM/FM-FDM MODE

1.4.5.1 Introduction

The baseband noise characteristic of an angle modulation receiver may be defined in terms of the C/N ratio at the demodulator input and the system non-linearities. The C/N ratio is primarily dependent upon spacecraft EIRP and earth station G/T ratio. In the ATS system, spacecraft EIRP ranges from 49.4 dbm to 56.5 dbm while the earth stations G/T have theoretical ratios of 32.2 and 39.6 db for parabolic antennas of 40 feet and 85 feet in diameter, respectively. It is thus possible for an earth station with a 40-foot antenna to operate at a C/N ratio near 7 db, while an 85-foot station may operate (using higher spacecraft EIRP) at a C/N ratio of 20 db. This large range of operational C/N ratios highlights the importance of determining the relationship between the baseband noise characteristics and the overall link C/N ratio. To this end, the noise characteristics are discussed in terms of four significant components, defined as follows:

(I) = Intermodulation noise which varies with the degree and form of modulation and is caused by system non-linearities, but is not a function of C/N ratio.

(R) = Thermal noise which varies linearily with decreasing C/N_o (carrier-to-noise density ratio).

(N_i) = Threshold noise due to impulse (or "click") noise that is a function of C/N and varies in a non-linear manner with C/N.

(Δ) = Threshold noise due to impulse noise that is not only a function of C/N (varies in a non-linear manner with C/N ratio) but also the degree and form of modulation employed.

At low C/N ratios (7 to 10 db), the threshold components (N_i) and (Δ) or ($N_i + \Delta$) are predominant in the lower portion of the baseband. In the intermediate range of C/N ratios, which for the ATS system is 11 to 15 db, thermal noise (R) predominates. At high C/N ratios (20 db), intermodulation noise (I) predominates since the other noise components, which are a function of the C/N ratio, become insignificant.

1.4.5.2 Thermal Noise

The spectral characteristics of the thermal noise power at the output of an FM discriminator varies as the square of the baseband frequency for high C/N ratios. The resulting output baseband noise power spectrum is commonly termed parabolic and is characteristic of the FT mode of operation at high C/N ratios.

Figure 1.65 shows the baseband idle noise characteristics (no carrier modulation) in the FM/FM-FDM mode without de-emphasis. At C/N ratios above 10 db, the primary contributor to the noise spectrum in the 312-kHz to 5564-kHz baseband is thermal noise (R). It can be seen that the R component increases as the square of the baseband frequency. At C/N ratios below 10 db, the threshold effects become increasingly prominent, especially at the low end of the baseband frequency spectrum.

System test tone-to-noise performance can be improved at the high end of the base band with the use of de-emphasis to equalize the noise component, R, across the baseband. Figure 1.68 shows the equalization of the baseband idle noise based on the standard CCIR 1200 channel de-emphasis network (recommendation 275-1, Oslo, 1966), as well as the CCIR 240 channel de-emphasis network. Characteristically, the noise is increased at the low end of the baseband, while at the high end, it is decreased relative to the idle noise without de-emphasis.

Optimum de-emphasis for the FM/FM-FDM mode depends on the amount of increase in noise which can be tolerated in the low end of the baseband to improve the high end and must take into account any increase in non-linear noise in the low end of the baseband due to system non-linearities. For the particular case shown, a maximum improvement of 4 db is realized at the high end while the low end degradation does not exceed 4 db for the 1200-channel network. On the basis of the 240-channel de-emphasis network the noise is equalized such that a maximum test tone-to-idle noise improvement of 4 db is realized at the high end of the baseband, while the low-end degradation does not exceed 3 db.

1.4.5.3 Threshold Noise

At C/N ratios of 10 db or less the noise level in the lower portion of the baseband is greater than predicted from theory for thermal noise (refer to figure 1.65).

This phenomenon of increased low frequency noise in the baseband noise spectral characteristics at the FM discriminator output for the threshold region has been analyzed in a number of publications (42-44). It is explained by noting that the baseband noise consists not only of thermal (parabolic) noise, but also a flat noise which is a critical function of C/N. This flat noise spectrum is sometimes called impulse (or "click") noise because its amplitude is proportional to the number of impulses ("clicks") per second. The flat noise spectrum arises from the fact that the frequency response of the baseband filter is essentially flat within the regions of interest for an impulse input. The flat noise consists of two components: N_i, the threshold noise which is only a function of C/N, and Δ, the threshold noise which is due to the degree and form of modulation as well as the C/N ratio. At low C/N ratios (below 10 db), the threshold noise components become dominant in the low end of the baseband relative to the thermal noise.

It can be seen in figure 1.65 that as C/N is decreased, the N_i component causes the noise spectrum to become flat in the low end of the baseband as discussed above. In going from a C/N ratio of 18 db to 8 db, the N_i threshold component at 342 kHz increased the total idle noise approximately 1 db (increase above the parabolic noise change due to the decrease in C/N).

When modulation is applied, the Δ component is present. This case is shown in figure 1.66. In going from a C/N ration of 18 db to 8 db, both threshold components ($N_i + \Delta$) now increase the total noise approximately 13 db at 342 kHz above the expected 10 db increase in parabolic noise due to the C/N noise. Thus the Δ component contribution is approximately 11.7 db above the idle noise terms ($R + N_i$) at this baseband frequency. To arrive at the above results, single tone modulation (10-MHz peak deviation) was used so that baseband intermodulation products would not contribute to the increase in noise with modulation. Although the form of modulation used to simulate multichannel telephony is different from that used for this test, the significant Δ noise component contribution discussed above is indicative of the presence of this component when a white noise-like signal is used for modulation.

1.4.5.4 Non-Linear Noise

Intermodulation and harmonic non-linear baseband distortion in the FM/FM-FDM mode is caused by three basic sources (for single carrier operation) in the IF/RF region:

a) amplitude response non-linearities

b) phase response non-linearities

c) spectrum truncation of the modulated signal

These affect the modulated signal spectrum in such a way that linear distortion occurs. It is not until the demodulator operates on the IF-RF signal spectrum that new frequencies or non-linear distortion is generated in the baseband. Also, the non-linearity of the FM modulator and demodulator creates non-linear distortion. In the baseband amplifier, the chief cause of non-linear distortion is the non-linear dynamic amplitude transfer characteristic.

The sensitivity of the system to amplitude response deviations of the frequency modulated downlink signal is reduced as the index of modulation is increased[48]. Since for nominal 1200-channel conditions the modulation index is large, the importance of amplitude response deviations is greatly reduced and thus is not considered significant for the ATS modes of operation.

It should be noted that harmonic distortion is insignificant compared to intermodulation when a band-limited white guassian noise signal is used for modulation. The harmonic distortion is insignificant for two reasons: (1) the number of harmonic products of any particular order is at least an order of magnitude less than intermodulation products of the same order; and (2) the magnitude of the harmonic products is several db below the level of the intermodulation products of the same order.

The non-linear noise characteristics of the system are determined by two techniques; multitone tests and noise loading tests. In the noise loading test, the system is modulated with a band-limited white guassian noise signal (which simulates multichannel telephony) in a manner which follows CCIR Recommendation 353-1, Oslo, 1966. The signal density-to-total noise density ratio (NPR) and the signal density-to-idle noise density ratio (TPR) are measured in several channels across the baseband in order to determine the baseband noise characteristic. The total intermodulation noise level from all effects is determined from the loaded noise (NPR) and idle noise (TPR) measurements as follows:

$$K = \frac{(TPR)(NPR)}{TPR-NPR} \quad \text{(numeric)}$$

where K is the signal density-to-intermodulation noise density ratio. In the threshold region it should be noted that the above equation yields the signal density-to-$(I + \Delta)$ density ratio, thus it cannot be used to determine K.

There is a definite relationship between the results of single and two tone tests and signal density-to-intermodulation noise density ratio determined from the NPR/TPR results. These relationships are quite complex from the standpoint that the relative spectra of various orders of intermodulation noise must be determined for all significant causes of intermodulation noise, the sum total of which combines into the total nonlinear noise spectrum that exists at the baseband output of the earth station receiver. These relationships have been developed in several papers for most of the causes of nonlinear noise previously discussed (39, 26, 43, 49). Typical relationships are developed in subsection 7.7.

Figures 1.69 and 1.70 show the results of single and two tone tests, respectively, performed at Rosman (1200 channel spectrum). Referring to the two tone test (figure 1.70) it may be seen that the second and third order intermodulation products exhibit a frequency dependence across the baseband. The is characteristic of phase non-lineariy in the IF filters, either in the spacecraft, or in the ground receiver.

As shown in figure 1.70 the second and third order IM products are the dominant components for the system. This fact coupled with the baseband frequency dependence of the IM products leads to the conclusion that the linear and parabolic IF/RF group delay factors are the principal sources of the IM noise level in the FM/FM-FDM mode of operation. Utilizing the techniques developed in subsection 7.7 it is possible to compute the resulting second and third order group delay IM noise spectra for a band-limited white guassian noise input. The IM noise level for each order is then computed as a function of baseband frequency by utilizing the above spectra and the measured ratios from the two tone tests. The resulting values are shown as curves B and D in figure 1.67.

Comparison of the signal density-to-intermodulation noise density ratios presented in figure 1.67 shows that the linear group delay (second order intermodulation) is the limiting factor in the channel performance (Rosman, 1200 channel spectrum). The effect of parabolic group delay (third order intermodulation) (curve D of figure 1.67) is added (on a power basis) to the linear group delay to provide the overall signal density-to-intermodulation noise density characteristic. (curve A of figure 1.67). A comparison of the intermodulation spectrum computed from NPR/TPR (curve C of figure 1.67) shows agreement within ±2 db with the spectrum computed from the multitone test data. This close agreement between the two methods reinforces the conclusion that group delay is the predominant source of the intermodulation distortion in the FT mode of operation.

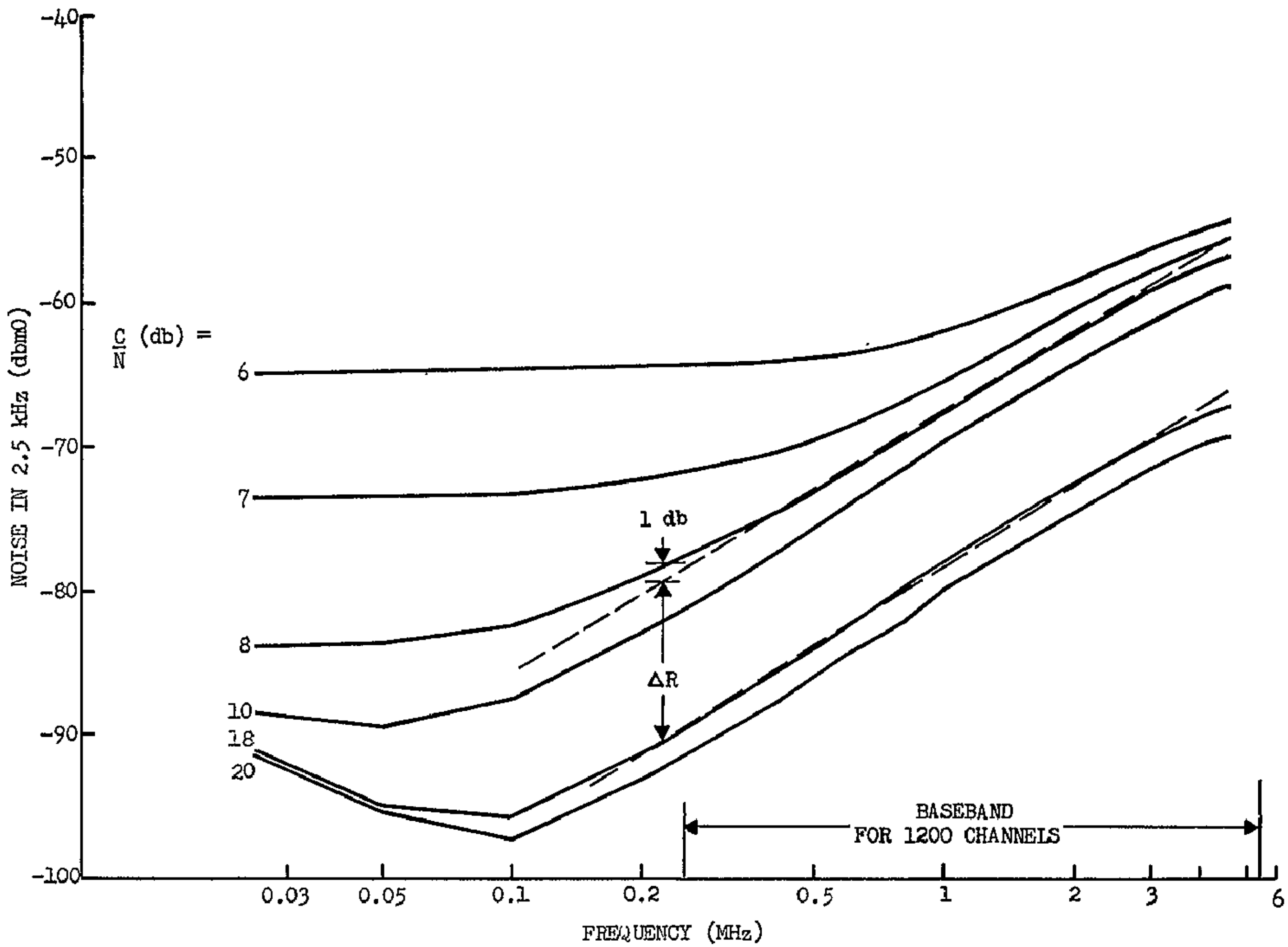
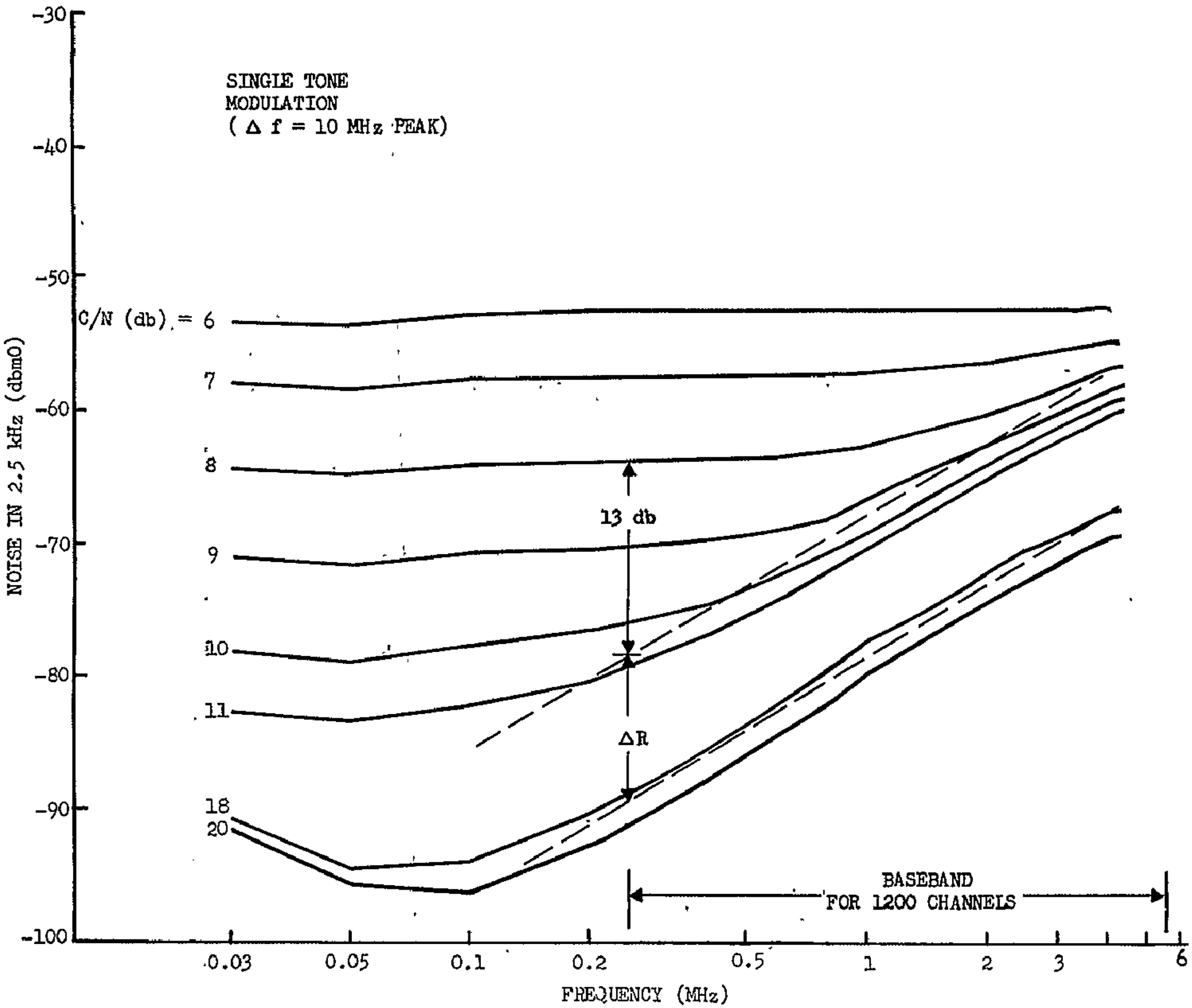


Figure 1.65. Idle Noise Spectrum For Various C/N Ratios (FT Mode)


SINGLE TONE
MODULATION
(Δ f = 10 MHz PEAK)
NOISE IN 2.5 kHz (dbm0)
-30
-40
-50
-60
-70
-80
-90
-100
C/N (db) = 6
7
8
9
10
11
18
20
13 db
ΔR
BASEBAND
FOR 1200 CHANNELS
0.03
0.05
0.1
0.2
0.5
1
2
3
6
FREQUENCY (MHz)

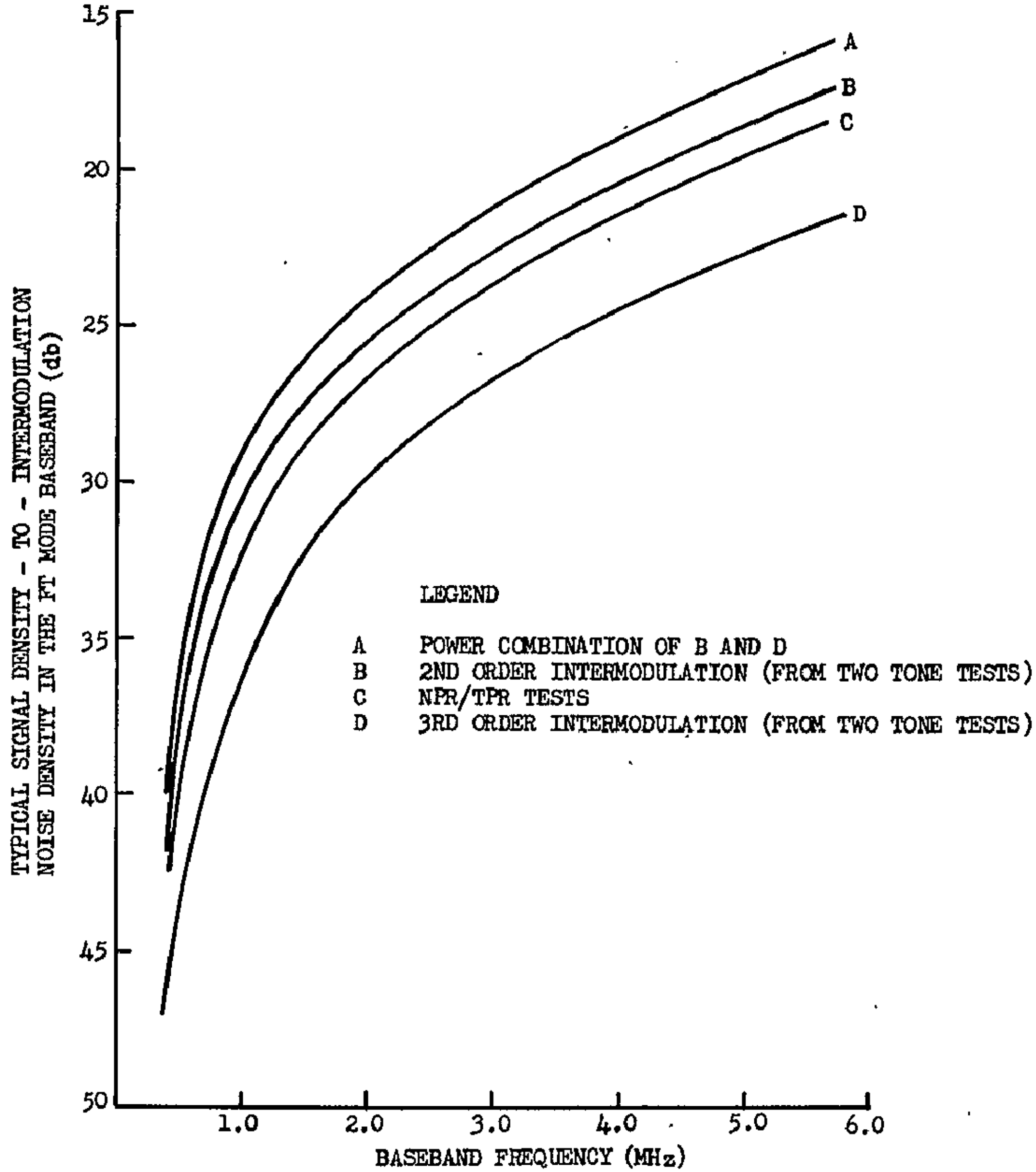
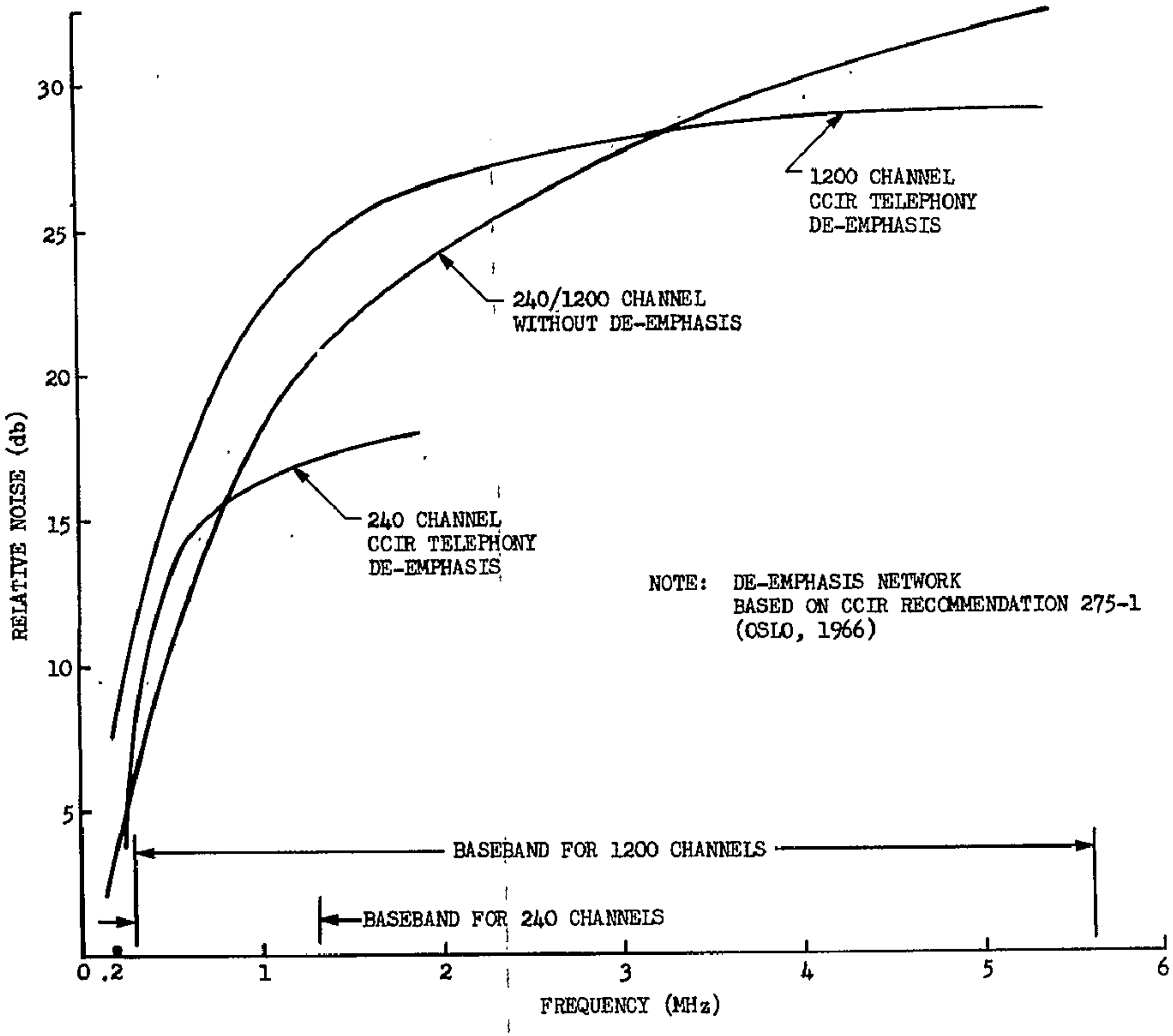


Figure 1.67. Intermodulation Noise Spectrum (FT Mode, Rosman, 1200 Channels)


RELATIVE NOISE (db)
FREQUENCY (MHz)
1200 CHANNEL
CCIR TELEPHONY
DE-EMPHASIS
240/1200 CHANNEL
WITHOUT DE-EMPHASIS
240 CHANNEL
CCIR TELEPHONY
DE-EMPHASIS
NOTE: DE-EMPHASIS NETWORK
BASED ON CCIR RECOMMENDATION 275-1
(OSLO, 1966)
BASEBAND FOR 1200 CHANNELS
BASEBAND FOR 240 CHANNELS
30
25
20
15
10
5
0
.2
1
2
3
4
5
6

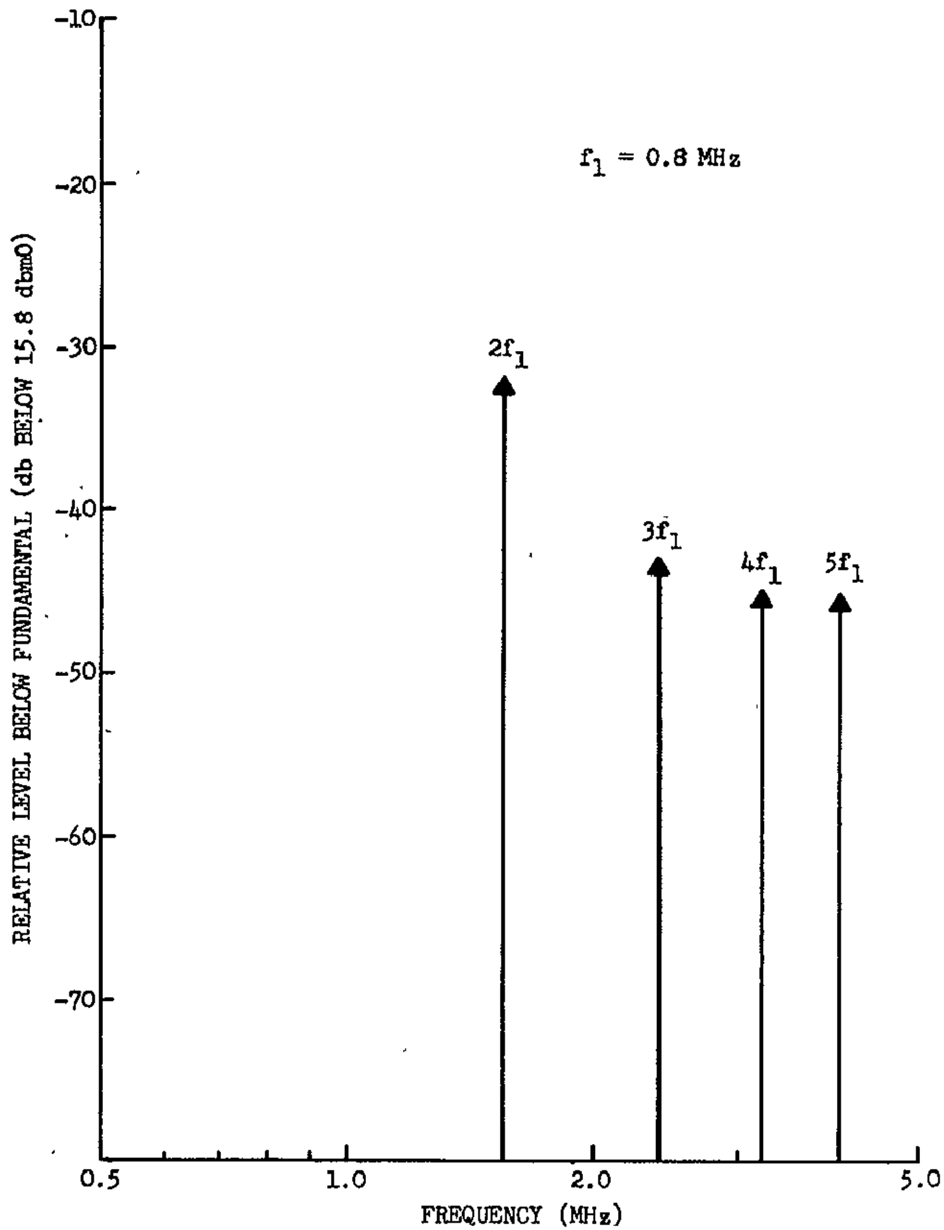


Figure 1.69. Single Tone Intermodulation Test Results (Rosman, FT Mode)

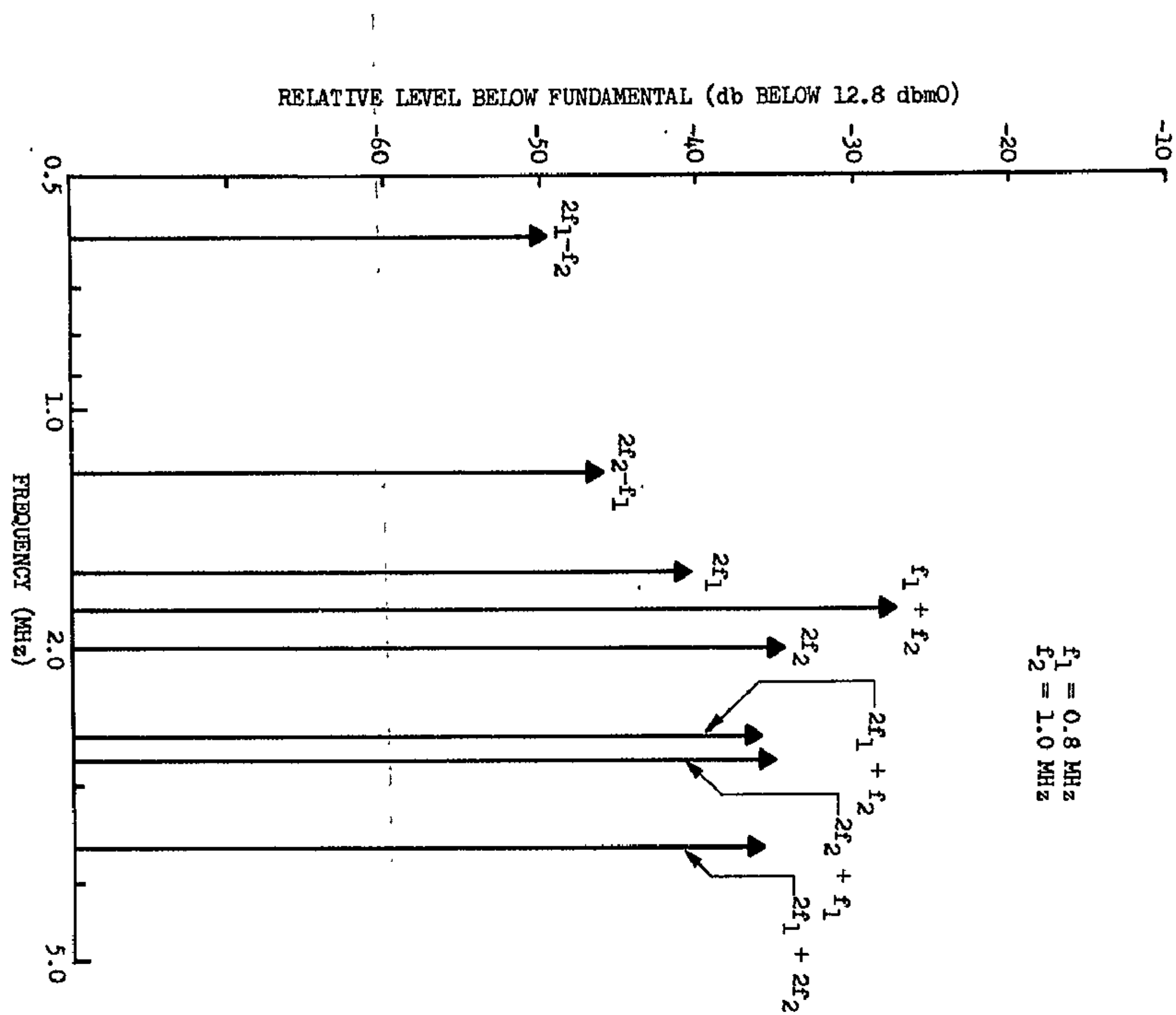


Figure 1.70. Two Tone Intermodulation Test Results (Rosman, FT Mode)

1.4.6 MULTIPLEX CHANNEL FREQUENCY STABILITY

Multiplex channel frequency instability can be produced by several factors: 1) multiplex equipment; 2) short term and long term master oscillator instability; and 3) satellite doppler. The effect of the first of these is to introduce instabilities which can be readily corrected and is not considered in this discussion. The second effect includes oscillator jitter noise, 60 Hz incidental modulation and long term oscillator frequency drift. The oscillator phase jitter and 60-Hz incidental modulation appear on the RF carrier and sidebands alike, therefore, their effect is minimal. The master oscillator frequency is regulated by a phase lock loop, providing very stable long term frequency characteristics.

The effects of satellite doppler remain, then, to be discussed in this section. There are basically two sources of doppler.

1.4.6.1 Effect of Range Rate

From spacecraft acquisition tables, range rate values relative to the earth station are given at half-hour intervals over extended periods of time. If these values of range rate are plotted against time, it is seen that range rate as function of time is approximated by

$$\dot{r} = A \operatorname{Sin} \frac{\pi t}{12} \qquad (1)$$

where:

A = max range rate in a 24-hr period

t = time in hours

From the acquisition tables, A is seen to vary nominally from 3 to 10 ft/sec. If a radiating body is moving relative to an observer, then the difference in observed frequency due to the time rate of change of range between the body and the observer is given by

$$\delta F = \frac{\dot{r} f}{C} \qquad (2)$$

where:

δF = frequency shift

$\dot{r}$ = velocity of the radiating body relative to the observer (range rate)

f = frequency of radiation

C = speed of light

In the case of a satellite, equation (2) applies both to the uplink and to the downlink, so that the frequency shift (doppler) between the ground transmitted signal and the ground received signal is

$$\delta F = \frac{2\dot{r} f}{C} \qquad (3)$$

Substituting (3) into equation (1), and assuming a maximum range rate of 10 ft/sec, we obtain

$$\delta f = \frac{2(10)f}{C} \cdot \operatorname{Sin} \frac{\pi t}{12} \quad (\mathrm{Hz}) \tag{4}$$

From this equation, the change of δf over any period in the range rate cycle can be calculated. If we set the argument of the sine term equal to $\pi/2$, then δf will be maximum and becomes:

$$\delta f = \frac{2(10)f}{C} \tag{5}$$

Since the uplink and downlink signals are both FM, the quantity of interest is the difference in frequency shift between the RF carrier and the sidebands of interest (differential doppler). In the ATS system, this difference is greatest for a sideband at the high end of the baseband. The highest sideband is 5.6 MHz. For ease of calculation, a 5-MHz sideband is chosen and equation (5) becomes: $\delta f = 0.10$ Hz.

Satellite station changing maneuvers affect the value of relative range rate. From May 2 through 12, 1968, ATS-3 changed position from 84° W longitude to 62.7° W longitude. During this time a range rate value of 52 ft/sec was observed. Substituting this value for $\dot{r}$, and again assuming a 5-MHz channel subcarrier (sideband), equation (3) gives the result $\delta f = 0.53$ Hz.

The 0.53 Hz frequency change due to differential doppler represents the worst case observed for the ATS satellites. Figure 1.71 extends this calculation to a spectrum of values of range-rate and sideband frequencies. CCIR report 214-1 suggests a maximum range rate for synchronous satellites of 5.8 meters/sec. The sideband frequency shift due to differential doppler corresponding to this value of range rate can be read off figure 1.71 as 0.18 Hz. The frequency shift corresponding to a 5-MHz sideband is marked on the graph. In both cases the frequency shift of the sideband is negligible.

1.4.6.2 Effect of Spin Modulation

A pronounced 1.6-Hz frequency variation has been observed in the multiple access mode (SSB uplink, PhM downlink). This is caused by the satellite receiving antenna phase center being slightly offset from the spin axis, so that this phase center approaches and recedes from the earth station at a rate of 1.6 cycles per second. The method of determining the amount of frequency deviation in the FM/FM-FDM mode is to calculate the diameter of the circle described by the rotating phase center and then to calculate the differential doppler in a 5-MHz multiplex channel. This calculation (see section 7.6) shows that the corresponding frequency deviation at the 1.6 Hz S/C spin rate in a 5-MHz channel is 0.0005 Hz, which again is negligible.

1.4.6.3 Conclusions

Since the worst case for $\dot{r}$ was 52 feet per second and this was during a change in satellite position, the computed sideband frequency shift of 0.5 Hz is, for all practical purposes, negligible.

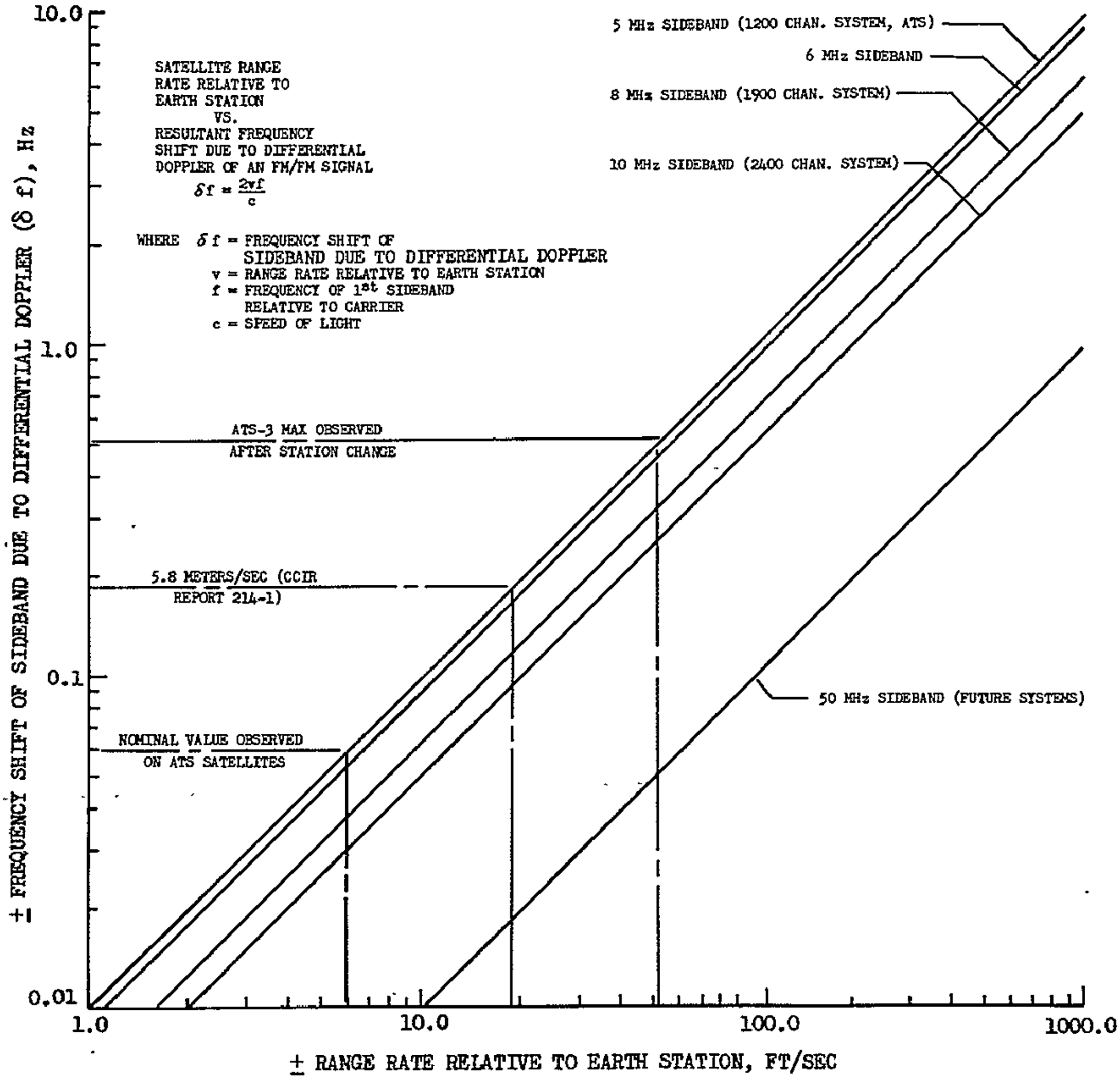


Figure 1.71. Differential Doppler of an FM/FM Signal

1.4.7 DATA ERROR RATE

The data error rate in an FDM channel is primarily a function of the channel TT/N ratio and the channel characteristics. The mode of system operation produces only second order effects which are of no significance in the ATS system. Since the discussion of data error rate presented in section 1.1.2.8 is applicable to the FM/FM mode, the reader is referred to that section for the test description and results.

2. SHF COMMUNICATIONS EXPERIMENT LINK CALCULATIONS AND IMPLEMENTATION – DELETED