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Apr 3rd, 12:00 AM

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F. D. McLamb
Pan American World Airways, Florida

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ACQUISITION OF S-BAND TELEMETRY DATA DURING SPACECRAFT LAUNCH PHASES

F. D. McLamb
Pan American World Airways, Florida

Whenever one sets out to write a paper dealing with space exploration, the temptation is strong to try to cover everything, from the philosophy of why we are in the space business, to the detailed component description of our own favorite spacecraft. It is therefore, worth while to define the limits of the topic of this paper. The object is to compare the problems encountered in the acquisition of S-band telemetry data from spacecraft during the launch phases, with those encountered in the deep space phases. The paper is also limited to a discussion of the Pioneer, Mariner and Surveyor missions.

In the discussion of telemetry mission support, the point of primary concern is data quality, which is directly related to the system signal-to-noise ratio (S/N). It is primarily from this point of view that this paper discusses support problems.

There were some valid reasons for transferring some telemetry link frequencies from the 215 to 260 MHz band to the 2200 to 2300 MHz band. Of primary importance was the lower noise environment at S-band. Also of importance was the improvement in overall antenna system gain for a given size directional antenna on the ground and on the spacecraft. If you consider system antenna gain as the sum of the transmitting and receiving antenna gains, fixed parabolic sizes will give an increase in system gain proportional to the square of the communication frequency. During launch, an omni-directional spacecraft antenna must be used since the spacecraft may not be stabilized and the aspect angles from the multiple ground stations vary widely. Any improvement in system antenna gain with increase in frequency due to the ground antenna alone, is cancelled by the increase in free space attenuation. Even though the transition to S-band improved system performance in the deep space mode, during the launch phases, it did nothing but complicate the acquisition problem with narrower beam widths. For example, the beamwidth of the 85' antennas on the Range decrease from 4 degrees at 230 MHz to 0.4 degrees at 2300 MHz.

The Air Force Eastern Test Range, stretching from Cape Kennedy to the Indian Ocean, has been successfully supporting launches, requiring S-band telemetry support, since 5 November 1964. This first launch was Mariner C. Figure 1 shows the AFETR land stations capable of supporting S-band telemetry requirements, and how these stations are related to a typical trajectory. This launch would typically have had injection into a 100 nm parking orbit west of Antigua and injection into mission trajectory west of Africa. Both Mariner and Surveyor launches used this basic technique with flight azimuths variable from 90° to 114°, to provide a longer launch window. The Pioneer launches were made with a fixed flight azimuth with injection into mission trajectory northeast of Ascension, after a variable coast phase from second engine cut off.

Obviously these land stations (Cape Kennedy, Grand Bahama Island, Antigua, Ascension and Pretoria) will not give continuous coverage with a spacecraft altitude of 100 miles and a flight azimuth that might change from 90° to 114°. The AFETR has instrumented three ships that can be located to cover the most crucial phases of a launch. These are the Sword Knot, Coastal Crusader and Twin Falls. For a Pioneer launch they would typically be located between Antigua and Ascension. For Mariner and Surveyor one would be located in the South Atlantic and two in the Indian Ocean. Future mission support could be bolstered by the three Apollo Ships that have S-band telemetry systems and the Apollo/Range Instrumented Aircraft. The availability of these systems, for specific AFETR launches, will be dependent upon Apollo support requirements, that dictate world-wide deployment. The two ARIS Ships assigned to the Western Test Range (Arnold & Vandenberg) may also be available for future AFETR launch support.

The telemetry systems procured for aircraft, ship and land stations were designed for multiple mission support and therefore are not "optimum" for any particular mission. In general they are designed to support telemetry requirements in frequency bands from 100 MHz to 2300 MHz with data formats outlined in the Telemetry Standards by the Inter-Range Instrumentation Group. Figure 2 is a generalized block diagram of the S-band system at each station. A high gain automatic tracking antenna acquires a signal in the 2200-2300 MHz band, amplifies the signal in the preamplifier, and converts the signal to the 300-400 MHz band. A multicoupler then feeds the signal to various tracking and data receivers. The tracking receiver completes the loop to the Antenna Servo System. The data receivers demodulate the signal and feed it to recorders, demultiplexers and displays. Each of the AFETR stations also has the capability of predetection recording the signal.

Table I summarizes the characteristics of the S-band auto-tracking antennas presently installed on the AFETR. Each of the characteristics are important when comparing launch support problems with those encountered in deep space support. The antennas in the Deep Space Network have antenna gains 2 to 10 db greater than the best AFETR antenna. The maximum antenna rates, required when tracking the deep space targets, are close to the earth rate of 0.25°/minute. Figures 3 and 4 give the antenna elevation and azimuth velocity requirements for an antenna tracking a target in a 100 nm circular orbit with a maximum elevation angle of 83°. For the case selected, all of the antenna systems could meet the maximum elevation velocity requirements of 2.8° per second but only the TAA-5-12 (Twin Falls) and the TAA-5-24 (Sword Knot & Coastal Crusader) antennas meet the maximum azimuth velocity requirements. AFETR planning of station commitments must carefully consider these dynamic limitations. Even with computer aided acquisition/reacquisition techniques, loss of auto-track near zenith could cause loss of data for 30 to 60 seconds.

This might not be considered a significant interval when the deep space tracking is in terms of hours, but it is significant during the critical launch maneuvers when the total station support time would be 400 seconds. The Mariner launches were supported with broadband manual tracking antennas. Three foot diameter dishes were installed on the land stations (except GBI) and 2' diameter dishes on the ships. They have been maintained as back up to the larger antenna systems and can be used for prime coverage on zenith passes. The only S-band antenna at Pretoria is the 3' dish.

The preamplifiers on the Range are the tunnel diode type with a noise figure of 4 db. For comparison, the DSIF facilities use cooled preamplifiers providing system noise temperatures less than $100^{\circ}K$.

The selection of the approach to support S-band telemetry requirements with down conversion to the 300 to 400 MHz band was based upon the availability of standard receivers in this band and the relatively easier task of transmitting the lower band of signals from the antenna to the receiver complex. With the narrow band, phase modulated signals to be received at S-band, particular emphasis was placed upon the phase and frequency stability of the conversion process. The initial systems procured have a frequency stability better than 1×10^{-9} and phase jitter less than 0.6°rms.

The tracking receivers, procured for most of the antenna systems on the Range, use a wide predetection bandwidth. This allows the system to track a wide variety of data spectrums with large frequency drifts without returning or adjusting the tracking receiver. This is particularly desirable in the acquisition mode, since it precludes a simultaneous space and frequency acquisition problem, that could be encountered with narrow bandwidths. The one major drawback to this general design approach is the limitation in the tracking system sensitivity. The nominal value for the tracking sensitivity is zero db S/N in the 500 kHz tracking IF bandwidth (-113 dbm with a system noise figure of 4 db). The S-band tracking systems on the RIS Sword Knot and Coastal Crusader employ a bank of 1 kHz wide predetection filters to give a tracking sensitivity equivalent to a zero db S/N in a 1 kHz bandwidth. Thirty of these filters are grouped such that spectral components within a 25 kHz bandwidth are sampled, and tracking accomplished on the component giving the highest S/N. Additional systems are under procurement for the remainder of the AFETR stations and for the ARIS Ships.

The data receivers on the AFETR were also procured to support a wide variety of mission requirements. The basic receiver accepts plug-in tuning heads, IF filters and demodulators. The AGC time constants and the video bandwidths are switch selectable.

To support the Pioneer, Mariner and Surveyor launch requirements the data receivers were operated in the long loop PM mode (synchronous phase demodulator with feed back to the receiver first local oscillator) with a threshold loop noise bandwidth of 100 Hz. The receiver capability is such that the loop bandwidth could have been narrowed to 5 Hz but then the receiver could not have tracked the Doppler frequency rate. Figure 5 is a plot of the Doppler frequency shift and rate for a 100 nm circular orbit, showing a maximum shift of $\pm$ 58 kHz and a maximum rate of 2.45 kHz/S.

The phase locked loop in this receiver is adaptive, in that its performance varies with input signal-to-noise ratio. The receivers were designed for the selected loop bandwidth to occur at 0 db signal-to-noise ratio in the double sided loop noise bandwidth, with an IF amplifier bandwidth of 2.5 kHz. The threshold loop damping factor is 0.707. Figure 6 is a plot of the receiver phase locked loop bandwidth and tracking rate characteristics as a function of the receiver IF signal-to-noise ratio. The tracking rate is based upon a loop tracking error plus loop noise of one radian. It can be seen that the adaptive characteristic of the receiver matches the changing launch support requirements. At acquisition, when the signal is weakest and the Doppler rate the lowest, the loop bandwidth is smallest, giving the best sensitivity. If it is assumed that acquisition is accomplished at a -8 db S/N ratio, a 20 db increase in signal will increase the loop bandwidth from 150 Hz to 350 Hz and increase the Doppler tracking rate from 1.8 kHz/S to 6.4 kHz/S.

Four deep space probes with S-band telemetry systems have been launched on the AFETR: Mariner C and D and Pioneer VI and VII. This discussion will also contain the problems associated with the Surveyor launches since the support reouirements caused similar support problems. These spacecraft will be compared for range support requirements dictated by modulation techniques, data formats, power levels and antenna gains. These spacecraft all switched from lower power to high power, and from omni-directional to directional antennas, after launch.

The Pioneer spacecraft is placed in a Heliocentric orbit with an orbit of 0.8 AU to 1.0 AU and with an inclination of 0.1° to 0.6° relative to the ecliptic. The spacecraft gathers interplanetary information on solar and galactic phenomena which is important to the Apollo program.

The S-band telemetry data link is PCM/PSK/PM. The launch format was 64 bps synchronously biphase modulating a 2048 Hz carrier. At launch the 40 milliwatt transmitter is phase modulated at a peak deviation of 0.9 radians. Support commitments were based upon the transmitting antenna nulls to -21 db. In the deep space support area, the data rate is lowered to 8 bps and the transmitter output power is increased to 8 watts. After proper orientation, the transmitter output is fed to the colinear array of dipoles, to give an antenna gain of 11 db. This gives an improvement in system data signal-to-noise ratio of 64 db, that could be traded directly for increased range.

The limit in the launch phase is not however, the data bandwidth; it is the ability of the data receiver and the antenna tracking system to reliably lock to the transmitted signal. For reliable acquisition, the data receiver requires a 0 db S/N ratio in the 10 kHz predetection bandwidth and for stable phase lock a +10 db S/N ratio in the 100 Hz loop bandwidth. The majority of the tracking systems on the Range require a 0 db S/N ratio in the 500 kHz predetection bandwidth.

The most stringent launch phase requirement is the minimum signal level for the tracking receiver. The difference between this tracking system S/N requirement, and a +12 db S/N ratio in a 10 Hz noise bandwidth in space, is 35 db. This, combined with the increased transmitter power (23 db), and the increased antenna gain (32 db), gives a difference in the launch and deep space system signal-to-noise ratio of 90 db. This assumes a common receiving station for both launch and deep space support. Any improvement in the capabilities of the earth stations supporting the deep space phases, such as increased antenna gain or lower system noise temperature, would add directly to this difference. Launch support with the system at GBI would give a 5 db margin in the tracking system at 1000 miles. There would still be a 5 db margin in the data system at 70 million miles if the antenna could track and if the data receiver and demodulator were locked.

A similar evaluation can be made of the two Mariner launches carrying S-band telemetry packages. The purpose of these Mariner-Mars launches was to conduct a close-up (fly-by) scientific observation of the planet Mars. The S-band telemetry link was again PCM/PSK/PM. The launch data rate of 33-1/3 bps modulated a 600 Hz subcarrier, requiring a 2.5 kHz receiver IF filter. For deep space support the modulation characteristic was switched to 8-1/3 bps on a 150 Hz subcarrier. Replacing the omni-directional antenna with a parabolic dish for deep space support, gave an antenna gain of 23 db instead of the -19 db level (-19 db over 90% of the sphere) during launch. The difference in data S/N is 56.2 db and the difference in the required system signal-to-noise ratio is again 90 db.

The Surveyor series had as their ultimate goal, soft landing of instrumented packages on the moon. It cannot be termed a "deep space" mission, but it is included in this discussion due to its similar launch support problems. The telemetry format consists of 550 bps PCM data frequency modulating a 3.9 kHz subcarrier oscillator which phase modulates the S-band carrier. For support, a 10 kHz IF filter was used. The transmitter power is switched from 0.1 to 10 watts and the antenna gain is switched from -19 to +27 db after the launch phase. The difference in data S/N is 66 db. With a required +12 db in the 600 Hz data bandwidth in the Lunar configuration, compared with the 0 db in the 500 kHz tracking IF in the launch phase, the difference in the required system S/N is 83.2 db.

For these narrow band data systems, the obvious approach to improving range support is to improve the tracking system sensitivity. As noted previously this has been accomplished on two ships and tracking receiver systems are presently under procurement that will provide similar capability on all AFETR stations. With these new tracking systems the limiting system characteristics are the required data S/N and the carrier phase lock by the data receiver. Even though the receiver could be locked at negative S/N ratios, the frequency shift rate and short support interval for each station precludes data commitments that require acquisition at lower than 0 db S/N ratio in the IF noise bandwidth. For Mariner and Pioneer, the system limitation will be receiver lock. With the low modulation index of 0.3 radians, the system limitation for Surveyor is the required data S/N ratio.

With the improved tracking systems, the telemetry stations have solved the sensitivity problem associated with the Pioneer, Mariner and Surveyor launches, at a cost in system complexity. Acquisition must be accomplished with a simultaneous search in space and frequency. The antenna must be pointed in the proper direction at the same time the tracking receiver is tuned to the correct frequency, to accomplish antenna auto-track. The data receiver must then be tuned to achieve phase lock. The process is aided somewhat by using the same receiver for tracking and data. Even then, acquisition at the horizon (+2°) takes 15 to 30 seconds. Reference to Figures 3,4 and 5 will give an idea of how fast the acquisition probability would decrease, if not accomplished close to the horizon. With a launch trajectory that would produce a maximum antenna elevation of 83°, the probability of acquisition or reacquisition at elevation angles above 30°, approaches zero. To improve the acquisition probability, each station is provided with its calculated antenna angles and Doppler frequency shift characteristics, related to liftoff time. The actual transmitter frequency, measured just prior to liftoff, is transmitted down range to offset the Doppler curves. The telemetry station at Antigua and all stations uprange are tied together in a computerized acquisition system. A radar or telemetry antenna can obtain pointing information from another antenna that may be on track. Ascension, Pretoria and the three RIS can acquire from their own computer programs. These programs can be updated during the launch, with data relayed from the Cape computer facility. It has not been necessary to automate the receiver tuning, but it could, of course, be accomplished with much the same technique.

The acquisition of the spacecraft at mission objective also requires a search in both space and frequency. However, the longer search time available in the absence of the high angular and frequency shift rates, makes it a comparatively easy one.

The intent of this paper has not been to make light of the deep space support problems, but to point out how the selected data and spacecraft characteristics for the Pioneer, Mariner and Surveyor programs, have complicated the launch support requirements, and to show how these problems have been resolved on the AFETR.

TABLE I

AUTOTRACK S-BAND ANTENNA CAPABILITY

ANTENNA	GAIN (db)	BEAM WIDTH	AZIMUTH VELOCITY	AZIMUTH ACCELERATION	ELEVATION RANGE	ELEVATION VELOCITY	ELEVATION ACCELERATION
TAA-2A	48	0.4°	15°/sec	$7.5^\circ/sec^2$	$4^\circ-86^\circ$	15°/sec	$7.5^\circ/sec^2$
					$4^\circ-0^\circ$	1°/sec	$7.5^\circ/sec^2$
					$86^\circ-90^\circ$	1°/sec	$7.5^\circ/sec^2$
TAA-3A	40	1.0°	15°/sec	$7.5^\circ/sec^2$	$4^\circ-86^\circ$	15°/sec	$7.5^\circ/sec^2$
					$4^\circ-0^\circ$	1°/sec	$7.5^\circ/sec^2$
					$86^\circ-90^\circ$	1°/sec	$7.5^\circ/sec^2$
TAA-3	39	1.0°	15°/sec	$7.5^\circ/sec^2$	$4^\circ-86^\circ$	15°/sec	$7.5^\circ/sec^2$
					$4^\circ-0^\circ$	1°/sec	$7.5^\circ/sec^2$
					$86^\circ-90^\circ$	1°/sec	$7.5^\circ/sec^2$
TAA-5-24	40	1.2°	30°/sec	$60^\circ/sec^2$	$10^\circ-70^\circ$	30°/sec	$60^\circ/sec^2$
					$10^\circ-0^\circ$	12°/sec	$60^\circ/sec^2$
					$70^\circ-80^\circ$	10°/sec	$60^\circ/sec^2$
					$80^\circ-96^\circ$	5°/sec	$60^\circ/sec^2$
					$0^\circ-10^\circ$	7°/sec	$60^\circ/sec^2$
TAA-5-12	35	2.4°	30°/sec	$200^\circ/sec^2$	$0^\circ-80^\circ$	30°/sec	$160^\circ/sec^2$
					$-5^\circ-16^\circ$	5°/ sec	$160^\circ/sec^2$
					$81^\circ-96^\circ$	5°/ sec	$160^\circ/sec^2$

TABLE II

SPACECRAFT TELEMETRY CHARACTERISTICS

	PIONEER	MARINER	SURVEYOR
Transmitter Frequency	2292MHz	2298MHz	2295MHz
Antenna Gain	-21/+11db	-19/+23db	-19/+27db
Transmitter Power	.04/8W	1.5/10W	0.1/10W
Modulation Index	0.9	1.0	0.3
Modulation	PCM/PSK/PM	PCM/PSK/PM	PCM/FM/PM
Subcarrier	2048Hz	600/150Hz	3.9kHz
Data Rate	64/8 bps	33-1/3/ 8-1/3 bps	550 bps

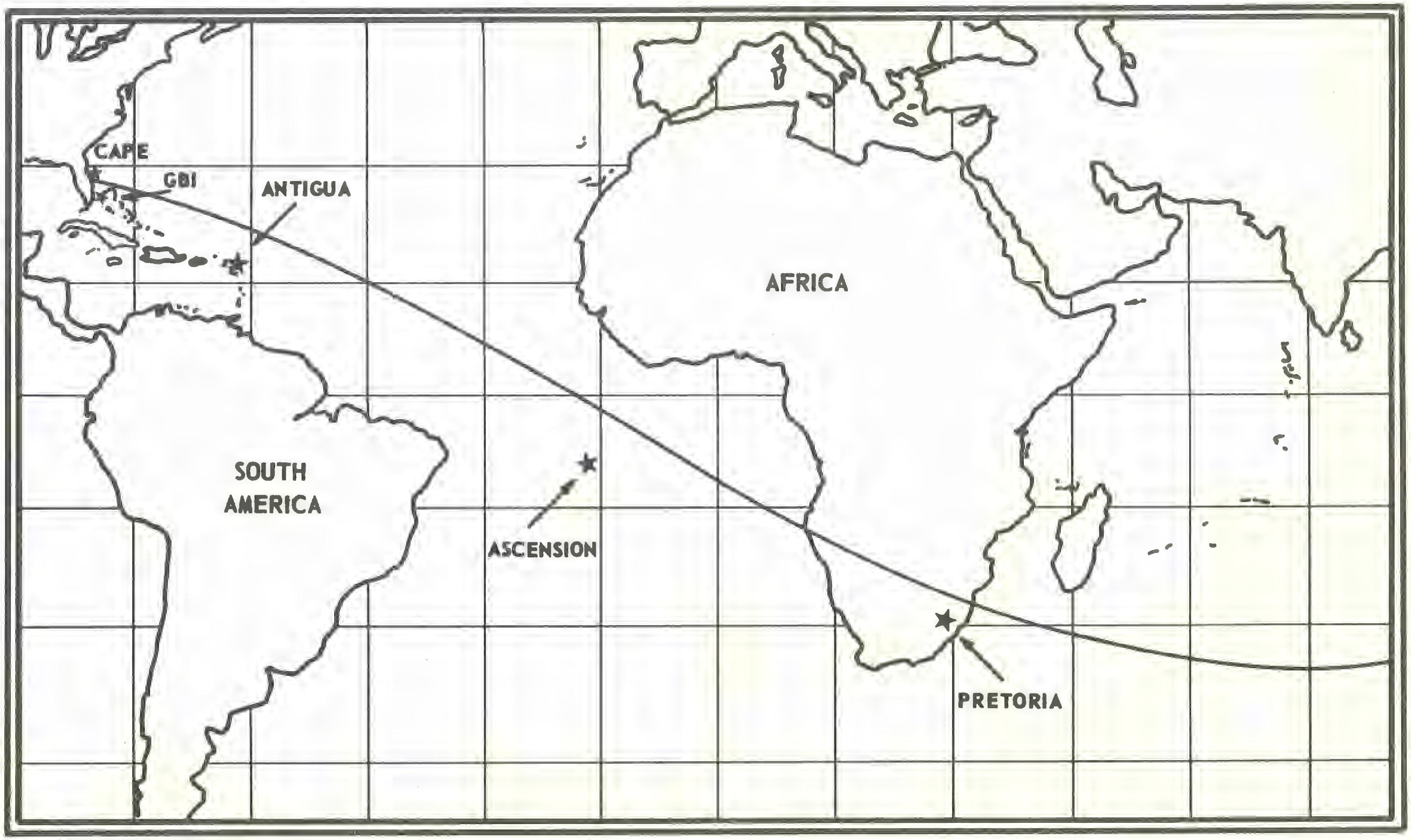

FIGURE 1 AFETR TRAJECTORY FOR 102° FLIGHT AZIMUTH

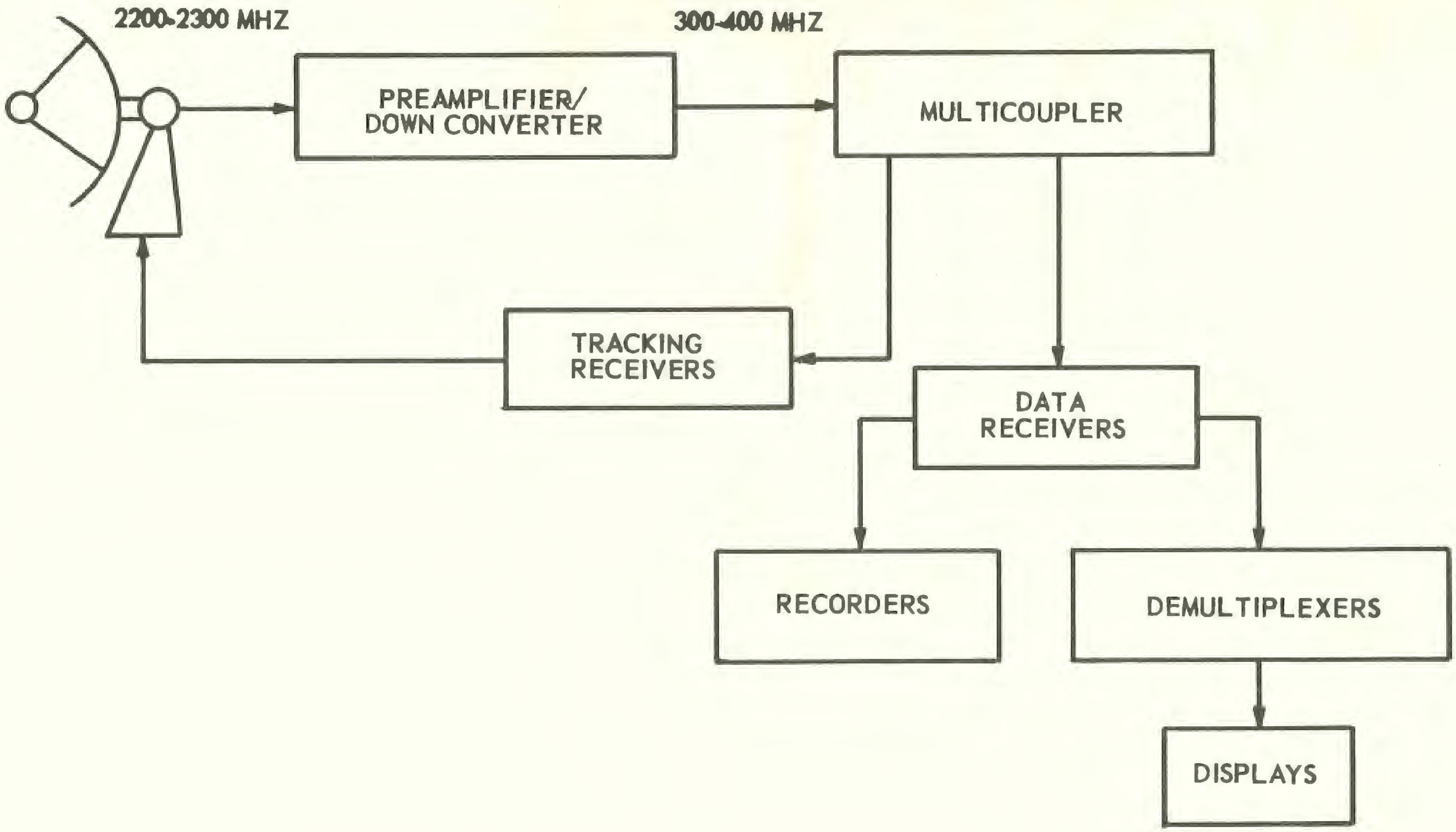

FIGURE 2 TYPICAL AFETR SUPPORT CONFIGURATION FOR ACQUISITION OF S-BAND TELEMETRY DATA

FIGURE 3 ANTENNA ELEVATION VELOCITY FOR 100-NM CIRCULAR ORBIT

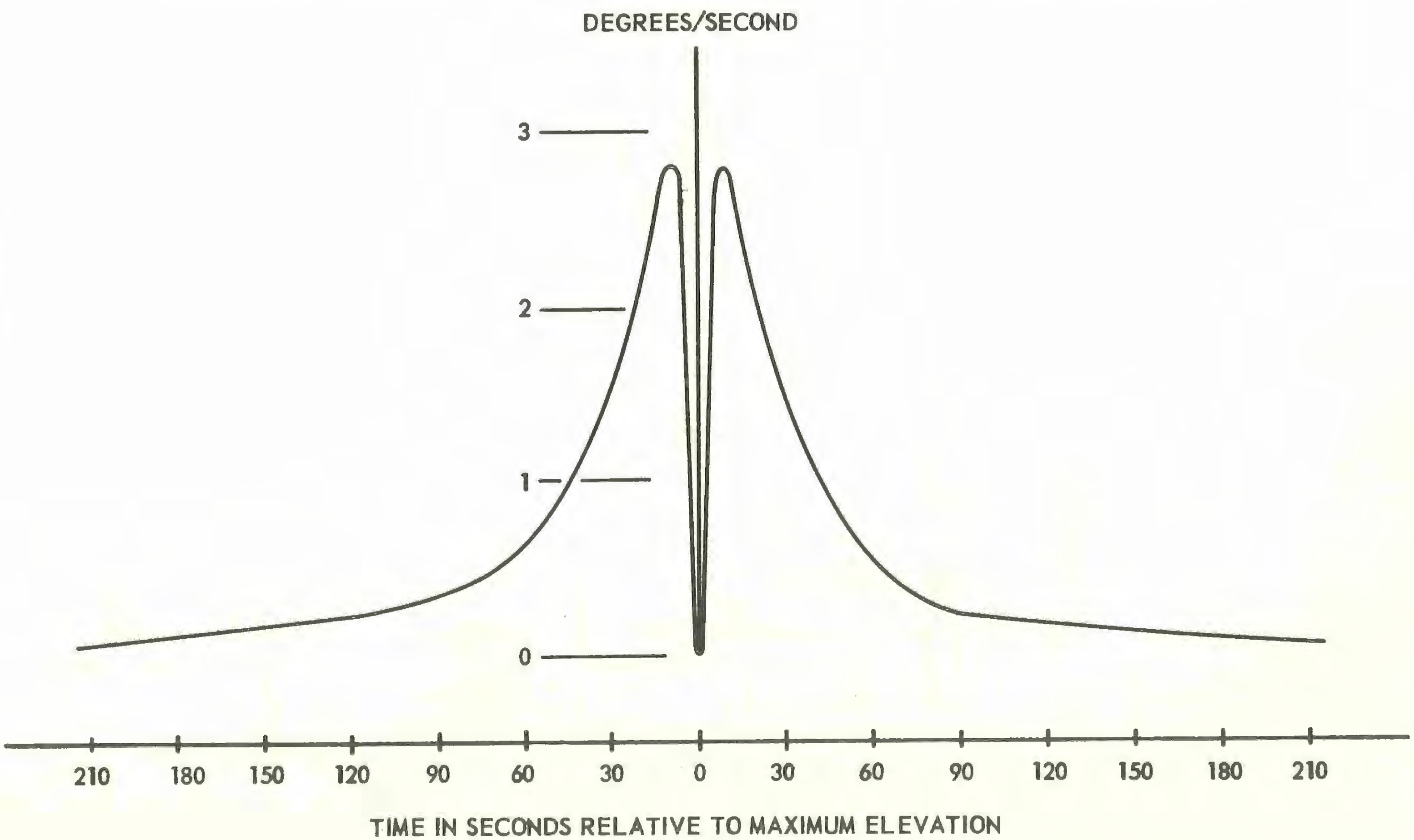

FIGURE 4 ANTENNA AZIMUTH VELOCITY FOR 100-NM CIRCULAR ORBIT

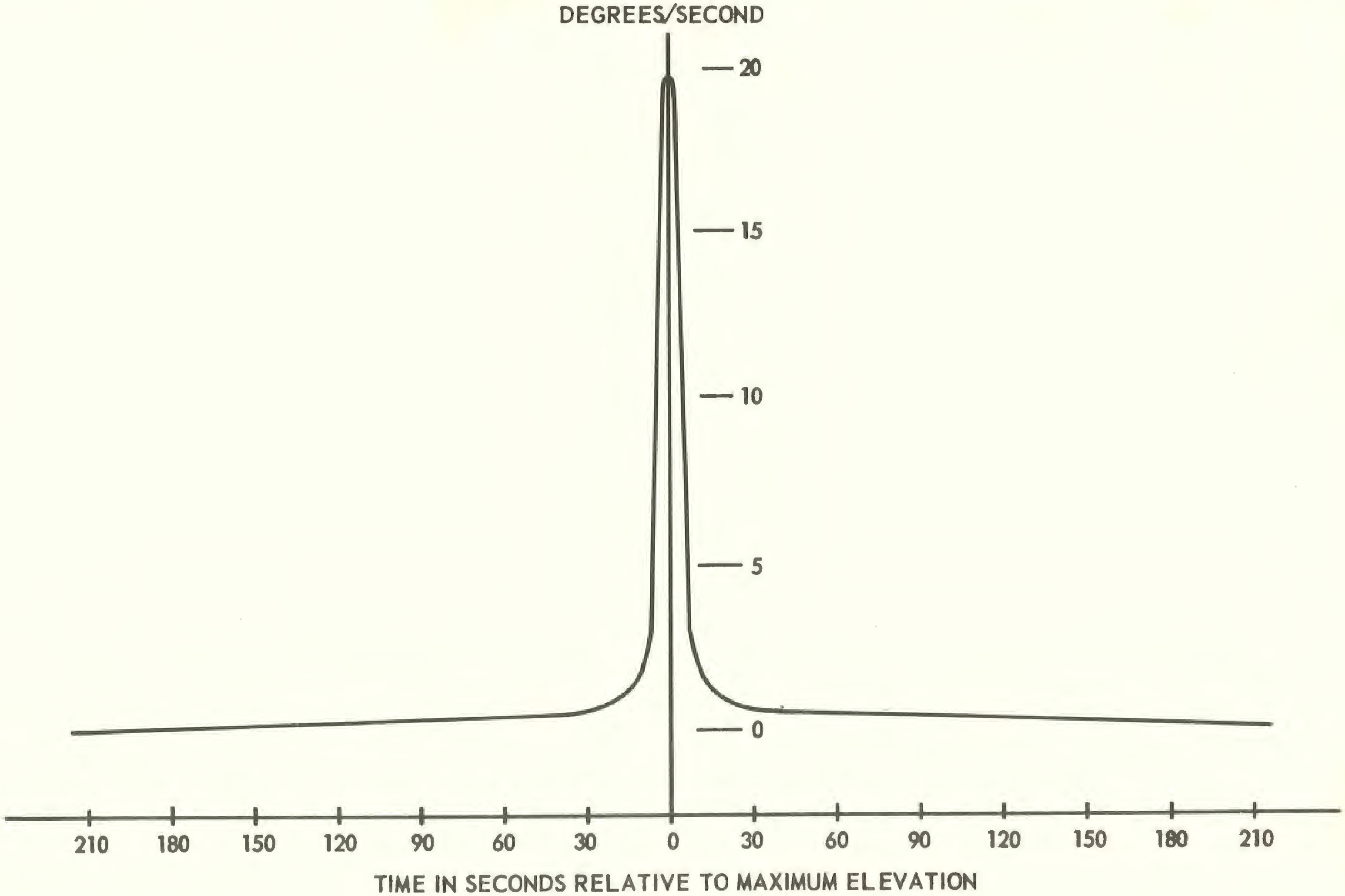

FIGURE 5 DOPPLER FREQUENCY SHIFT AND RATE FOR 100-NM CIRCULAR ORBIT WITH TRANSMITTER FREQUENCY OF 2300 MHZ

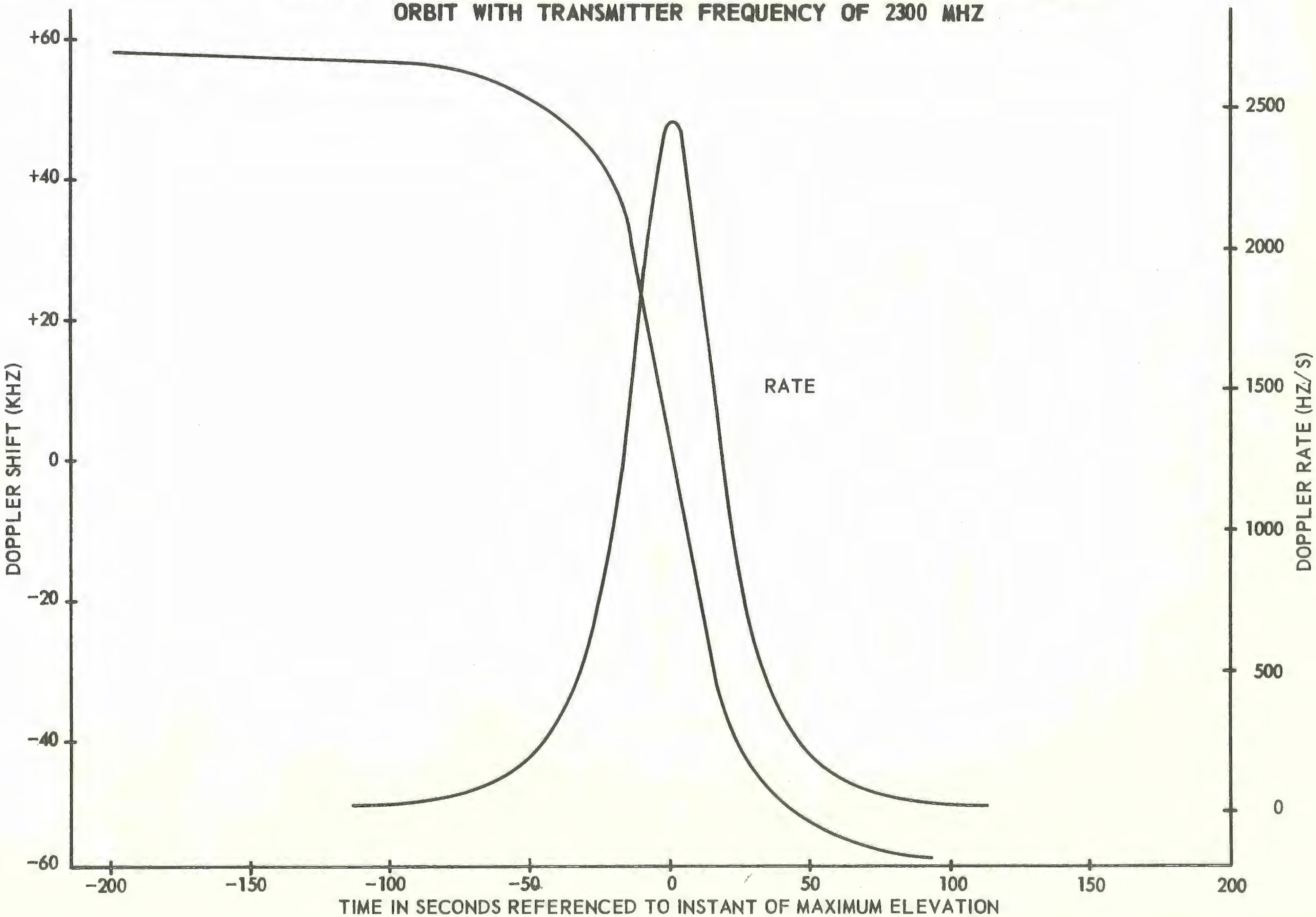

FIGURE 6 RECEIVER LOOP BANDWIDTH AND MAXIMUM TRACKING RATE VS IF S/N RATIO