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L5 SYSTEM:

Jumbogroup Multiplex Terminal

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The jumbogroup multiplex (JMX) translates basic jumbogroup signals to and from the L5 line spectrum. Each of three jumbogroups provides 3600 4-kHz voice circuits. In addition to frequency translation, the JMX provides regulation and equalization on a jumbogroup basis and automatic one-for-one protection.

Performance objectives are discussed and interpreted from the perspective of their influence on the design philosophy and approach used and the resultant physical realization. All subsystems are presented in detail. Particular mention is made of the double-balanced diode-ring modulator developed for JMX application.

I. INTRODUCTION

While gross performance objectives for analog multiplex equipment are available, the detailed statement of design objectives is part of the development task. The basic guiding principle is that the resultant system, the aggregate of line and terminal equipment, must provide transmission paths of quality and reliability appropriate to the Bell System communication network, and it must do so at a cost sufficiently lower than other alternatives to warrant development by Bell Laboratories, manufacture by Western Electric, and purchase by Long Lines and the operating telephone companies.

The basic function of the jumbogroup multiplex (JMX) terminal is to translate basic jumbogroup signals to and from the L5 line spectrum. Each of the three jumbogroups is composed of six mastergroups. These signals must not be corrupted or distorted by the JMX in a manner or degree that would compromise the quality of transmission. The equipment must be reliable and maintainable. Derivable from these considerations are a host of performance objectives, including those discussed in the following sections.

1.1 Terminal noise

The overall objective on noise, including thermal noise and intermodulation, for a 4000-mile, transcontinental, L5 system is 40 dBrnc0.[1] Of the total, 39.4 dBrnc0 is allocated to the L5 line, and the remaining 31.2 dBrnc0 is allocated to the aggregate of all terminal equipment. While the L5 line is, in a sense, a totally new design entity, such is not the case in the associated terminal equipment. The JMX has to share the terminal noise allocation with an existing hierarchy of equipment, including channel, group, supergroup, and mastergroup banks. Consider a representative transcontinental connection including two channel banks, five supergroup multiplex (LMX) terminals, seven mastergroup multiplex (MMX) terminals, and eight JMX terminals. Assuming 18 dBrnc0 performance for the LMX and MMX terminals and 10 dBrnc0 for the channel banks, a maximal allocation of 18 dBrnc0 results for the JMX. Allowing 1 dB for misalignment and other vagaries, including the possibility of other connections more demanding than the one cited, the JMX design objective was set at 17 dBrnc0, with the realization that an even lower number would be desirable. In essence, it appeared that at least initially the design philosophy should be to obtain the lowest noise possible.

To put the 17-dBrnc0 objective into perspective, it is helpful to view the JMX challenge relative to the most comparable multiplex available, the MMX-2.[2] In an optimally designed multiplex terminal, the controlling noise sources are the modulators and the associated amplifiers following the modulators. Normally, the intermodulation distortion of the modulators is greater than that of the other transmission apparatus, so that lowest signal levels are found at modulator outputs. Since levels are low at such points, the noise figure of the following amplifier is of greatest importance. Levels are chosen to minimize the combined noise from these critical nodes. Since the JMX uses multiple steps of modulation and demodulation, while MMX-2 uses single steps, the JMX has twice as many critical nodes in each transmission path as the MMX. Furthermore, the bandwidth of the jumbogroup signal is six times that of the mastergroup signal. For third-order intermodulation distortion alone, the number of products the JMX must contend with is 16 dB greater than in the MMX. In a sense, JMX must be many decibels better than MMX-2 to yield comparable noise performance.

1.2 Crosstalk

Based on studies of typical system configurations, with the multiplicity of occasions for crosstalk, an objective of 85 dB equal-level coupling loss (ELCL) has evolved for analog multiplex equipment. This objective was assumed for the JMX.

The sources of crosstalk in multiplex equipment are many and varied, and include many modes not encountered elsewhere. Crosstalk may occur between different jumbogroup signals, between different portions of the same jumbogroup, between signals at different stages in the modulation-demodulation process, and in an intelligible or noise-like fashion. Coupling may exist between signals, between carriers, between pilots and carriers, etc. While an exhaustive discussion of crosstalk is inappropriate here, one typical illustrative example will be mentioned.

Given a carrier with a tone 4 kHz removed from the carrier at a level 79 dB lower than the carrier level, intelligible adjacent channel crosstalk appears in almost every channel at a level approximately 85 dB below the level of the interfered channel. Because of this mode of crosstalk, spectral purity of JMX carriers is important. Since JMX carriers are as high in frequency as 91.648 MHz, filtering, shielding, and grounding are critical. Common ground impedances of very small magnitude are sufficient to cause unacceptable crosstalk performance.

1.3 Spurious tones

Tones falling in a voice channel are particularly annoying. Often, tones generated from several sources add coherently (voltage addition). Because of the multiplicity of sources of tones, the design objective for JMX was that no tone falling in the jumbogroup passband should have a level exceeding −70 dBm0. This becomes particularly challenging when, in the JMX, the source of the tone may be a 15-dBm, 91.648-MHz carrier, and transmission levels are as low as −43 dB. The resulting implications on isolation of separate paths, carrier balance, and filtering of carrier leak signals are significant.

1.4 Frequency offset

The transcontinental objective on frequency offset is less than 2 Hz. This implies an accuracy requirement of one part in 10^8 on the effective carrier frequencies used in the JMX.

1.5 Passband distortion

The overall misalignment objective for a transcontinental L5 connection is less than ±4 dB. This requires that the JMX passband be flat to ±0.2 dB. In addition, since the JMX may carry digital signals, delay distortion must be limited.

1.6 Reliability

The L5 line,[3] with its automatic line-protection switching system,[4] is highly reliable. If terminal equipment is not to add noticeably to the mean outage time for a transcontinental connection, based on the system configuration considered earlier, the objective for each JMX path (transmit or receive) becomes less than 0.14 minute per year. This corresponds to an equivalent failure rate of about 200 FIT's (mean time to failure is 500 years), assuming that the mean time for repair is one hour.

1.7 Maintainability

While it is difficult to become quantitative relative to maintainability, several observations of a qualitative nature may be made. Each piece of transmission equipment can handle as many channels as a whole L4 system. The equipment may be housed in unmanned main stations.[5] Many modes of failure are of a subtle nature. It therefore seems desirable to use automatic, remote diagnostics extensively. Routine measurements at the bay should be held to a minimum. Most troubleshooting on site should require no removal of modules prior to trouble isolation. Status indicators should be provided for the controlled and trouble states of the equipment. In short, the equipment should be easy to maintain and difficult to operate incorrectly.

1.8 Cost

The cost of the JMX on a per-channel basis may be reasonably viewed from two perspectives: (*i*) its contribution to the total terminal cost for the terminal equipment required to take a voice signal from voice frequency to basic jumbogroup frequency and back, including signaling, and (*ii*) its contribution to the cost of an L5 system for a system length of a few hundred miles or more. It has been estimated that the per-channel cost of the JMX amounts to less than 2 percent of either the terminal or line cost; therefore, the JMX cost would have very little influence on the total cost of providing a voice channel.

II. GENERAL DESCRIPTION

2.1 Transmitting circuits

An overall block diagram of the transmitting arrangement, typical of any jumbogroup, is shown in Fig. 1. Basic jumbogroup signals, composed of six mastergroup signals, and a 5.888-MHz jumbogroup pilot are fed to the JMX from the basic jumbogroup trunk bay (BJGT).[6]

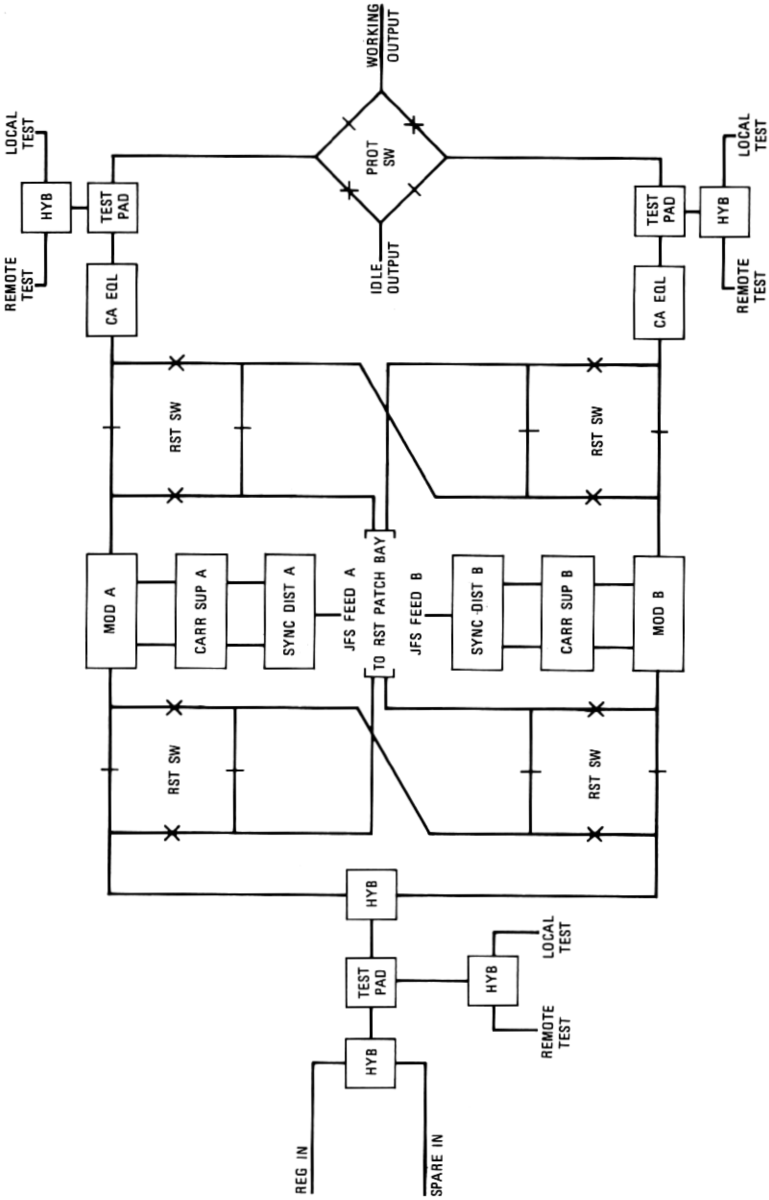

Fig. 1—Jumbogroup transmitting arrangement.

These signals, contained between 0.564 and 17.548 MHz, first enter the JMX at the transmitting jack field. Two input ports are provided. The first or regular input is that through which the signal normally passes. The second or spare input is provided for emergency patching purposes and is normally terminated. These two inputs are combined in an input hybrid transformer and then connected to a test pad that provides a low-loss (0.6 dB) through path and a high-loss (30 dB) bridging path. The high-loss or low-level output is fed to a splitting transformer, and provides a local and a remote test point, both of which are isolated from the transmission path by about 33 dB of loss. Local test points are accessed via jacks mounted at the front of the bay. Remote test points are provided to allow access for automated, centralized test equipment. The low-loss pad output is fed to a splitting hybrid that provides signals to the redundant A and B paths of the transmitting side.

The basic jumbogroup signal then passes through the restoration access switches which, when operated, are capable of providing an appearance of the basic jumbogroup signal and access to the input of the associated modulator at the restoration patch bay. These switches are connected in a manner that allows monitoring of the interbay cabling when the switches are in the unoperated condition.

The basic jumbogroup signal then goes to the modulators, where it is filtered and translated to any one of three jumbogroup line assignments. Multiple steps of modulation are used, and the required carriers are provided by the associated carrier supply. Carrier supplies are redundantly provided for each jumbogroup. Each carrier supply provides the carrier signals for an associated modulator and demodulator. Carriers are generated by appropriately mixing internally generated signals with signals provided by the sync-distribution circuit. There are two sync-distribution circuits per bay, each of which uses redundantly provided jumbogroup frequency supply (JFS)[7] signals to generate a number of highly stable reference signals for transmission to all of the A or B carrier supplies.

The jumbogroup signal, at line frequency, is then fed through the output restoration switch to the cable equalizer. The output restoration switch, connected in a manner similar to that of the input restoration switch, provides access to the modulator output. The cable equalizer, located in the transmitting line-interface unit, compensates for the loss of the cable connecting the JMX to the L5 line bay.[6] Levels are adjusted in the transmitting line interface to provide a stepped preemphasis for transmission over the repeatered L5 line.

The cable equalizer output passes through a test pad which provides a high-loss access for local and remote testing and a low-loss path to the transmitting protection switch. The transmitting switch accepts the A and B output signals as inputs, and provides a working and idle output. The state of the switch, set by the switch-control circuitry, determines which input will be connected to the working and idle outputs. Both outputs are fed to unequal-ratio hybrid transformers which provide a high-loss (7 dB) output for monitoring purposes, and a low-loss (1 dB) output that is connected to the transmitting jack field. The working output signal is then cabled to the L5 line bay, and the idle output, available for emergency patching through spare cabling, is normally terminated.

2.2 Receiving circuit

On the receiving side (Fig. 2), the complete L5 spectrum is redundantly cabled to the receiving jack field of each jumbogroup equipment. The signal first passes through a test pad that provides high-loss access for testing and a low-loss connection to the associated cable equalizer. The cable equalizer compensates for the loss of the cable between the L5 line bay and the JMX. The signal is then fed to an input restoration switch which is capable of providing an appearance of the L5 line signal and access to the demodulator input at the restoration patch bay.

The received signal then goes to the demodulator where the desired jumbogroup is selected and translated to basic jumbogroup frequency. After passing through an output restoration switch, which can be used to gain access to the demodulator output for the restoration patch bay, the signal is fed through a test pad to the basic jumbogroup equalizer, a manually adjustable, multistage equalizer that will provide* the capability of correcting for misalignment accrued over many miles of the repeatered L5 line on a jumbogroup basis. The signal then goes to the regulator which monitors the level of the received jumbogroup pilot and modifies its gain accordingly.

The regulator output is fed through another test pad to the receiving protection switch. Working and idle outputs are connected to unequal-ratio hybrid transformers that provide access points for automatic monitoring in addition to output signals connected to the receiving

* Space and power have been provided for the jumbogroup equalizer in the JMX bay. Determination of the appropriate characteristics of this equalizer awaits evaluation of misalignments for working L5 systems.

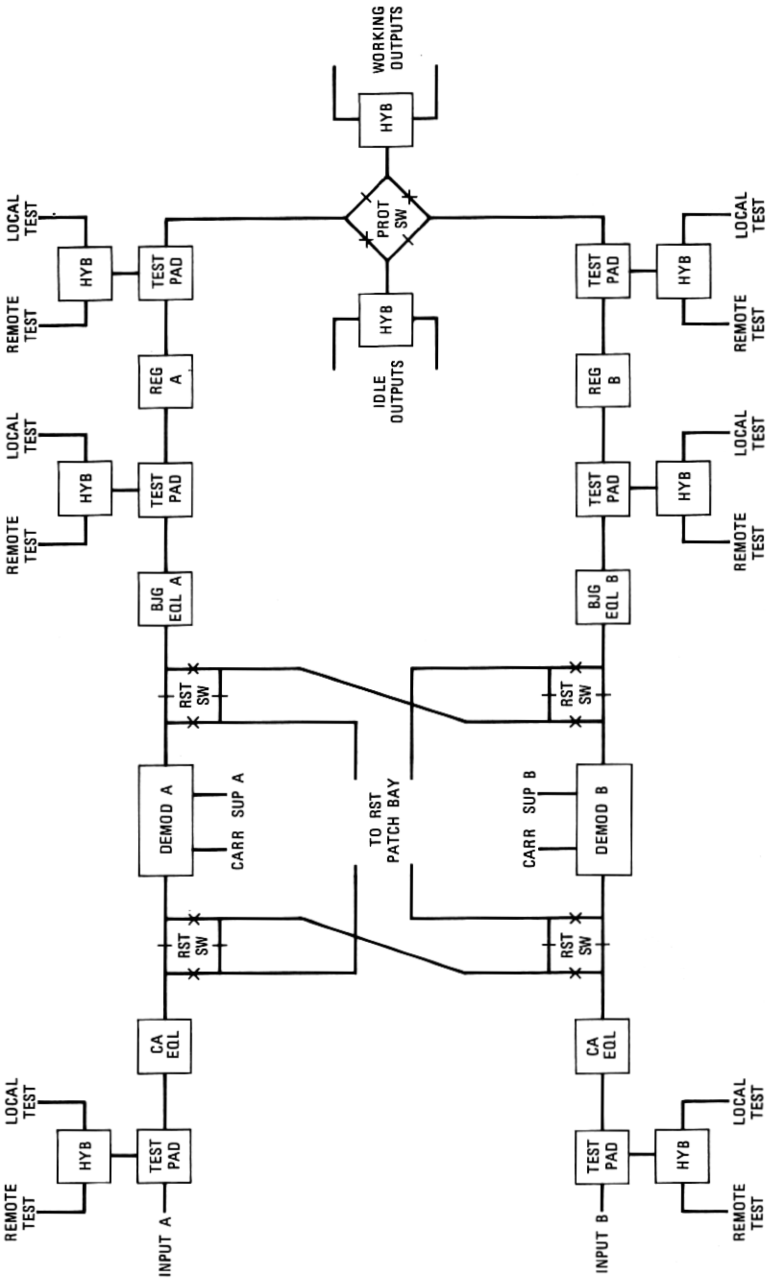

Fig. 2—Jumbogroup receiving arrangement.

patch field. Additional equal-ratio hybrid transformers are used to provide dual appearances of the working and idle output signals. One of the working output signals is cabled to the BJGT. The remaining ports, available for emergency patching, are normally terminated.

III. JMX SUBSYSTEMS

3.1 Modulators and demodulators

The modulator and demodulator subsystems for all three jumbogroups are shown in Fig. 3; transmission levels are as indicated. In each case, the subsystems used in the A and B sides are identical.

Three types of amplifiers are used in the modulator and demodulator subsystems. The 9-dB fixed-gain amplifiers and the 12 ± 2-dB adjustable amplifiers are transmission quality amplifiers with a controlled transmission band running from 0.5 to 100 MHz. They are realized in the hybrid integrated circuit (HIC) technology. The 9-dB amplifier is designed for low-level application and has a 5-dB noise figure. The 12-dB amplifier has been designed to handle higher signal levels without introducing appreciable intermodulation distortion. Both amplifiers are multistage, major-loop feedback designs with 75-ohm input and output impedances. The 15-dB carrier drive amplifier is designed to provide a 15-dBm carrier signal for the modulator. In addition to providing highly linear gain for carriers up to 91.648 MHz, this amplifier provides at least 40 dB of reverse isolation to control crosstalk that might otherwise be established through the carrier drive path. A multistage local-feedback design with printed-circuit realization is used. All amplifiers use feed-through filters for battery connections.

The 17A modulators are double-balanced diode-ring modulators using Schottky barrier diodes and 75:300-ohm center-tapped transformers.[8] These are highly linear modulators providing at least 40-dB carrier and signal balance. Nominal port impedances are 75 ohms. A single design is used throughout the JMX. More will be said about the 17A modulator in Section 3.16.

The filters[8] have been designed on a system basis; i.e., the loss requirements have been specified in an interactive manner in an attempt to reach a global optimum without placing undue stress on any one design. Often the attenuation required for some undesired sideband can be obtained more easily through the combined effect of two or more filters than in a single filter. The systems of filters were specified to provide combined attenuation to undesired modulation

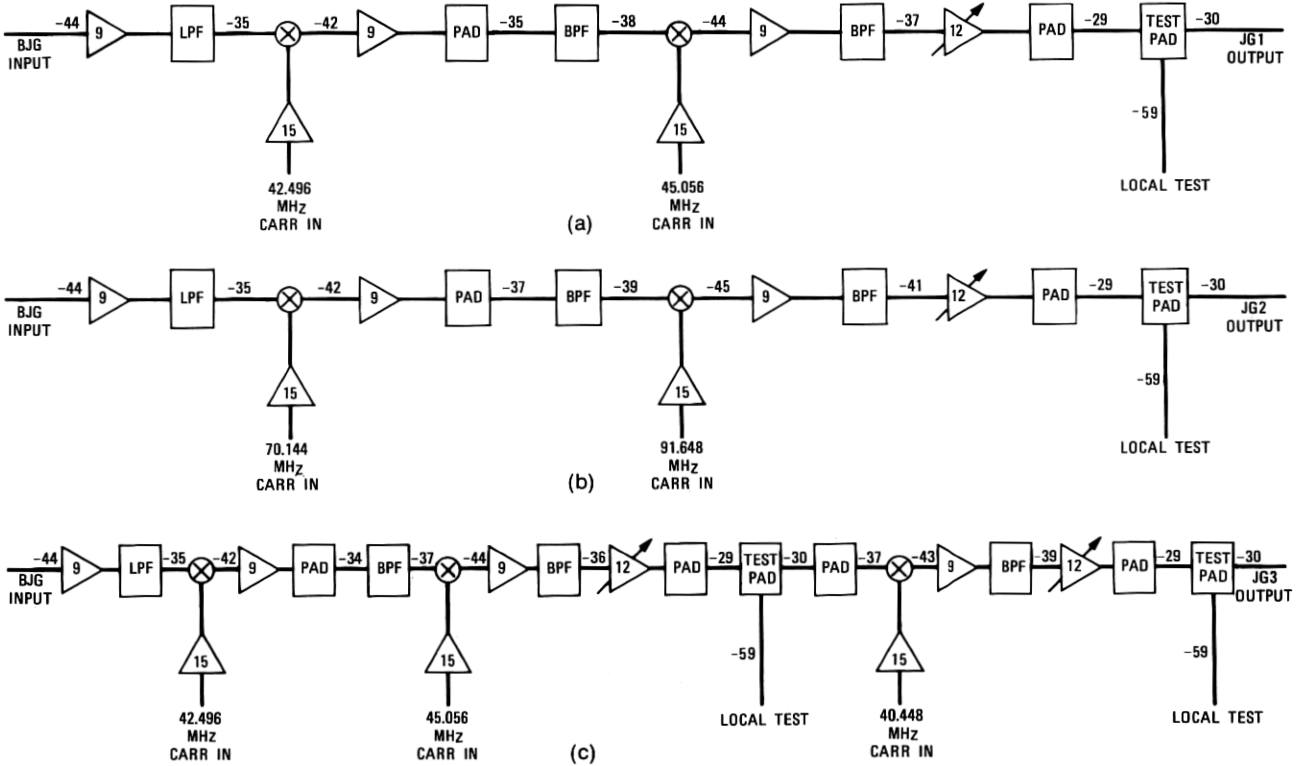

Fig. 3—Modulator and demodulator subsystems for jumbogroups 1, 2, and 3. (a) Jumbogroup 1 modulator. (b) Jumbogroup 2 modulator. (c) Jumbogroup 3 modulator.

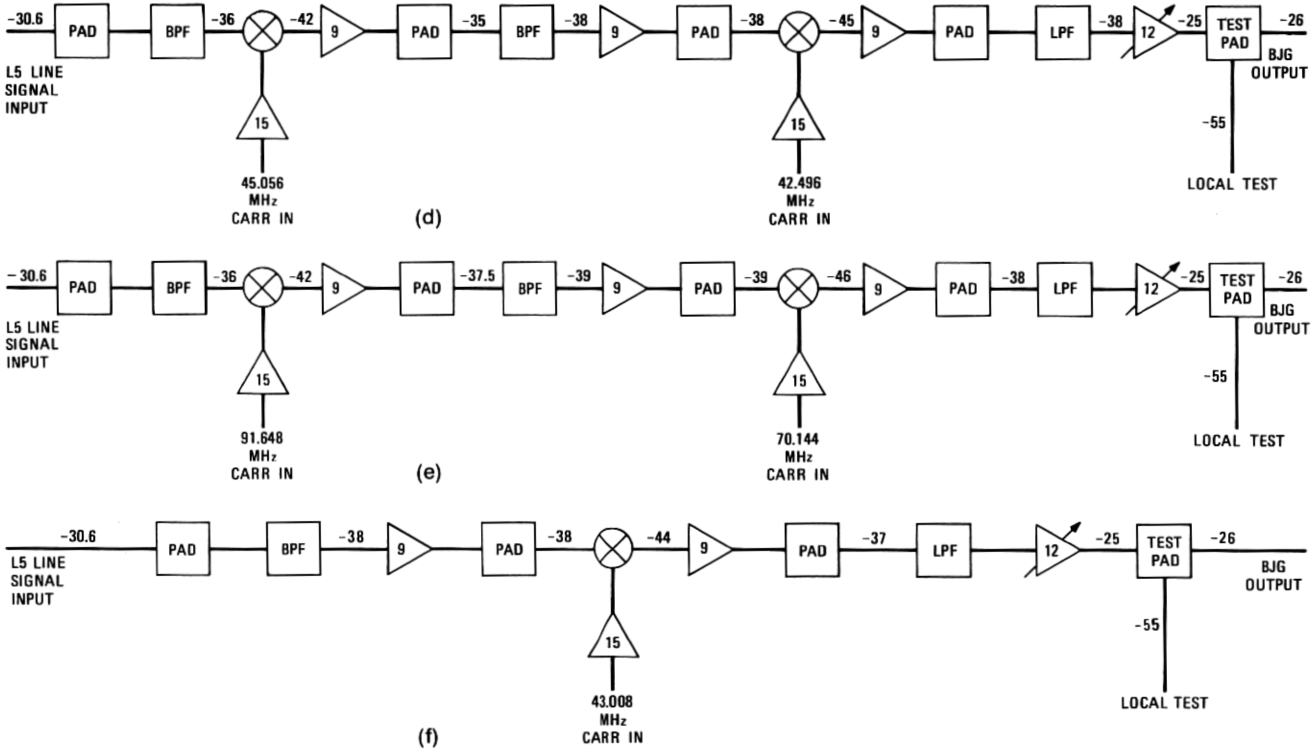

Fig. 3 (cont.)—(d) Jumbogroup 1 demodulator. (e) Jumbogroup 2 demodulator. (f) Jumbogroup 3 demodulator.

products and carrier leak sufficient to keep them at least 85 dB lower than the level of the desired sideband. All filters have nominal input and output passband impedances of 75 ohms.

3.2 Jumbogroup 1 modulator

Ideally, the basic jumbogroup signal fed to the JMX should contain no energy above 17.548 MHz. If some disturbance is present above the desired input spectrum, it could corrupt the message spectrum either by being superimposed as a result of linear transmission through the modulator (signal leak) or by being translated into the message band via the modulation process. Accordingly, after the input signal is raised to the appropriate transmission level via the input amplifier, it is passed through a low-pass filter to reject any spurious high-frequency disturbance. The basic jumbogroup spectrum is then translated in frequency using a 42.496-MHz carrier. The signal is amplified and its level is adjusted to a more optimal value for a subsequent step of modulation. Next, a bandpass filter selects the lower sideband between 29.948 and 41.932 MHz. The signal is modulated once more, using a 45.056-MHz carrier. After amplification, the lower sideband located at 3.124 to 20.108 MHz is selected by a second bandpass filter. The modulator subsystem output level is then achieved through the use of an adjustable 12-dB amplifier, a fixed-loss pad, and a test pad that introduces a 0.6-dB loss in the signal path and provides a bridged test point with 30-dB isolation.

The net frequency shift provided by the jumbogroup 1 modulator is 2.56 MHz. Since the input spectrum overlaps the output spectrum for jumbogroup 1, multiple steps of modulation are mandatory. Signal leak prohibits using one step of modulation (or demodulation) for jumbogroup 1.

3.3 Jumbogroup 2 modulator

Jumbogroup 2 is processed in a manner similar to that for jumbogroup 1. The first step of modulation uses a 70.144-MHz carrier. The first bandpass filter selects the lower sideband between 52.596 and 69.580 MHz. The second carrier frequency is 91.648 MHz, and the jumbogroup 2 signal occupies the band of 22.068 to 39.052 MHz. The net shift for jumbogroup 2 is 21.504 MHz.

It is often more desirable to use the lower sideband, since many of the undesired byproducts of modulation corrupt the upper sideband. In jumbogroup 2, using a single step of modulation and selecting the lower sideband would cause the most difficult filtering—attenuation of carrier leak and rejection of the upper sideband—to be done in the neighborhood of 40 MHz. Using two stages of modulation greatly facilitates this task by shifting the chore to the region of 20 MHz.

3.4 Jumbogroup 3 modulator

Jumbogroup 3 uses three steps of modulation. The first two steps are identical to those of jumbogroup 1. The third step of modulation uses a 40.448-MHz carrier. The third bandpass filter selects the upper sideband between 43.572 and 60.556 MHz. The net frequency shift is 43.008 MHz.

With either one or two steps of modulation, the attenuation of carrier leak and the rejection of the nearby sideband would require filters of questionable realizability for jumbogroup 3. Thus, three steps of modulation were necessary. The first two steps may be viewed as providing a baseband signal with significant separation between the lowest signal frequency and dc. The result is that adjacent sidebands are separated by about 6 MHz after the third step of modulation. This, coupled with the use of the upper sideband (in this case, no spurious modulation products overlapped the upper sideband), greatly facilitates filter synthesis.

3.5 Jumbogroup 1 demodulator

Following a slight level adjustment to place the signal at a more optimal level for the first step of demodulation, the jumbogroup 1 signal is selected from the L5 line signal by the first bandpass filter whose passband extends from 3.124 to 20.108 MHz. Using a 45.056-MHz carrier, the first step of demodulation shifts the input spectrum up in frequency. Following amplification and level adjustment, the second bandpass filter selects the lower sideband signal between 24.948 and 41.932 MHz. The filter output goes through a 9-dB amplifier-pad combination to provide isolation between the filter and the following modulator. This signal passes through a second stage of demodulation using a 42.496-MHz carrier. The signal is amplified, and the lower sideband signal at basic jumbogroup frequency is selected by the output low-pass filter. The basic jumbogroup signal is further amplified, then fed to a test pad that provides a local bridged test point.

The jumbogroup 1 demodulator is similar in most aspects to the jumbogroup 1 modulator. It uses the same carriers and uses filters with identical passbands (although the detailed nature of the rejection bands is not always the same).

Modulators of the type used in the JMX are bilateral. That is, a signal applied to the output port will be translated in frequency and appear at the input port in the same manner that signals applied to the input are translated and appear at the output. Consider a modulator with conversion loss C terminated on its output by a load whose return loss, with respect to the average modulator output impedance, is R_o, and terminated on its input by a source whose output return loss, relative to the average modulator input impedance, is R_i. Signals appearing at the modulator output will have some energy reflected back through the modulator, and some of this energy will, in turn, be reflected from the source output through the modulator once more. The result will be an echo-like signal superimposed on the original signal at the modulator output. The reflected signal will be attenuated relative to the original signal by $2C + R_o + R_i$ dB.

The modulator input and output impedances are complex and periodically time-varying, and are not capable of being carefully controlled and manipulated without significant decrease in conversion efficiency. In practice, the average input impedance is controlled to some nominal value. For the JMX, this nominal value is 75 ohms. Similarly, amplifiers, pads, and in-band filter impedances are designed to be 75 ohms. Filters are designed to pass in-band energy and reject, principally through reflection, out-of-band energy. Consequently, filters typically have rejection-band terminal impedances corresponding to open or short circuits.

Assume that a modulator is driven from a filter and operates into an amplifier. If the amplifier input impedance has an average return loss of $R_o = 18$ dB, relative to the modulator output impedance, the filter out-of-band return loss is $R_i = 0$ dB, and the conversion loss is $C = 6$ dB, then the reflected signal will be suppressed 30 dB relative to the signal with which it adds, assuming that the signal that appeared at the filter input was an out-of-band signal. The interfering signal will be at the same frequency as the interfered signal and will add on a voltage basis, depending on the phase relationship between the two signals. If the angle is constant across the band, a slight level shift will occur. If the angle is not constant, but changes slowly with frequency, passband distortion, gradually changing with frequency, will be introduced. This can be compensated for through the use of simple deviation equalizers designed to attend to the aggregate distortion introduced by filters and other apparatus. If, however, the angle of the reflected signal changes rapidly, as it would if the angle of the filter output impedance changed in the region of resonance of a crystal, then sharp, unequalizable notches could be introduced into the jumbogroup passband. The reflected energy could cause variations in passband loss as large as ±0.27 dB for the relative levels indicated above. This was, in fact, experienced in initial measurements of jumbogroups 1, 2, and 3 receiving equipments, and required the introduction of 9-dB pad-amplifier combinations to improve the return loss of driving impedances for selected modulators, as indicated in Fig. 3.

3.6 Jumbogroup 2 demodulator

The jumbogroup 2 demodulator is functionally identical to that of jumbogroup 1. It uses the same carriers and has filters with the same passbands as the jumbogroup 2 modulator.

3.7 Jumbogroup 3 demodulator

The jumbogroup 3 signal is demodulated in a single step; thus, all three jumbogroups traverse four modulators during the modulation/demodulation process. After level adjustment, the jumbogroup 3 signal is selected from the L5 line spectrum by a bandpass filter with a passband between 43.572 and 60.556 MHz. The signal then goes through a 9-dB amplifier and pad to provide isolation between the filter and the following modulator. The jumbogroup 3 signal is then demodulated with a 43.008-MHz carrier and, following amplification and level adjustment, is sent through a low-pass filter to isolate the basic jumbogroup signal. Following additional amplification, the signal passes through a test pad that provides local test access.

3.8 Observations

A major and critical aspect of the design of an FDM terminal involves the ordering of apparatus and the settings of internal levels in the modulator and demodulator subsystems. The output of a double-balanced diode-ring modulator contains the dominant upper and lower sidebands, carrier leak, and a multitude of other signals.[9] The energy in either sideband is of a magnitude comparable to that of the energy in the carrier leak. If the modulator output is fed through a bandpass filter into an amplifier, then the undesired sideband and the carrier leak can be attenuated so that the total signal power carried by the following amplifier is greatly reduced. This tends to reduce the intermodulation distortion generated by the amplifier. It also tends to degrade the effective noise figure of the amplifier by an amount equivalent to the filter passband loss. Furthermore, should the signal next be fed to a subsequent stage of modulation, the next modulator is presented with a broad band of noise covering not only the message band, but the image band as well. If the order of the amplifier and filter is reversed, then the thermal noise problem is mitigated at the expense of increased intermodulation distortion in the amplifier. The more beneficial arrangement depends upon a number of parameters, including filter loss, amplifier noise and intermodulation distortion, modulator intermodulation distortion, and carrier leak. While preliminary analysis of the gross characteristics of the various transmission elements is helpful in establishing a starting point, the optimal subsystem configuration can only be obtained through extensive, if not exhaustive, examination of the various possible configurations. This has been done for all modulator-demodulator subsystems using noise-loading techniques.[10]

It has been found that the setting of internal levels is equally important. Signal and carrier levels also were optimized using noise loading.

3.9 Carrier generation

Jumbogroup signals are translated to their L5 line-frequency allocation through multiple steps of modulation. The net frequency translation they experience may be viewed as having been achieved through a single modulation step using an equivalent carrier frequency as follows. Consider the first step of modulation to have used a carrier of frequency f_1. Following the first step of modulation, a signal of frequency f_s would be translated to $f_1 - f_s$. The second step of modulation, using carrier frequency f_2, would translate the signal to $f_2 - f_1 + f_s$. The net translation is $f_e = f_2 - f_1$. In jumbogroups 1 and 2, where two steps of modulation are used, the above applies. For jumbogroup 3, a third modulation step, using a third carrier frequency f_3, is employed. In this case, the equivalent carrier is $f_e = f_3 + f_2 - f_1$. To demodulate the jumbogroup signals accurately, only the equivalent carrier frequencies need be generated at the receiver. This principle is used extensively in the JMX. The equivalent carrier frequencies are 2.560, 21.504, and 43.008 MHz for jumbogroups 1, 2, and 3, respectively. The frequency stability of these frequencies is determined solely by the stability of the jumbogroup frequency supply (JFS).[7]

The JFS generates three reference signals at frequencies of 20.480, 2.560, and 1.024 MHz. The second and third reference signals are obtained from the first through division of a 20.480-MHz signal by 8 and 20, respectively. These signals are further processed by the sync-distribution circuits to yield the 2.560- and 21.504-MHz signals which are fed to the carrier supplies. The carrier supplies, using the appropriate input signals and locally generated signals, generate the carriers for modulation and demodulation. The functional separation between the JFS and sync-distribution circuit is somewhat arbitrary. The counters that provide the division by 8 and 20 operations could have been located in the sync-distribution circuit, or much if not all of the sync-distribution circuit could have been housed in the JFS. Since it may be feeding up to 20 JMX bays, failure of the JFS could be catastrophic; therefore, the JFS should be as uncomplicated as possible, with every effort made to maximize its reliability. The only exception to this rule was the inclusion of the count-down circuitry in the JFS. These counters are implemented using high-speed emitter-coupled logic. It was expected that locating such circuitry in the JMX could cause the generation of high-level spurious tones for which appropriate shielding and filtering might prove unachievable.

3.10 Sync-distribution circuit

The sync-distribution circuit is shown in Fig. 4; amplitudes are indicated in dBm. Three reference signals at 1.024, 2.560, and 20.480 MHz are cabled to the input from the JFS. The 2.560-MHz signal is amplified, filtered, and passed through splitting hybrids to provide three −5-dBm output signals, which are then cabled to the appropriate (A or B) carrier supplies, where they are used as needed. The 20.480- and 1.024-MHz signals are amplified, filtered, and mixed in a 17A modulator to provide an output at 21.504 MHz. This signal is filtered, amplified, and passed through splitting hybrids to provide three −5-dBm output signals, which are cabled to the appropriate carrier supply inputs. Level adjustments are provided as required. Local test points are provided for the combined three-tone input signal, for both output signals, and for both intermediate signals through 30-dB bridging test pads. All these test points appear at jacks mounted in the face plate of the sync-distribution circuit drawer.

3.11 Jumbogroup 1 carrier supply

The JMX bay is arranged to process three jumbogroup signals in any arrangement; that is, it can process three jumbogroup 1 signals, one each of jumbogroups 1, 2, and 3, etc. There is no fixed assignment of the equipment to limit the flexibility with which the JMX is used. Since it is not known *a priori* which jumbogroup any given position will

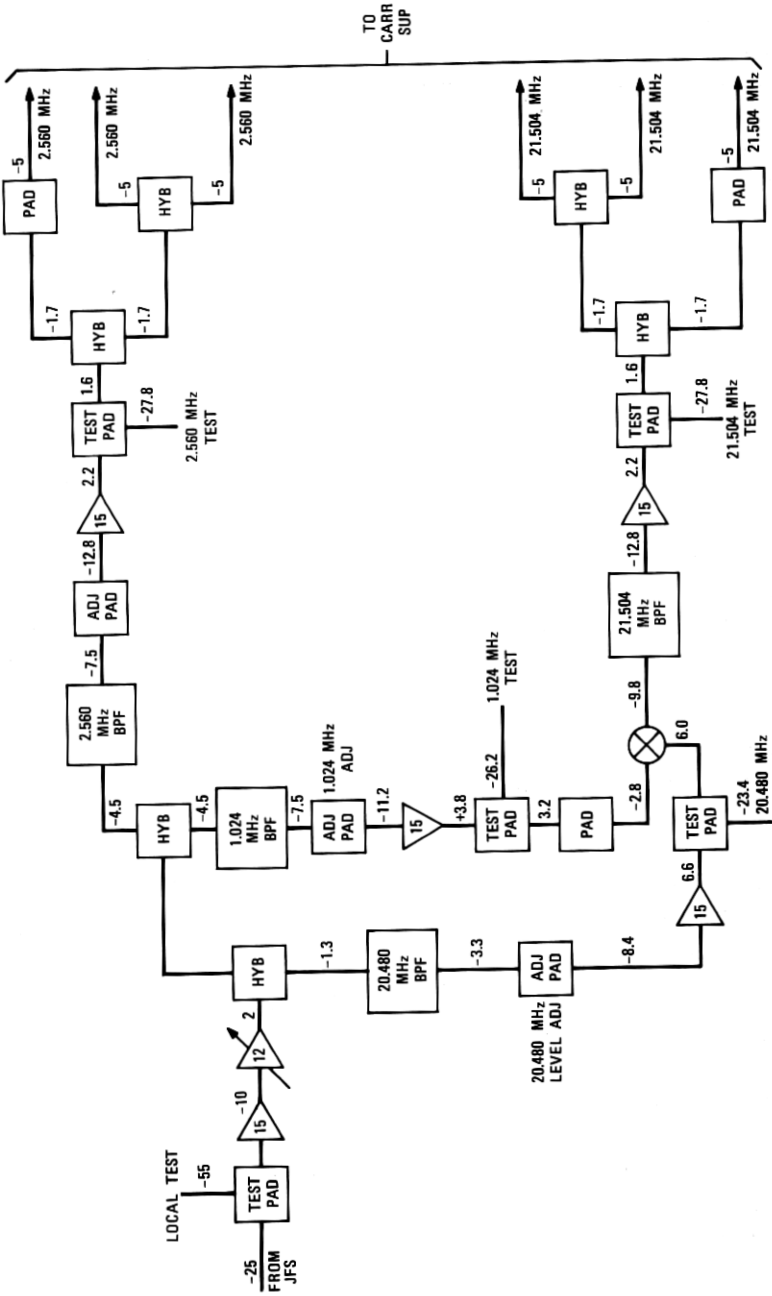

Fig. 4—Sync-distribution circuit.

handle, the sync-distribution outputs are fed to all locations. Those which are required are used. Those not required are automatically terminated when the carrier supply drawers are installed.

The jumbogroup 1 carrier supply terminates the 21.504-MHz input signal, as shown in Fig. 5; amplitudes are indicated in dBm. This carrier supply contains a temperature-compensated crystal oscillator that generates a −15-dBm, 42.496-MHz signal whose frequency stability is typically good to one part in 10^6. As with all dc-powered apparatus used in the JMX, this oscillator uses feed-through filters on the battery leads to prevent coupling between circuits through common dc paths. The oscillator output is amplified and passed through a splitting hybrid. One of the hybrid outputs passes through a fixed pad, a level adjustment, a phase-adjust network, a low-current 14-dB amplifier, a crystal bandpass filter, a 15-dB amplifier, a bridging test pad, and a splitting hybrid whose outputs each experience further noncrystal filtering to yield two 0-dBm output signals.

The phase-adjust network is provided to facilitate the matching of the A and B side signals from the modulators (demodulators) prior to manual operation of the protection switch. The match is made to minimize the mean-squared error between the output signals to achieve hitless switching. This will be covered in more detail later.

As indicated earlier, the spectral purity of the carrier signals and isolation between carrier ports are of special importance. It may appear desirable to reverse the order of the crystal filter and the 15-dB amplifier which follows it. The amplifier introduces both thermal noise and harmonic distortion. However, the signal level into the crystal filter would then be on the order of 10 dBm. The reliability of a crystal degrades significantly when it is exposed to levels exceeding 0 dBm. Accordingly, the arrangement shown was used. While the crystal filter provides sufficient rejection in the immediate vicinity of the carrier, achieving sufficient rejection elsewhere requires further filtering. This is accomplished through the use of noncrystal LC filters placed in both output legs. This output arrangement provides a net isolation between carrier supply outputs equivalent to the trans-hybrid loss of the transformer plus twice the output filter loss.

The second output of the input splitting hybrid is mixed with the 2.560-MHz input in a 17A modulator to yield a product at 45.056 MHz. This signal is similarly amplified, crystal filtered, further amplified, and passed through a 30-dB bridging test pad. The low-level output is fed to a 6-dB splitting pad that provides two test appearances, one local and one remote. The higher-level output is fed to a splitting

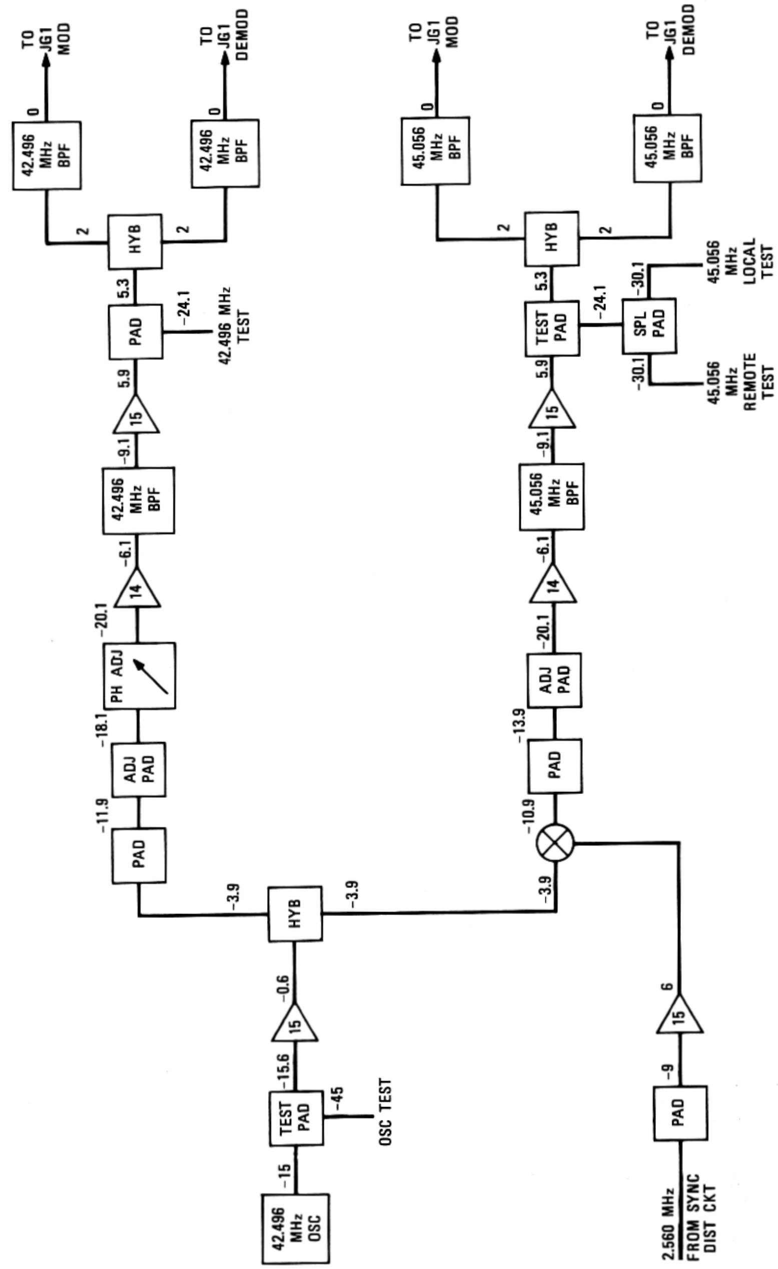

Fig. 5—Jumbogroup 1 carrier supply.

hybrid, where its outputs are further filtered to yield two 0-dBm carrier signals.

The carrier signals are cabled to the appropriate modulators and demodulators as indicated. On the transmitting side, the first modulator uses the 42.496-MHz carrier, while the second uses the 45.056-MHz carrier. Each of these carriers is only as stable as the stability of the local oscillator. However, the effective carrier frequency, which is the difference between the actual carriers used, is orders of magnitude better since it depends only on the stability of the JFS. For purposes of accurate demodulation, the stability of the local oscillator is not important. Other considerations—namely, the matching between filter rejection peaks and the location of the tones to be rejected—require that the actual carrier frequencies do not wander too far from their nominal values. The carriers must be at least as stable as a few parts in 10^6.

3.12 Jumbogroup 2 carrier supply

Functionally, the jumbogroup 2 carrier supply is very similar to that for jumbogroup 1, as shown in Fig. 6. In this case, the 2.560-MHz input is terminated and the 21.504-MHz input is mixed with the locally generated 70.144-MHz signal. For jumbogroup 2, the phase-adjust network is located in the path of the input reference signal prior to mixing with the locally generated signal, while for jumbogroup 1 the phase-adjust network was located in the through path of the locally generated signal. Functionally, either location is acceptable. The relative positions shown were chosen because they facilitated network realization.

3.13 Jumbogroup 3 carrier supply

Jumbogroup 3 requires three carriers for modulation and one carrier for demodulation; the first two steps of modulation for jumbogroup 3 are identical to those for jumbogroup 1. As shown in Fig. 7, the 42.496- and 45.056-MHz carriers are generated in the same way as for jumbogroup 1. Since only one appearance of each signal is required, no splitting hybrids are needed at the outputs. Following the second step of modulation, the jumbogroup signal has a net translation of 2.560 MHz. The third step of modulation and the one step of demodulation must both use carriers dependent solely on the JFS. The desired net translation for jumbogroup 3 is 43.008 MHz. This requires the generation of a 40.448-MHz carrier for the third step of modulation, and a 43.008-MHz carrier for demodulation. Both sync-distribution

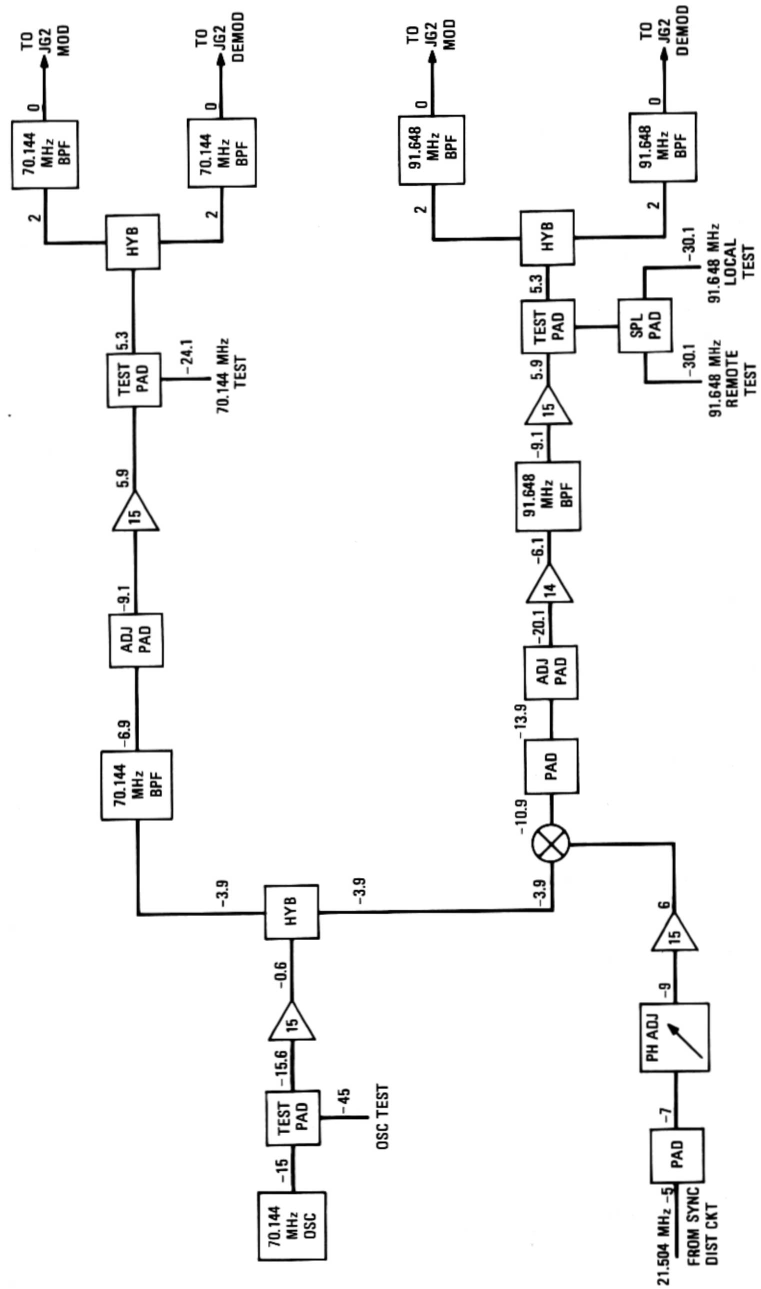

Fig. 6—Jumbogroup 2 carrier supply.

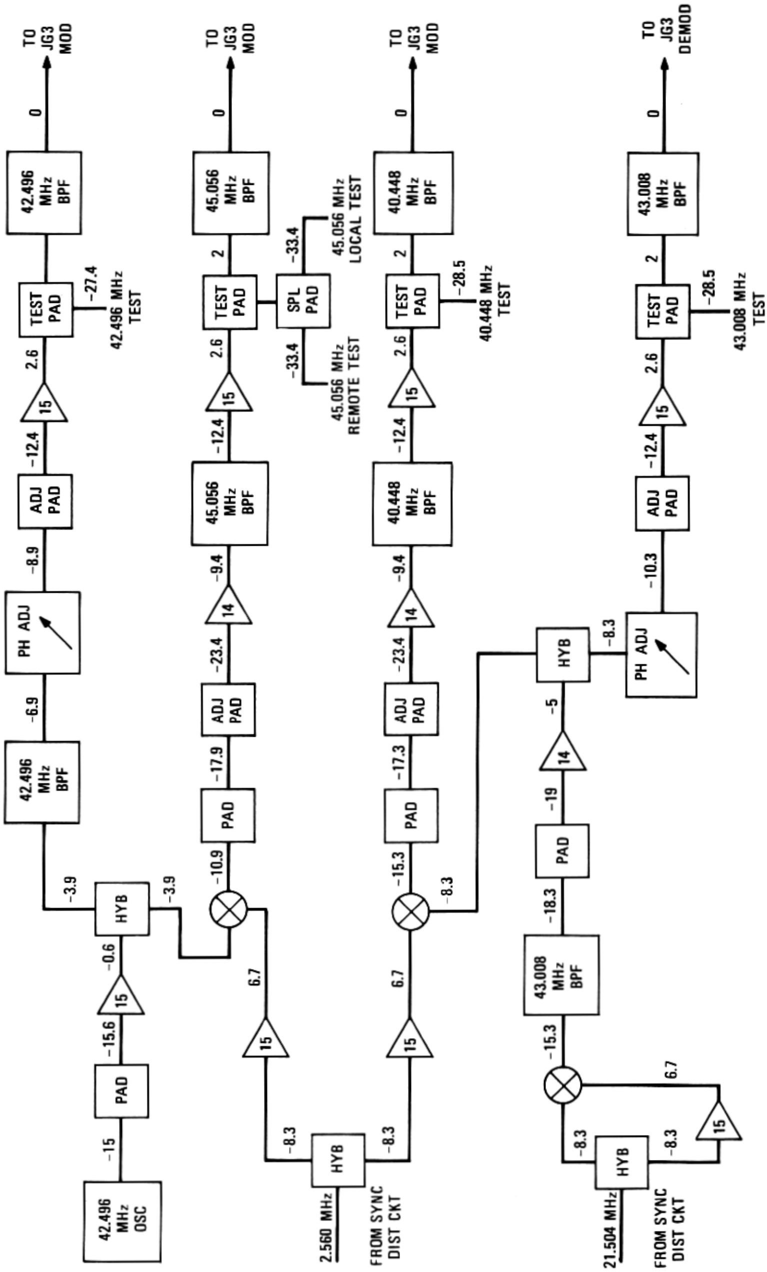

Fig. 7—Jumbogroup 3 carrier supply.

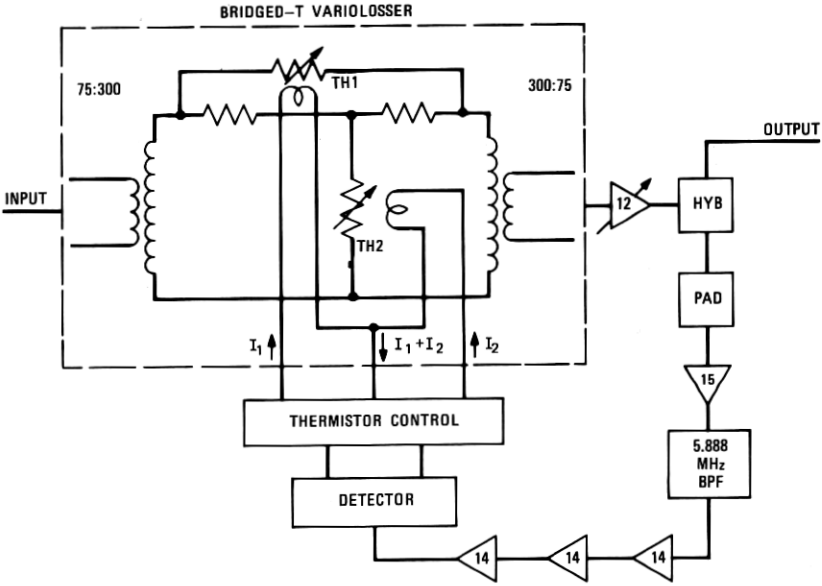

Fig. 8—Basic jumbogroup regulator.

signals are used. The 43.008-MHz carrier is obtained by doubling the 21.504-MHz input. The 43.008-MHz signal is then mixed with the 2.560-MHz input to form the 40.448-MHz carrier. Once again, all net translations depend only upon the stability of the JFS. Two phase-adjust networks are required for jumbogroup 3, one for modulation and one for demodulation.

3.14 Jumbogroup regulator

The jumbogroup regulator, shown in Fig. 8, compensates for level variations that might be introduced in the jumbogroup passband by the L5 line or terminal equipment between the remote transmitting BJGT and the regulator input. A bridged-T variolosser, using indirectly heated thermistors in the shunt and bridging arms, provides a level control of ± 5 dB dynamic range. Control currents are automatically adjusted in a complementary manner in accordance with the level of the received 5.888-MHz jumbogroup pilot. In the event that the jumbogroup pilot is lost, the regulator automatically assumes a mid-range setting. An operational amplifier, connected as an integrator, provides high dc gain in the control loop. This results in a residual error of less than 0.01 dB over the full regulation range.

To facilitate maintenance, the jumbogroup regulator is equipped with a manual reset feature. Operation of the reset switch locks the regulator in the midrange state. This feature is particularly valuable when noise loading tests are being made. An indicator lamp is lighted when the regulator is manually placed in the reset state.

3.15 Protection switching

For each jumbogroup, both transmitting and receiving, A and B paths are provided. These paths emanate from a splitting hybrid and terminate on a 2×2 protection switch. It is the principal function of the protection-switching circuitry to monitor the integrity of the A and B paths, to assure that a good signal is fed from the protection switch when possible, and to activate alarms as appropriate. The circuitry also provides for the control of restoration switches and the manual operation of the protection switch in a hitless manner.

As shown in Fig. 9, both working and idle output jumbogroup pilot signals are monitored by the protection-switching circuitry. The switch control detector emits a dc signal proportional to the level of the jumbogroup pilot. On the transmitting side, the pilot frequencies are 8.448, 27.392, and 48.896 MHz for jumbogroups 1, 2, and 3, respectively; receiving, all jumbogroup pilots are at 5.888 MHz. If the idle signal is lost for more than 0.1 second, a minor alarm condition is indicated. If the working output is lost and the idle output is present, the switch changes state. If this causes a good signal to be present at the working output, and the signal is not present at the idle output, a minor alarm is indicated. If both outputs are lost simultaneously for more than 0.1 second, the switch does not change state, but a major alarm is indicated. Alarms are indicated both in real time and with memory. Switching is nonrevertive; that is, once a service-providing condition has been established, the switch will remain in that state; neither A nor B output is preferred. This arrangement avoids unnecessary hits on jumbogroups that might be heavily loaded with digital signals.

In the event that the working output appears lost while the idle signal is present and operation of the protection switch fails to correct the situation, no further switching occurs. Such a condition would most likely be due to failure of the circuitry monitoring the working output. A major alarm would be indicated.

Manual control of the protection switch is provided. If no trouble condition is indicated, manual operation of the appropriate control switch will cause the protection switch to change state. To facilitate

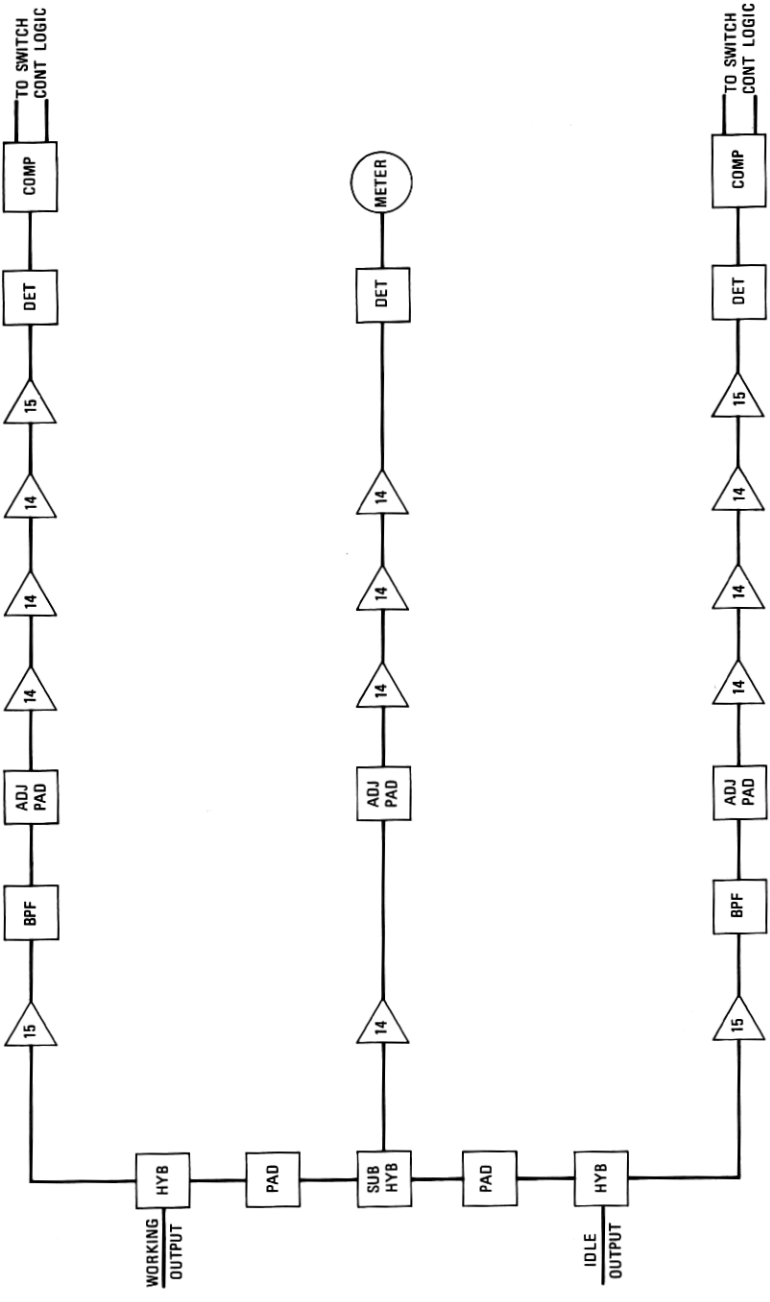

Fig. 9—Protection switching.

this operation in a hitless manner, a variable-sensitivity monitor of the degree of match is provided. The idle and working outputs are subtracted in a special hybrid transformer, yielding an error signal. This error is amplified and detected, and the resultant dc signal is fed to a meter. The meter reading is indicative of the energy in the error signal. Given that the gain of the A and B sides are closely matched, the meter reading is indicative of the phase difference between the A and B sides. Adjustment of the phase network in an associated carrier supply corresponds to varying the phase, constant with frequency, of one side relative to the other. By altering the phase network adjustment to null the meter reading, the best possible phase match is achieved. Since this procedure uses the actual message loading present at the time, it results in the best match over the most meaningful portion of the jumbogroup passband. Inability to reach a very low meter reading is indicative of gain mismatch. This can be corrected by making gain adjustments as appropriate, through the use of the bridged test jacks provided on all modules.

Once A and B paths have been matched, the protection switch is operated manually. In this mode of operation, the switch contacts are sequenced in a make-before-break manner to avoid the momentary open that might otherwise result.

If the manual operation would cause the protection switch to select an apparently failed side, the control logic will not normally respond to the manual command. In this instance, an additional, recessed button must be depressed by the craftsperson to allow him to override the inhibit feature of the control logic.

Restoration access switches are operated via the switch-control logic. Upon command for restoration switch operation, the switch-control logic locks the protection switch in its existing state. It then operates those restoration switches associated with the unused side. When the control logic is in this state, an indicator lamp is lighted at the bay.

3.16 17A modulator

Frequency translation is achieved in the JMX through the use of a double-balanced diode-ring modulator, the 17A. The important performance parameters of such a modulator include conversion loss, passband distortion, intermodulation distortion, carrier balance, and signal balance.

Conversion loss, which gives rise to the difference in level between the input signal and the desired output signal, has a theoretical minimum value of 3.9 dB as a result of the partitioning of input energy into the multitude of sidebands generated by the modulation process. Additional loss is introduced principally through diode dissipation, transformer loss, and whatever additional padding is introduced owing to other considerations. While conversion loss can be offset by adding appropriate gain in the amplifiers preceding and following the modulator, the tendency of increasing conversion loss ordinarily is to result in increased noise, either because levels are increased internal to the modulator, or because the effective noise figure of the following amplifier is degraded, or both.

Passband distortion is introduced principally through transformer roll-off and circuit parasitics. Mutual coupling decreases with decreasing frequency, and shunt capacitance becomes dominant as frequency is increased. Although transformer design can be optimized for a specific frequency range, the design of a single transformer for the multitude of input and output spectra encountered in JMX modulators is particularly challenging. While passband distortion is usually equalizable, prudent design requires that such distortion be minimized at its source.

Intermodulation distortion is influenced by diode nonlinearities, diode match, transformer and circuit balance, carrier waveform, and signal level.[9] Intermodulation distortion may fall in-band or out-of-band, relative to the desired sideband. Unlike most other parameters of interest, in-band intermodulation distortion cannot be mitigated once it is generated. Consequently, this type of distortion must be controlled at its source.

Ideally, in a double-balanced modulator, neither input signal nor carrier should appear at the output. Circuit imperfections preclude realization of these objectives. Carrier balance and signal balance depend on diode match, transformer balance, and circuit layout. Typically, the carrier input level is 70 to 80 dB higher than the level of the output signal. These relative levels are chosen because they result in optimal intermodulation performance. Furthermore, JMX carriers run as high in frequency as 91.648 MHz. Consequently, sizable levels of carrier signals may appear at the output. Since they may subsequently fall within a message spectrum, such carrier leak must be attenuated. While carrier leak is theoretically filterable, rejection peaks well in excess of 100 dB are required. Furthermore, unfiltered carrier leak may significantly increase the total power that an amplifier directly following a modulator must handle. This can give

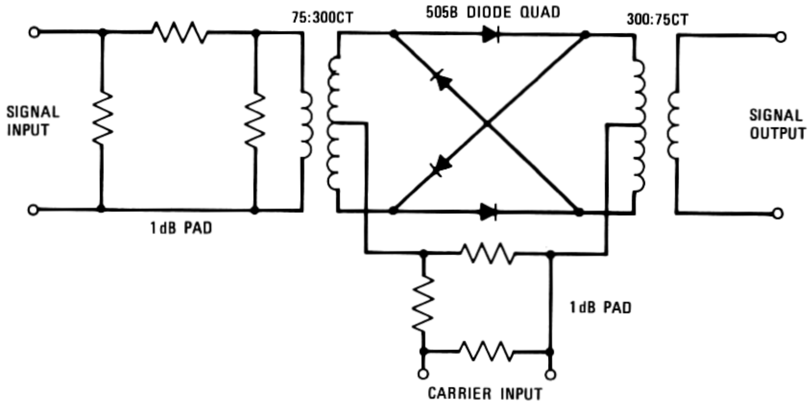

Fig. 10—17A modulator.

rise to further nonlinear distortion in the amplifier. Finally, any noise entering the carrier port from the carrier-drive amplifier will appear at the output to the extent that carrier balance allows. Should a portion of this noise overlap the output message spectrum, it will contaminate the signal in an unfilterable manner. Accordingly, good carrier balance is critical, second only in importance to intermodulation distortion.

Signal leak, by design of the modulation process (i.e., the selection of modulation steps and carrier frequencies), is always filterable. Nevertheless, signal leak at times gives rise to extremely demanding distrimination objectives.

The 17A modulator is shown in Fig. 10. The center-tapped transformers have a 75:300-ohm impedance ratio with a 7:7 + 7 turns ratio. These transformers introduce less than a 0.05-dB passband shape over any jumbogroup band. Transformer balance exceeds 55 dB.[8]

Shottky barrier diodes are used. They provide essentially instantaneous switching at all JMX carrier frequencies, and appear to be purely resistive up to 350 MHz. Their I-V characteristics are extremely linear in the region running from 2 mA to 20 mA. In this region, their resistance is about 40 ohms. Diodes are selected to yield matched quads. Each quad has less than 15 mV mismatch at 2 mA and at 20 mA.

The 1-dB pads at both signal and carrier inputs were found experimentally to result in improved intermodulation distortion, carrier and signal balance, passband distortion, and return loss.

Circuit layout was optimized experimentally. Topological symmetry was found to be critical. This was achieved, for example, by using four manually inserted crossovers as opposed to partial use of printed-circuit land connection.

The 17A modulator has a conversion loss of 6.2 dB, passband distortion not exceeding 0.1 dB, less than 0 dBrnc0 of noise at optimal signal levels, and, when driven by its associated carrier-drive amplifier, signal and carrier balance of at least 40 dB.

IV. PHYSICAL ARRANGEMENT

The JMX is housed in a shop-wired, shop-tested, 11-foot 6-inch, unitized double bay. It is arranged to contain all the equipment to process three jumbogroup signals. Each jumbogroup position is independent of other positions and contains transmitting and receiving jack fields, transmitting and receiving switch-control logic units, and redundant modulator and demodulator subsystems, carrier supplies, regulators, equalizers, transmitting and receiving line interface units, and detectors. Common equipment includes redundant sync-distribution circuits at the lower left of the bay, and a summary alarm circuit at the upper right. Sixteen dc-to-dc converters are located at the top of the bay, just above the fuse panels. Alarm cutoff and lamp buttons are at the lower right just above the writing shelf. Redundant battery feeds and JFS inputs are provided. Several photographs of the JMX equipment are contained in Ref. 11 of this issue.

V. OPERATIONAL FEATURES

No at-the-bay routine maintenance is planned for the JMX. Rather, each jumbogroup is automatically and remotely monitored by the transmission surveillance system[12] associated with L5. Eleven critical test points are provided for each jumbogroup position. These include the transmitting input, the transmitting A and B outputs, the receiving A and B inputs and outputs, the A and B regulator inputs, and two carrier supply test points. These eleven access points are concentrated in a remotely controllable 1×12 switch. Through this arrangement, detailed analysis of JMX performance is possible with little intervention by a craftsperson.

All the above-mentioned test points, in addition to others, are also provided at the bay. It is possible to verify the integrity of any transmission-related module without removing it from the bay, through the use of the test points provided.

Verification of the integrity of the many status and alarm indicators is facilitated through the lamp-test feature. Depressing the three lamp-test buttons allows the location of any failed lamp in seconds.

VI. JMX BAY EVALUATION

The JMX has undergone extensive field evaluation. Both functionally and operationally, the equipment operated superbly. The poorest jumbogroup noise performance obtained was 12 dBrnc0.

The poorest equal-level coupling loss obtained was 90 dB. This was measured between A and B sides of the same transmitting or receiving jumbogroup, and was due to coupling through the subtracting hybrid transformer of the circuitry used to evaluate the degree of match between the associated A and B sides. This is a well-controlled coupling, not expected to vary from system to system. Most other forms of coupling were so low as to be unmeasurable.

Extensive testing of regulation and protection switching showed these features to operate without fault.

Ten JMX bays were constructed by Western Electric for use in the Lillyville, Pennsylvania-Hillsboro, Missouri route. This equipment has been providing commercial service since January 1, 1974.

VII. ACKNOWLEDGMENT

Taking into consideration the bandwidth of the signal it processes and the frequencies at which it operates, the JMX is the quietest analog multiplex terminal ever designed. The success of the design is a tribute to the technical excellence and total dedication of its design team which included J. S. Young, T. B. Merrick, G. W. Kattke, B. B. Garg, S. J. Davis, A. G. Favale, and W. D. Radwill.

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