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Rain-Fade Simulation and Power Augmentation for Satellite Communication Systems

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SUMMARY

The design and implementation of an automated rain-fade simulation and power augmentation system is presented. The system experimentally simulates and measures the effects of RF power fade on a 20-GHz communications link using a multimode traveling wave tube amplifier for loss compensation. Precision, computer-controlled attenuators are used in the fade simulation. Test plans for analog and digital testing are discussed.

INTRODUCTION

The successful development of high-frequency satellite communications systems requires designers to address and overcome many complex scientific problems. One of these problems, called rain fade, is associated with the transmission of electromagnetic signals through moisture in the Earth's atmosphere. Rain fade is characterized primarily by the attenuation of the radiofrequency (RF) signal between the spacecraft and ground terminal, which results in a lower power level at the receiving terminal. Additionally, moisture degrades the quality of the received data on the rf carrier. This problem becomes more severe as link frequencies reach into and above the K_a-band, because of the relationship between signal wavelength and water droplet size (ref. 1). The ability of a satellite communications system to compensate for these

propagation effects is the subject of experimental investigation at the NASA Lewis Research Center.

The rain-fade simulation and power augmentation system under development consists primarily of two components. The first, used to simulate the effects of rain, is a high-resolution RF attenuator. The attenuator can be operated manually or by computer, thus permitting elaborate rain-fade scenarios of various rain intensities, durations, and rates of onset to be analyzed for their effects on the communications link. The second component in the system is the high-power amplifier, or more specifically, the multimode traveling wave tube (TWT). The tube was specifically designed with a control anode that allows the tube's electron beam current to be adjusted to three levels, thereby providing three distinct RF output power modes. Thus, the RF power in the communications link can be raised to a higher power mode to compensate for rain fade and lowered during clear sky to conserve direct current (dc) drive power. The multimode traveling wave tube, rain-fade simulator, and automated power level feedback system will be discussed in greater detail in later sections.

The rain-fade simulation and power augmentation system is being developed as part of a complex satellite communications test program. The program has served as the test bed for the Advanced Communications Technology Satellite (ACTS) investigating time division multiple access (TDMA) communications at 30-GHz uplink and 20-GHz downlink frequencies¹ (ref. 2). The power

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¹ Actual channel frequencies are 27.5 to 30.0 GHz, uplink, and 17.7 to 20.2 GHz, downlink.

augmentation function, to be performed aboard the spacecraft in the transmitter subsystem, would thus operate in the 20-GHz band. All hardware, testing, and operation of the rain-fade simulation and power augmentation system is therefore carried out at or about the 20-GHz frequency.

HARDWARE

The rain-fade simulation and compensation system is made up of many important RF and digital components (fig. 1). The TWT, rain-fade simulator, control computers, and other link components are shown in the figure. Interconnects between the components are not specified, but include RF waveguide and coaxial lines, IEEE-488 and RS-232 interface buses, and customized cables. In the simulation a 30-GHz signal is received by the spacecraft transponder from the transmitting ground terminal. Once received, the signal is subjected to a series of frequency translations, routing, and processing. The signal enters the downlink transmitter subsystem at 20-GHz for amplification and transmission to the receiving ground ter-

minal. Within the downlink path is the rain-fade simulator, under the control of an experiment control and monitor (EC&M) computer. A fade sensor built into the receiving ground terminal samples the incident signal strength and reports the status to the network control computer (NCC). Based on predetermined power thresholds, the NCC issues mode change commands to a digital routing processor (DRP) that, in turn, controls the TWT onboard the spacecraft. Meanwhile, digital data received by the ground terminal are compared with the original data pattern, and bit-error-rate (BER) measurements are performed.

The two main components of the RF segment, namely, the TWT and the variable attenuator, are described in the following sections. The digital control circuitry, control software, and their operation with the RF hardware are described in later sections. The rain-fade simulator function is now being tested using both rotary-vane and solid-state attenuators. (The system and hardware are designed to minimize changes for direct replacement of one type of unit with another.) Both types of attenuators are described below.

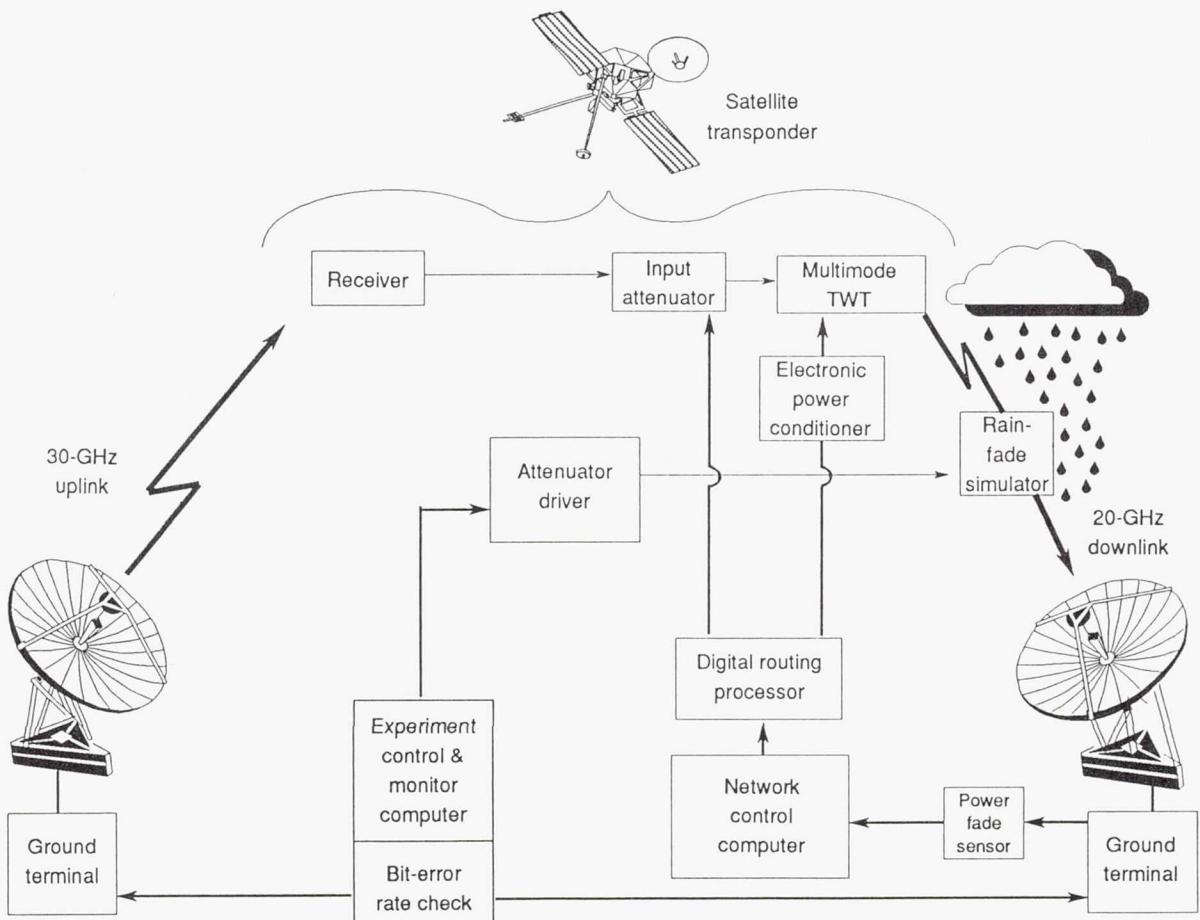


Figure 1. - System diagram.

Rotary-Vane Attenuator

In order to provide continuously variable attenuation over the full 17.7- to 20.2-GHz band of the communications channel, a precision rotary-vane attenuator (RVA) mechanism was developed. The rotary vane attenuator, whose use in microwave applications is well established, can control attenuation at high RF power levels in a continuous fashion which most accurately mimics the onset of moisture-laden clouds.

The rotary-vane attenuator and precision positioning mechanism are shown in their integrated configuration in figure 2. The RVA assembly uses WR-42 rectangular waveguide RF input and output ports that transition immediately to circular waveguides in the moveable vane section.

The actual RF attenuation occurs within the rotatable, cylindrical housing centered between the waveguide ports. Within this housing is a thin card of resistive material that absorbs a portion of the energy traveling through the waveguide. The angular relationship between the electric field of the incident wave and the vane of the attenuator determines the level of attenuation imposed by the RVA. When the field is oriented perpendicular to the vane, the absorption of RF power by the RVA is minimum, with the incident signal experiencing only the RVA insertion loss (approx. 0.6 dB). When the vane is oriented parallel to the incident electric field, the attenuation is maximized at approximately 40 dB. Thus, precision control of the position of the vane will permit accurate and repeatable attenuation levels to be obtained. The vane housing is rotated by means of a worm gear over a mechanical range slightly greater than 90°. With this approach, the full attenuation range of the RVA can be utilized.

The RVA (vane) is positioned through the use of

a precision stepping motor and motor controller (Computer Corp. models M57-51 motor and 2100-1 preset indexer). The motor shaft can be positioned with resolutions up to 50 000 steps per shaft revolution. This precision far exceeds current system requirements, but can be invoked, if desired, through controller switches. For the intended application, a resolution of 25 000 steps per revolution was selected. To span the entire 0 to 90° RVA mechanical range at the reduced resolution, the position indexer covers approximately 150 000 steps. In this configuration, the velocity and acceleration/deceleration rates are selectable within the ranges of 0.0001 to 20 revolutions per second (rps) and 0.01 to 990 rps/s, respectively.

To ensure that the RVA operates over the proper mechanical range (including a small safety margin) an electromechanical system of cams and limit switches was used. Primary and secondary (idler) shafts support customized gearing and adjustable cams to trim the range of RVA motion to slightly greater than 90°, corresponding to six full turns of the motor shaft. A slip clutch with an adjustable breakaway torque on the primary shaft protects the mechanism from damage in the event of failure or misadjustment. The motor acceleration and deceleration rates are limited to 1.5 rps/s to prevent damage to the RVA mechanisms, but the rates can be changed to meet test requirements. The automatic control of the RVA's and discussions of the indexing electronics and limit switches are presented in "Computer Control" section.

The rotary-vane attenuator, precision positioning mechanism, power supply, and microprocessor indexing unit together constitute a remote-controlled attenuator assembly. Two attenuator assemblies, each operating in the 18.0- to 26.5-GHz frequency range, were used in this system. One was used as the rainfade simulator; the other as the input power controller for the TWT amplifier.

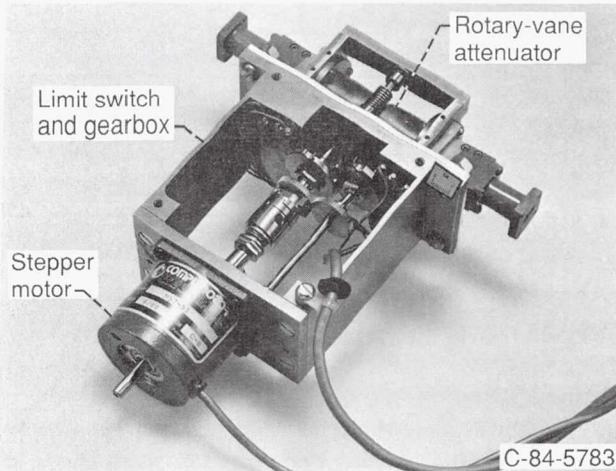


Figure 2. - Rotary vane attenuator.

Solid State Attenuator

Recent improvements in solid-state technology have lead to the development of high resolution, PIN diode attenuators. The compact size, high resolution, reliability, and fast switching speed make the PIN diode ideal for many microwave systems applications. Figure 3 shows a PIN diode attenuator developed by Hughes Aircraft Co. The construction of a PIN diode attenuator, as the name implies, consists of an intrinsic (I) layer enclosed between a P+ junction on the input side and a heavily doped N+ junction on the output side. As the bias voltage is increased from 0 to 5 V, the PIN diode's attenuation increases linearly from its insertion loss value of less



Figure 3. - PIN diode attenuator.

than 1.0 dB until the diode approaches saturation at a maximum attenuation of approximately 29 dB. The attenuation level remains within a 1-dB tolerance (better for low-attenuation values) through the downlink band. When the device is at maximum attenuation, it has a greater VSWR than when its attenuation is lowest; for this reason isolators are used to prevent reflected energy from interfering with adjacent components. The PIN diode attenuator uses WR-42 rectangular waveguide as the RF input and output transmission media. An SMA coaxial connector is used to supply the 0- to 5-V control voltage from the power supply. The attenuation resolution of the PIN diodes is only limited by the voltage resolution of the controlling power supply. For this application 0.1-dB attenuation steps are easily obtained by using 10-mV control-voltage increments. The PIN diode attenuator can accept an input power level of up to

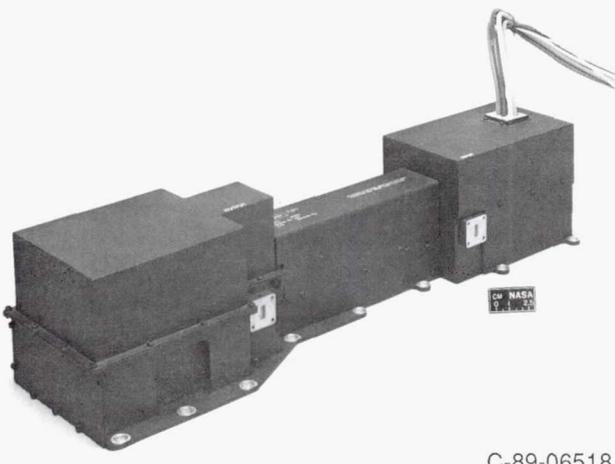


Figure 4. - Hughes model 918HA multimode traveling wave tube.

1.0 W continuous wave RF without physical damage. One outstanding advantage of a solid-state device is the speed with which it changes states. The Hughes diodes can execute a 10- to 90-percent attenuation transition in 250 nsec. This capability for large attenuation jumps in such a short time makes the PIN diode attractive for use in intricate rain scenarios involving rapid power fluctuations.

Traveling Wave Tube

Technology development programs performed by NASA in the early 1980's led to the fabrication of a 20-GHz, 50-W, multimode traveling wave tube (designated model no. 918H; ref. 3). The tube, built under contract to the Government by Hughes Aircraft Co. (Contract NAS3-23345) contains a modulation anode that permits control of the electron beam current used in the amplification process. As a result, the tube can be operated in any of three discrete power modes: low, medium, or high. The tube recovers power from the electron beam through the use of a multistage depressed collector. The tube uses a helix, slow-wave circuit supported by three beryllia rods. A photograph of the TWT is shown in figure 4.

The TWT is powered by a dedicated high-voltage electronic power conditioner (EPC). The power modes on the tube can be selected by computer through the digital routing processor or manually via a command and control system that interfaces with the EPC. Tube operating parameters are presented in table I for all three power modes. Mode switching and settling is completed in approximately 1 second.

TABLE I. - TWT DIRECT CURRENT OPERATING PARAMETERS

RF operating mode	Cathode voltage, kV	Anode voltage, kV	Beam current, mA
Low	-9.8	-2.76	37.8
Medium	-9.9	-1.34	50
High	-10.1	0	64.2

Typical RF gain linearity curves for the model 918H TWT (S/N 101) are presented in figure 5. Sample test results at the 18.5-GHz operating frequency show a saturated 45-dB_m RF output power level for a 7.5-dB_m RF input when operating in the high-power mode. Of concern, however, is the transition period when the tube changes operating modes. For example, when the tube is operating at saturation in the low-power mode, a switch to the medium- or high-power modes would result in an

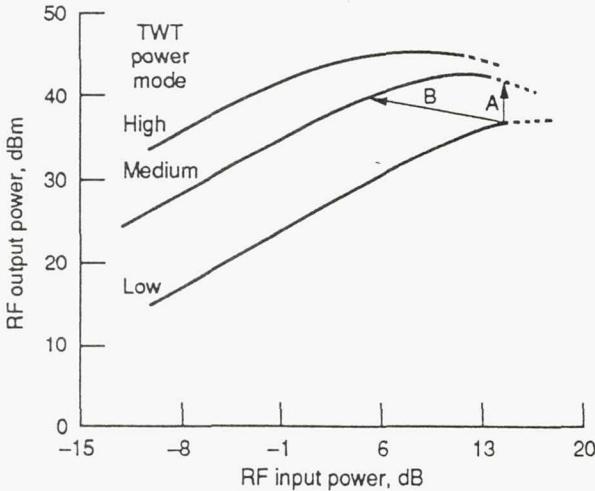


Figure 5. - TWT RF characteristics. Operating frequency, 18.5 GHz.

RF overdrive condition with possible damage to the tube. This path is shown as transition A in figure 5. To protect the tube and to provide a smoother transition between states, a variable attenuator was placed at the input to the tube. This attenuator, used as an input RF power controller, is an exact duplicate of the rain-fade simulators described previously. When the attenuator adjustment and TWT mode switching actions are activated simultaneously, the transition between states can be smoothed and generally described by path B. The interaction of the tube, rain-fade simulator, and input power controller are discussed further in the "System Operation" section.

COMPUTER CONTROL

Operation

Rotary-vane attenuator. - A block diagram of the remote-controlled RVA system is presented in figure 6. The stepping motor is driven by a motor driver unit that signals to the stepper motor. The motor driver is controlled by a microprocessor-based indexing unit that controls the motor position counter, velocity, and acceleration/deceleration rates. Using these functions, the RVA can be easily repositioned in virtually any programmable pattern, either by local selection, using front panel controls, or by computer-controlled sequences following preprogrammed equations.

Limit switches automatically terminate, through electrical feedback to the indexing unit, all motion that approaches the mechanical travel extremes of the equipment. This system protects the attenuator movement in both the clockwise and counterclockwise directions and

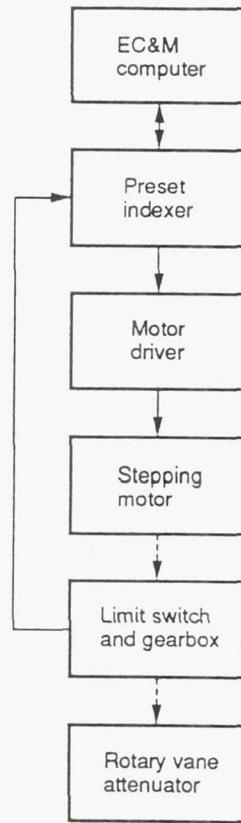
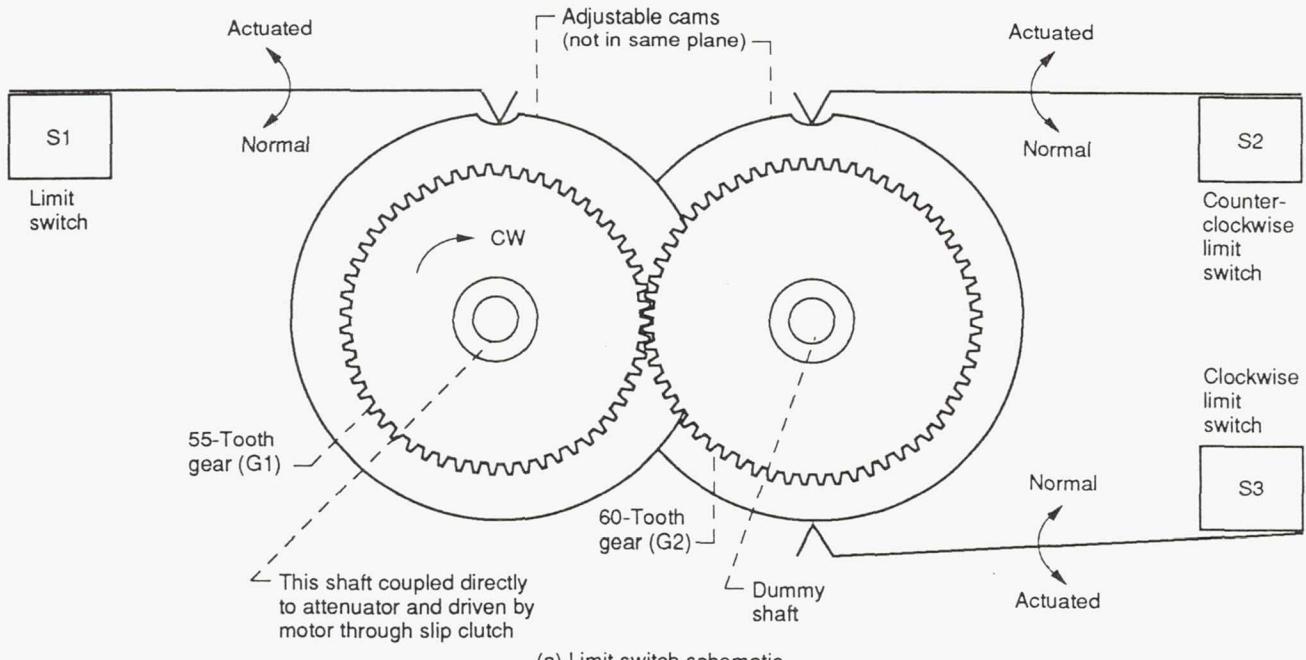


Figure 6. - Rain-fade attenuation simulator block diagram.

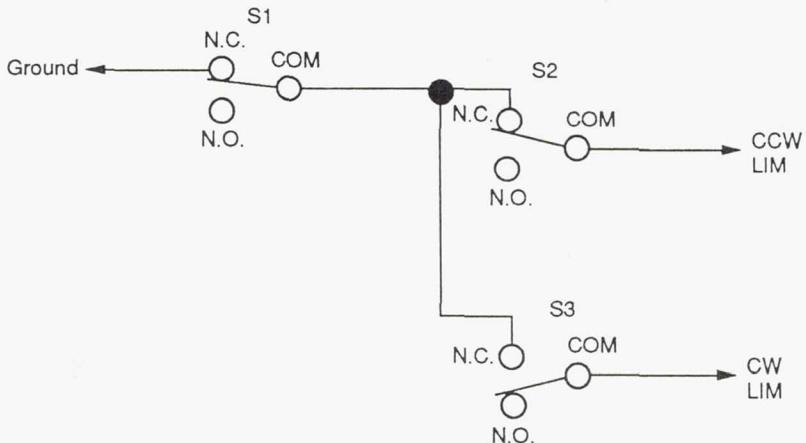
provides a repeatable reference point for system startup and operation.

The limit switch configuration is shown schematically in figure 7. The system is shown with the attenuator in its counterclockwise (CCW) limit position. Switches S1 and S2 are in cam detents, thus deactuated and completing a ground circuit for the CCW limit signal which feeds the preset indexer. As the attenuator shaft is rotated clockwise, switches S1 and S3 will not be deactuated simultaneously until the actuator shaft rotates through six full turns. The gearing in the system is set at a tooth ratio of 60 to 55, so that the idler shaft will only complete five and one-half revolutions. At this point (six turns from the CCW limit) switches S1 and S3 are in cam detents, thus deactuated and completing a ground circuit to the CW limit signal for the preset indexer.

Solid-state attenuator. - The PIN diode attenuator is controlled by a remotely controlled precision power supply. The power supply has self-contained measurement and readback capabilities to ensure the programmed voltage is supplied to the PIN diode and to protect the diode from damage. Overvoltage and overcurrent protection features protect the components in the event of a fault. All power supply commands can be accessed



(a) Limit switch schematic.



(b) Control schematic. (Counterclockwise position shown.)

- (a) Limit switch schematic.
- (b) Control schematic. (Counterclockwise position shown.)

Figure 7. - Rain-fade attenuation simulator limit switches.

through front panel controls as well as through the IEEE-48 computer interface. The EC&M computer can then vary the voltage applied to the PIN diode in order to simulate the onset and recession of a rain storm. As with the rotary-vane attenuation technique, the EC&M computer will perform BER tests to analyze the effects of the rain-fade simulation on signal transmission quality.

Calibration

In order to correlate the desired attenuation with either motor position or diode bias voltage, the attenuator

must be calibrated. The calibration is performed before integration of the attenuator into the system and need only be done once. The calibration yields a data file of motor positions (or control voltages) and corresponding RF attenuation levels in a format that may be randomly accessed by the computer. When, during system operation, an attenuation level is required, the computer retrieves the appropriate motor position (or control voltage) from the data file and executes the move.

Rotary-vane attenuator. - The RVA is calibrated by obtaining two motor positions for a given RF attenuation level. The first position is the actual indexer count at which a given attenuation is obtained when approached

from the minimum attenuation limit. The second position is that at which the same RF attenuation is obtained when approached from the maximum attenuation limit. Using this technique, the mechanical backlash errors are completely removed from the RVA motion. The mechanical limit switches are set for a slightly larger span than the RF attenuation range as part of the backlash correction (fig. 8). Typically, the minimum, or zero, attenuation position is at a point 4000 motor steps from the electrical limit of the minimum attenuation limit. Because of manufacturing tolerances within the RVA assemblies and operating frequency dependance, the position counts differ slightly from unit to unit. System calibration allows for these differences, making them transparent to the user after calibration.

The calibration process for the RVA's is fully automated. The computer begins by moving the RVA mechanism to the clockwise (positive) limit to establish a reference point. (This is the same reference point as that used during actual operation and during cold startup and system initialization.) The indexing unit moves the stepping motor counterclockwise 4000 steps to the previously set minimum RF attenuation position. The indexing unit then resets its internal counter to zero and begins RF measurements. The RF power meters measure power and record attenuation level. The RVA is then indexed in small increments in the negative direction until a given RF attenuation level is attained (within a selectable tolerance). Then the indexer stops, allowing the computer to record the actual attenuation level and indexer position. The computer then continues to move the indexer until the next attenuation level is attained, whereupon it stops movement and records the settled attenuation and position count. This process continues until the negative limit is reached (The limit switch terminates movement).

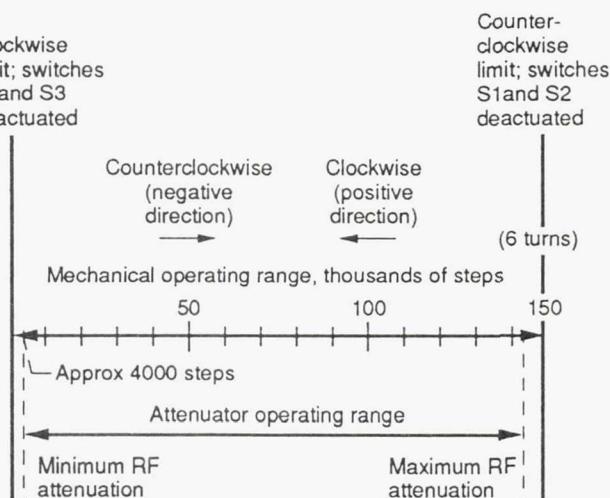


Figure 8. - Rotary vane attenuator operating ranges.

The computer then instructs the indexer to reverse the direction of motor rotation (to the positive direction) and, again, executes the move-and-measure routine until the positive limit is reached. Now, a complete set of calibration data is available that fully corrects for mechanical backlash, component aging, and direction of travel. For each attenuation level desired by the operator, a motor position is stored in the calibration data file for later recall during actual operation. The insertion loss of the attenuator is mathematically removed from the measurements at each data point. The calibration, which may be carried out unattended, is performed on each attenuator unit at each desired frequency.

The attenuation levels selected for system operation cover the full attenuation span in 0.5-dB steps. This resolution is suitable for most applications, but can be altered with simple modification to the software. The plot of a calibration data file for a typical attenuator is presented in figure 9. Calibration data file for each attenuator at selected frequencies have been created. Details on the RVA operation in the test system and the calibration data recall algorithm are included in later sections.

The calibration data file is stored in the computer for future reference. Calibration should be repeated periodically to account for mechanical wear or limit adjustments.

Solid-state attenuator. - A method of calibrating the PIN diode attenuator's voltage versus attenuation characteristic was needed to correct for the inherent nonlinearity of the diode as it approaches saturation. A calibration program was written to control a programmable power supply, power meters, and a signal generator. The program code steps the power supply through user-specified voltage increments and applies the voltage directly to the PIN. Power meters are coupled to both the input and output ports of the diode to yield actual attenuation values for each specific voltage. The

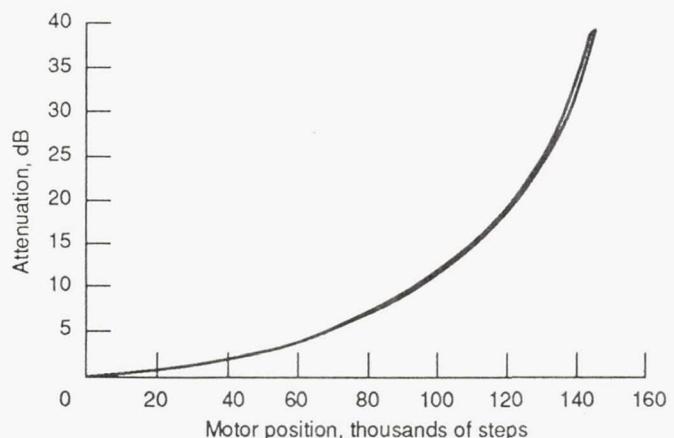


Figure 9. - Typical RVA calibration data. Frequency, 19 GHz.

programmed voltage value is checked against the power supply's own voltage readback value to ensure that the correct voltage is being supplied to the PIN diode. The calibration program also incorporates a redundancy check of the power meters to flag readings taken before the power meter has had sufficient time to settle. After all the measurements have been completed, the voltage is incremented to the next test value and the procedure repeats. The final program output is a table of programmed voltage, measured voltage, and calculated attenuation. The data are stored in the EC&M computer for recall during system operation. This calibration should be valid indefinitely unless an extreme temperature change is encountered.

SYSTEM OPERATION

Two attenuators are shown in a system configuration in figure 1. The block diagram, illustrating the rain-fade simulation and power augmentation subsystem, includes the two computers used to perform the testing and control of the system.

The first computer, the network control computer (NCC), is responsible for the general operation of the test bed, performing system operation and maintenance tasks. These tasks include the RF power augmentation function, which automatically increases or decreases the TWT RF output power to compensate for the rain fade. Thus, the NNC must, albeit indirectly, control the power control attenuator at the input to the TWT and send appropriate mode change commands to the TWT. Both functions are carried out by the digital routing processor (DRP), which provides the correct timing and synchronization. The second computer, the Experiment Control and Monitor (EC&M) computer, contains the rain-fade algorithms, calibration data files, and indexer motion commands and serves as the interface with the test operator. The EC&M computer issues the commands to increase attenuation using the rain-fade simulator.

A typical test sequence would begin with the operator invoking a preprogrammed rain attenuation model, describing the rate of onset (in decibels per second), duration (in seconds), magnitude (in decibels), and rate of recession (in decibels per second) of the experiment. With the TWT operating in the low-power mode, near RF saturation, and under clear-sky conditions, the EC&M computer would begin the rain simulation by referring to the calibration data file for the rain fade simulator to determine what motor position (or control voltage) yields the desired attenuation. The computer would then command the attenuator to move to the desired attenuation at a given rate. Once the desired attenuation is reached, the power level received by the

ground terminal would potentially drop below a preestablished threshold. This power threshold is determined based on an acceptable bit-error-rate performance below which effective communications is lost. In response to the lower received power level, the NCC initiates the command sequence to move the TWT from the low- to medium-power modes to compensate for the power loss. As part of this process, the digital routing processor also instructs the power control attenuator to change to maintain smooth transitions between modes and avoid pushing the TWT into gain compression. The initial and final positions of the input attenuator will be determined during system assembly so that interconnect losses and equipment configuration can be compensated for. The TWT anode control and power control attenuator can be adjusted simultaneously or sequentially to achieve smooth transitions. The TWT requires approximately 1 second to stabilize electrically, so nonlinear attenuator characteristics must be considered during mode changes.

The feedback system used to monitor and control the downlink power level was designed for use with either continuous-wave or burst-mode satellite operation. The more complex burst mode, used with time division multiplexing, uses an RF power meter (Pacific Measurements model 1018B) with gated sampling capability to measure peak power within a data burst. The meter then presents a dc voltage at a buffered output that is proportional to the measured RF power level. This dc voltage is fed directly to a threshold detector, which indicates overrange, underrange, and normal operating conditions, and then to the NCC through a 6809 microprocessor using a 2-bit digital code (TTL compatible). The voltage thresholds are adjustable using potentiometers on the threshold detector faceplate. Continuous-wave operation of the system can be performed using the same components, but synchronization of the power meter sampling window with the incoming data is not required.

CONTROL SOFTWARE

The software was developed to control, calibrate, and test operations for the power augmentation system. For demonstration purposes, the programs were written using a Hewlett-Packard model 236 computer/controller and the BASIC programming language.

The main computer program controls the attenuators, permitting the operator to move the RVA, for example, within the attenuation range and at various rates to simulate rain scenarios. The program begins by moving the motor to the RVA positive mechanical limit for the 0-dB reference point. For safety reasons this initialization procedure may be changed to start at maximum attenuation to avoid applying high RF power

levels where they are not wanted. Once a move has been created by the operator and input (via keyboard) into the computer, the program automatically retrieves the position parameters from the data files, then calculates and sends the appropriate acceleration/deceleration rates and motor travel velocities to the indexing unit. The computer automatically records and maintains the current motor shaft position so that potentially damaging moves will not be executed. The mechanical limit switches then serve as a backup system to avoid equipment damage in case of computer failure. Highly complex motor movements involving sinusoidal, multirate, or exotic shapes can be implemented through code changes in the main body of the program.

Software has also been developed for remote operation of the TWT amplifier. The control commands are sent from the computer to the digital routing processor to control power-up and power-down sequences and to signal transitions between output power modes. The program includes rules so that control commands are sent in proper order and at appropriate intervals to prevent damaging the tube during bias changes, power up, or power down.

CONTINUING EFFORTS

The rain-fade simulation and power augmentation system, once installed into the transponder test bed, will be subjected to extensive RF and digital evaluation. All three TWT power modes will be used during the testing to investigate the effects on link performance. Also of great interest in the testing is the ability of the TWT to change output power modes smoothly, with minimal disturbance to the system. Once the continuous-wave RF tests are performed to characterize these mode transitions, bit-error-rate measurements will be made using a unique digital test set (ref. 4). The BER test set uses a serial-minimum-shift-keyed (SMSK) modulator/demodulator pair and provides modulated digital data in either a bursted or continuous data stream format. Similar tests have been performed on other traveling wave tubes and yielded impressive results (ref. 5). Various burst rates and rain-fade conditions will be explored to assess their effect on system performance.

If systems studies indicate the need, the atmospheric propagation phenomenon known as scintillation will also be simulated and investigated. This phenomenon, which results in the sudden, short fluctuation of

signal amplitude and phase (usually less than a seconds duration) is caused by a non-uniform electron distribution in the ionosphere. Scintillation produces some errors in K_a-band communication systems and poses even greater problems for higher frequency satellites. PIN diode attenuators similar to those described in earlier sections have been developed that have the switching speed capabilities to simulate the scintillation effects.

CONCLUSIONS

The rain-fade simulation and power augmentation system described will help to answer many questions about atmospheric propagation effects on a digital communications channel. Additionally, the ability of the system to overcome these effects will be demonstrated during the experimentation phase of the program. The successful elimination of the rain-fade problems will then help to ensure clear, uninterrupted data transmission over a satellite communications channel.

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