MAF3065-8-9
15 December 1967

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Contract No. NAS 8-11835

FINAL REPORT

AROD SYSTEM CONCEPT AND APPLICATIONS STUDIES

Prepared for

NASA

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SECTION I

1. INTRODUCTION

This document is a final report on the work accomplished on Modifications No. 7 and 8, System Concept Analysis and AROD Applications Study, to NASA Contract NAS-8-11835 AROD System Test Model Hardware. The report contains analyses and observations pertaining to the system concepts, the implementation of these concepts, potential expansion of the concepts, and potential application of the system both with the present concepts and with modified concepts. The system concepts, in general, have proven to be quite versatile and permit the system to be adaptable to a large class of applications.

SECTION II

2. THE SYSTEM CONCEPT AND ITS IMPLEMENTATION

The concepts about which the AROD system is modeled are those stated in the Scope of Work for the AROD System Test Model Hardware. In the following paragraphs these concepts are summarized and the manner in which the equipment was implemented to satisfy the concepts is reviewed.

2.1 THE AROD CONCEPT

AROD is a vehicle-based CW radio frequency system, operating at S-band frequencies, for providing information on the position and velocity of launch or space vehicles. The output can be used for guidance of the vehicle, or for measuring vehicle performance.

Vehicle position is obtained by trilateration of the ranges from three ground stations, the ranges having been measured by the phase shift of a range modulation imposed upon the carrier. The vehicle velocity is obtained by processing of the slant range-rate from three or more ground stations, the range-rate having been obtained by measurement of the Doppler shift of the carrier.

Computation of position and velocity is performed on board the vehicle. The output is in digital form, in near-real time, and with an event-time correlation to within ten microseconds. The ground stations are simple and in most instances may be unmanned; no particular geometry of ground station location is required. Furthermore, no communication link or time correlation between ground stations is required. Operation of the ground stations is controlled from the vehicle by means of a vhf control link.

The AROD System has the capability of being used with any type of vehicle, and can provide nonredundant range data out to a limit determined by the particular range modulation being employed. Furthermore, the system is compatible with other S-band radio frequency systems; multipurpose use can be made of the AROD carrier for communications, telemetry, or other applications. The maximum unambiguous range was to be 2000 km for the Test Model equipment.

All frequencies and timing signals used in the AROD Vehicle borne System are derived from, or controlled by, frequencies derived from the master oscillator located in the Frequency and Time Reference section. These frequencies are phase coherent in the meaning of phase coherence as defined for use in this document. Time and event marker signals are similarly coherent. The timing is unambiguous over a five minute interval.

2.1.1 Range Measuring

The Vehicle Tracking Transmitter is Angle Modulated by a range signal. The range signal is processed through the Ground Transponder System and transmitted back to the vehicle with the phase coherence retained. In the Vehicle Tracking Receiver, the delay incurred by the range signal, in transit to the ground station and back, is measured by comparison of the returned signal with a reference range signal. The range modulation is appropriately chosen to measure out to the required maximum distance and to provide appropriate phase ambiguity resolution. The range is obtained by multiplying the measured delay by the appropriate constant.

2.1.2 Velocity Measuring

AROD determines the Doppler velocity of a vehicle with respect to a particular ground station by measuring the Doppler shift of the carrier frequency returned to the vehicle from the ground station. The return transmission is derived coherently in the ground transponder system from the carrier transmitted from the vehicle. Thus, the Doppler shift that is measured is the sum of that incurred in the forward and return transmission. The Doppler shift is measured by comparison with a Doppler reference frequency which is phase coherent with the vehicle tracking transmitter frequency.

2.1.3 Station Control and Signal Acquisition

A vhf station control link from the vehicle to the ground provides a means of controlling the ground station system from the vehicle. Ground stations are placed into operation, via the station control link, as required and as scheduled in the Vehicle System Control Section. Stations are placed out of operation in a similar manner. Ground Tracking Antenna pointing data is obtained from a direction finding system associated with the ground terminal of the vhf station control link.

The Ground Station Control Receiver does not require a frequency or time correlation search to receive the control signal from the station control transmitter; therefore, the Doppler and timing information which is obtained from the control link is used to aid the acquisition of the tracking signal from the vehicle. The ground transmitter inserts "Doppler inversion" in the retransmitted carrier to compensate for Doppler shift so that the return carrier arrives back at the vehicle at approximately the rest frequency of the vehicle tracking receiver. The Doppler compensation is removed from the ground transmitter by command from the vehicle after the acquisition is completed on the vehicle.

2.2 IMPLEMENTATION REVIEW

The implementation of the above concepts serves as a base upon which to discuss their modifications. The following paragraphs constitute a brief review of the methods, successes, and the critical areas in the design.

2.2.1 Modulation Method

The basic system requirements, long range operation, low power, high accuracy, large nonambiguous range measurement, rapid acquisition, signal dropout protection, protection against multipath, high flight dynamics, nonsensitivie equipment, and long term stability, all placed an important role in the selection of the modulation and demodulation methods. The detailed method of modulation could not be selected without considering the methods of acquisition and demodulation. However, the influence of these is discussed in paragraph 2.2.2. The chief constraints were transmitter power, allowable r-f bandwidth, and carrier frequency allocation.

There are three generic methods of modulation that may be used for ranging: Pulse, Phase-Coded CW, or Multiple Tone Angle Modulation. There are combination systems, but these constitute the basic forms.

For high accuracy, a high frequency tone is desired for fine range measurement. In terms of pulses, this means a narrow pulse. Because of a maximum bandwidth constraint, the modulation was limited to a bandwidth of the order of 6 MHz. A single sine wave at this frequency would yield maximum accuracy but no ambiguity resolution, i.e., there is no way to distinguish one wavelength from another. Multiple tones could be used to resolve these ambiguities just as the repetition rate could be tailored for maximum ambiguity resolution with a pulse system. In the former case, the added tones reduce the allowable energy available for the fine resolution tone. In the latter case, the peak-to-average power ratios become inordinate. Of course, there are methods to minimize these drawbacks.

The rejection of multipath was considered to be important for the optimum system operation. The degree to which multipath can be rejected is constrained entirely by the allowable radiated bandwidth. When the multipath delay is longer than the pulse width, pulse modulation can reject it; however, angle modulation in general has poor multipath rejection capabilities.

A good compromise between the advantages of angle modulation and pulse modulation is phase-coded CW, or biphase modulated pseudonoise (PN). It has the average power characteristics of angle modulation and the multipath rejection and ambiguity resolution of pulse modulation. The accuracy attainable is nearly that of the angle modulation. Pseudo-noise code modulation is near optimum, if not optimum, subject to all the constraints.

The system requirements not only specified high ranging accuracy but also high range rate accuracy. The latter could only be obtained from the carrier Doppler shift. Hence, a fully coherent system was essential. Furthermore, it was as necessary to protect the carrier from multipath as the ranging signal. Therefore, suppressed carrier transmission was required. This compounds the acquisition problem, since a search must be made in both time (range) and frequency (range rate). Although the carrier frequency search problem on the down-link was solved by the VHF Command Link, and on the up-link by the Doppler Reverse technique, there was still the time and frequency search for the modulation to be resolved.

As the ambiguity-to-resolution element ratio was high, a simple PN code would necessitate an inordinate search time in both range and range-rate. The latter because the Doppler shift could exceed the range loop bandwidth (necessarily small for high accuracy) by a factor of 100 to 1. The number of time slots or range resolution intervals was 80,000 or more. For this reason, a fast-slow coding method was devised. A slow code was run from the word length of the fast code. The latter was 511 bits long, the former, 127 bits. The total period was 2 x 511 x 127 resolution intervals. This solved the ambiguity and resolution problem.

The initial search was for the slow code, where only 127 bits needed to be searched. When acquired, the error was a small part of the 511 fast or "H code" bits. These could then be obtained by a short second search.

More important, the slow or "L Code" clock frequency was so low, approximately 12 kHz, that a range-rate search was not required. After L-code acquisition, rate-aid of the range loop by the carrier loop eliminated a Doppler search for the H code.

Once tracking in H code, the range and carrier loops respond only to H-code coded signals. Although until this, the multipath protection was minimal; in H-code track, the protection is the maximum possible under the constraints.

The most susceptible part of the system was the carrier loop. The dynamics of the system were such that it had to have a bandwidth greater than 200 Hz.

As all of the received energy can be used in both range and modulation tracking, the system threshold was determined by the carrier loop and the acquisition rates.

Although the system could have gone from L-code to complete H-code modulation, there was some concern with signal dropout and the comparatively long time for reacquisition. Consequently, the L-code and H-code modulations were time shared on a 50 percent duty cycle basis. In full track, the carrier loop used one interval and the range loop the next. As a result, there is a 6 db energy loss for each tracking function. This is a compromise to two things. First, the time-sharing H-code intervals is a concession to the practical circuit problems discussed in section 2.2.2. Second, time sharing the L and H codes was a concession to signal dropout. With a short loss of signal, H-code correlation could be lost, but by returning to L-code track, the tolerance was increased a thousand times. This allows rapid recovery when the signal returns.

The system threshold is about -128 dbm. Within a very few decibels, all system functions fail at the same point. That is:

1. The carrier loses track

2. The range error becomes excessive

3. The data error rate is excessive

4. The system cannot acquire or reaquire

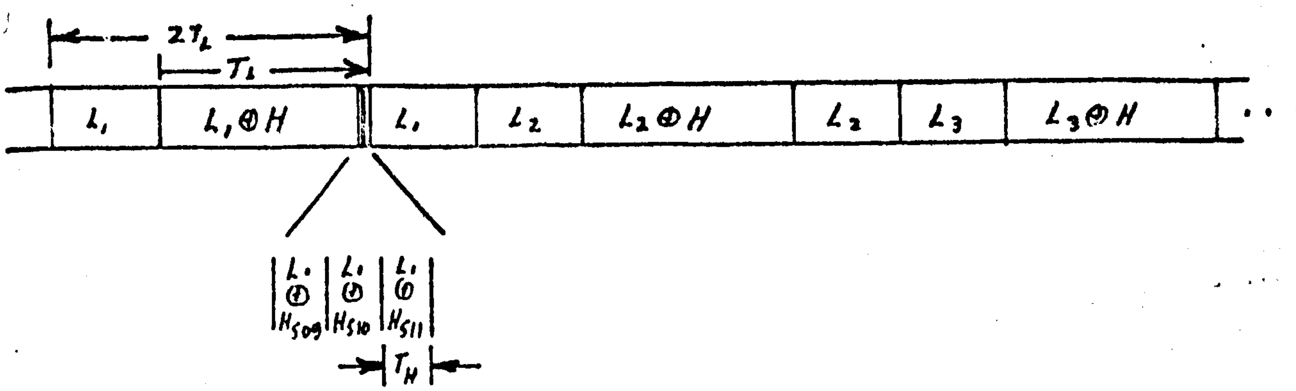
As a system, therefore, the selected method of modulation represents an optimum solution to the AROD design objectives subject to the stated constraints. Naturally, a large departure in objectives and/or constraints could alter this materially. With regard to the detailed method of modulation, this was done by phase modulating a CW signal $\pm \pi/16$ radians. This signal was then multiplied by eight to the final output frequency.

This necessitates a very wideband multiplier which causes gain bandwidth problems and erects undesired signals in the final output. This appeared to be the only practical method at the time of design. However, two other methods should be considered. One, multiplication by an odd integer of a balanced modulated signal. This requires only carrier modulation. The bandwidth need not be as wide in the multiplier and probably the side tone generation would be less. Second, direct balanced modulation at the final carrier should be considered. The switching-time vs power tradeoff at S-band was undesirable several years ago. New components and new techniques make this worth reconsidering.

2.2.2 Signal Processing or Demodulation

The details of the modulation and demodulation could be varied. Some of the problems observed might be relieved by detailed rearrangement. The basic modulation method is shown in Figure 2-1.

The time sharing intervals for carrier and range tracking were an equipment compromise. With no time sharing, two separate intermediate frequency channels are required. These need to track in gain and phase over a 70 db dynamic range. For long term stability over several years of unattended operation, this is very difficult; but by using one common channel, this problem was greatly alleviated. There is no reason to believe that this is not a justifiable compromise.



where

$$T_H = \frac{10^{-6}}{6.4} \text{ seconds}$$

$$T_L = 511 \times T_H, \; F_L = \frac{1}{T_L}, \; F_H = \frac{1}{T_H} = 6.4 \times 10^6 \text{ Hz}$$

$\oplus$ = modulo two addition

During acquisition (V1 - V2) H-code is removed.

Modulation is applied by modulo-two adding F_L and Data to every 8th L code interval ($2T_L$) starting with bit L_2. A ONE is 10 and a ZERO is sent as 01.

Figure 2-1. Transmitted Signal in Full Track (V4)

The demodulator operates such that the error signals are functions of amplitude and only to a second order are functions of the intermediate frequency phase. This means that a significant phase variation can be tolerated without causing a significant tracking error. Another way of expressing this is that the error point is transferred to the first demodulator, and subsequent filter phase-shifts and gain fluctuations only affect the tracking loop gains. They do not, to a first order, affect the error itself by causing a tracking bias.

During the acquisition mode, only the L code is transmitted from ground to vehicle on a "Reversed Carrier Doppler" such that the received carrier has essentially zero frequency error. The carrier loop vco is clamped by the Frequency Preset circuits to center frequency. The receiver reference code is $L \oplus F_L$. When the codes are not aligned, the signal in the i-f amplifier is similar to $L \oplus F_L$ which has components about every 50 cps. In principle as the codes come into alignment, the signal turns into F_L, a square wave at the L-code clock frequency. This square wave is multiplied by a square wave at the carrier "phase detector". The principle of this process is shown in Figure 2-2.

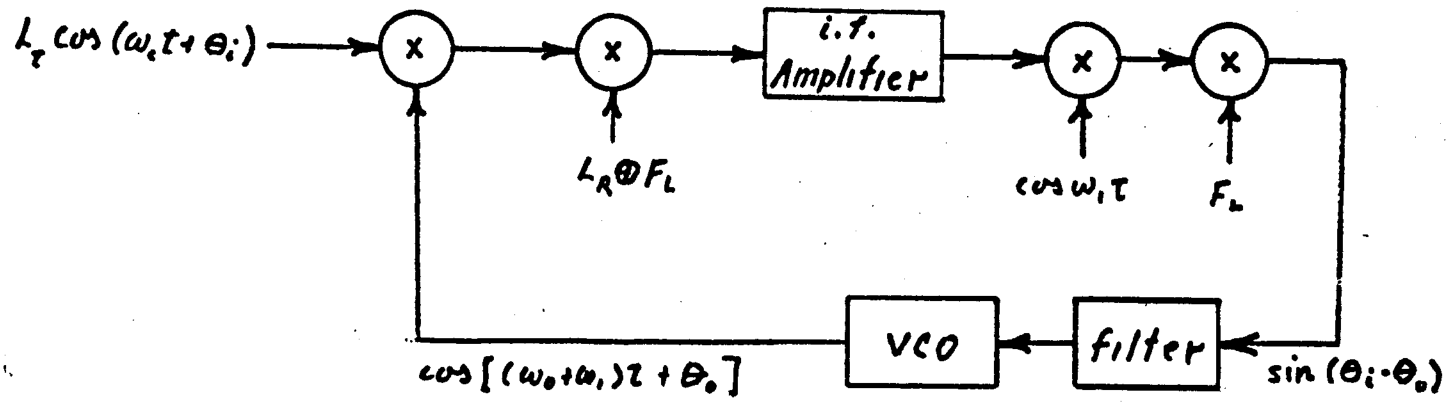


Figure 2-2. Simplified Demodulator

When the codes L_t and L_r are not in phase, the result is a signal similar to a pseudo-noise signal. The coherent agc is not operative. Consequently, the signal level is high. This causes the carrier loop bandwidth to increase. The result is that a significant portion of the modulation is tracked by the carrier loop. This in turn causes a high level of signal out of the synchronization detector (A_L detector), and the margin between false synchronization and proper synchronization is consequently reduced. A noncoherent agc helped this problem but did not completely cure it. The best cure may be the addition of a noncoherent acquisition sensor, with a corresponding increase in code search rate. This will have the side benefit of shortening the initial acquisition cycle. The carrier loop would be opened for the search with this mechanization to prohibit carrier tracking of the modulation components.

2.2.3 Frequency Synthesis

A fundamental factor in the AROD concept is the derivation of all carrier frequencies, code rates, measurement intervals, and data rates from a common frequency source. This poses a formidable problem in frequency synthesis when the desirability of transmitted frequency agility is recognized. The benefits to be gained by the

the use of this common source are, however, significant in both the performance and in the long term stability of the system. It has made practical velocity-aiding from vhf to S-band as well as from S-band to the code rate. It has also completely eliminated bias errors from the velocity measurement because both the frequency to be counted and the time interval over which it is counted are derived from the common source. The frequency preset technique used in the vehicle receivers would not be available without the common source. The problems involved in the use of the common frequency source lie almost entirely in the derivation of the S-band signals. Considerable difficulty was experienced in attaining frequency agility together with spectral purity.

Initially, an indirect frequency synthesis was used for the S-band signals. This synthesis uses a phase-locked loop with the oscillator output divided by a programmed number and then phase locked to a subharmonic of the master oscillator frequency. The fallacy of this approach is that the effective synthesized frequency is at the subharmonic which is locked to the output. Control of phase jitter became very difficult as the final output signal included a multiplication of about 350,000 from the synthesized source. The phase jitter in turn caused a high variance of the extracted velocity readings.

Replacement of the indirect synthesis by a direct synthesis has resulted in greatly alleviating this problem with very little increase in hardware. The concept of a single standard frequency source, therefore, has proven to have far more advantages than disadvantages and should be retained for this class of equipment.

2.2.4 Range Extraction

The AROD Range Extraction is a two-step process of coarse and fine measurement. The technique of heterodyning the code clock to a lower frequency has achieved the desired resolution and the technique for removing ambiguous readings between the coarse and fine registers has been largely successful. There are a few range phases which give erroneous outputs of the order of one H-code bit. These have been traced to improper phasing due to logic element delay in some signal paths. The signal delay paths in this system are critical and care must be exercised. The range anomalies can be removed by placing the mixers which heterodyne the range code clocks electrically closer to the reclocking circuitry. This may require that the reclocking circuitry be located in the range extraction unit or, conversely, that the mixers be located in the code control units.

In the present system, the range measurements are made simultaneously in all channels, although some equipment saving is possible with sequential range measurement. Preservation of this feature will be heavily weighted by the characteristics of the processor which converts the range measurements to position information.

2.2.5 Velocity Extraction

The velocity measurement is made by counting the cycles of the eighth harmonic of the S-band carrier frequency Doppler for a time of ten L-code periods or approximately 0.203 second. The Doppler frequency to be counted is superimposed on a bias frequency of 3.2 MHz so that the frequency counted will always exceed 1.8 MHz. The velocity data is further multiplied by two in the velocity extraction unit by comparing the phase of the Doppler signal at the beginning and at the end of the measurement period.

The present model contains design errors which insert a bias in the velocity data. A design which corrects these deficiencies has been breadboarded. The technique is satisfactory and the fundamental accuracy of the velocity measurement has been proven to be adequate for most of the applications studied.

2.2.6 Station Control

The vhf control link is used by the vehicle as an aid in the acquisition and release of transponders. This link contains the vehicle system control logic, vhf data modulator/transmitter, the transponder vhf station control receiver/data demodulator, and the station control logic. The basic function and operation of these units is described in the AROD System Description Report.

This link can be divided into two parts: the generation of the control data functions, and the transmission of the data.

The modulation/demodulation techniques were completely satisfactory and no changes are recommended. The low-pass filter used to attenuate higher order harmonics of the 18.75-kHz subcarrier was improperly specified in the test model; however, the proper filter characteristic presents no design problem.

The control logic was determined by the station handling philosophy and the acquisition steps required by the S-band tracking system. The station handling philosophy is determined from the class of mission, the number of stations to be used, etc. This philosphy is described in the AROD System Description Report and the equipment performed the function well. No changes are recommended for this mission profile.

Some problems were encountered with the acquisition/reacquisition logic and should be corrected in future equipments. The major problem was due to a complete dependence on the transmitter and receiver code states in the transponder. The acquisition states are described in the AROD System Description Report.

For example, the transponder receiver code control goes to the "reset" position, T-0, when the transponder is instructed to go to T-0. This was done to provide a reset pulse to the receiver coder in case the coder started at an undefined state. During the test program, this configuration complicated the acquisition/ reacquisition cycle by forcing the transponder receiver to release and reacquire needlessly. This can be eliminated by defining separate acquisition states for the Transponder Transmitter and Transponder Tracking Receiver as shown in Figure 2-3. First, consider the receiver code control. After initial power turnon by the STANDBY signal, the receiver code control is set to the TR-0 state and the transmitter code control is set to the TT-0 state. The receiver will then proceed through the acquisition steps to the H-code lock mode, T-2. The reacquisition logic for S-band received signal dropout will be identical to the present logic, as the transmitter code control will start in state TT-0. Upon receipt of the ON instruction, the transmitter will respond with L-code, if the receiver is not in state TR-0. The TRACK instruction will initiate the Doppler sweep and at the completion of the sweep, H-code is applied and the acquisition cycle at the transponder is complete. If the vehicle desires to reacquire, the RETURN-TO-STANDBY signal is used to reset the transmitter code control to state TT-0 and to reset the TRACK and ON registers. The transponder reacquires in the normal programmed manner. If the Transponder Tracking Receiver loses both L- and H-code lock and returns to state TR-0, the transmitter is returned to state TT-0 and the vehicle will then reacquire.

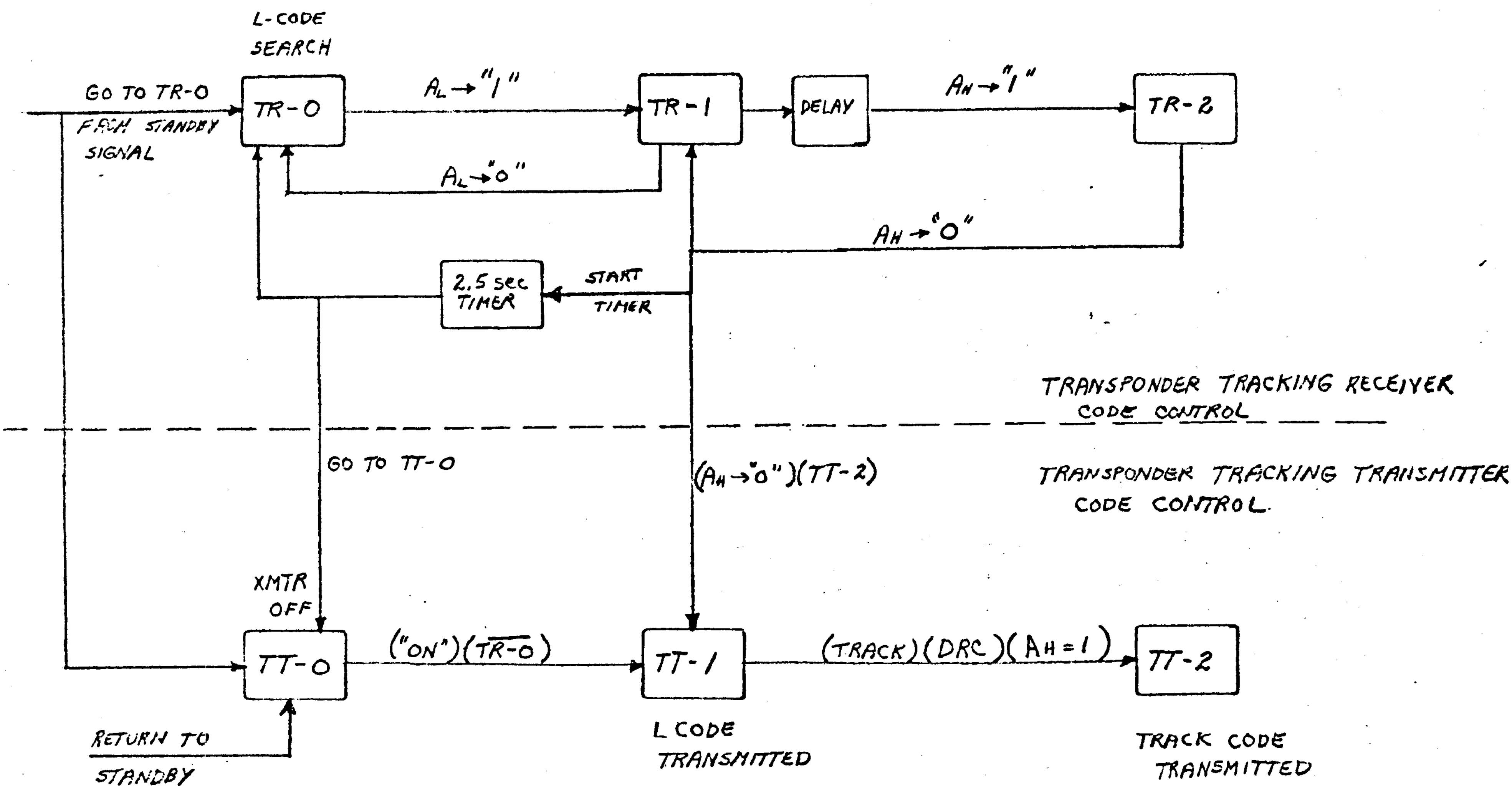


Figure 2-3. Proposed Code Control for Second Generation Transponder Code Control

SECTION III

3. EXTENSION OF SYSTEM CONCEPTS

The System Concepts discussed in Section 2 of this report formed the basis of the AROD Test Model Hardware design. In the following paragraphs, several potential modifications of the concepts are explored. These would result in accentuation of some of the system characteristics, usually with the sacrifice of others. In some of the cases, unused capability of the present system could be used for additional flexibility, and in others redundant capability may be eliminated with a consequent reduction of power and weight requirements.

3.1 EXTENSION OF RANGE CAPABILITY

With a view towards increasing the flexibility of the AROD system to adapt to a wide variety of uses, some thought has been given to the possibility of increasing the range capability beyond its present nominal 16,000 km.

There are two basic approaches to this problem. The first, preserves the same design objectives as are used in the present system configuration, and obtains a greater range capability by a judicious modification of the present modulation and demodulation techniques. This approach could possibly extend range to some extent, but without an increase in effective radiated power one might hope for only a 3 to 6 db increase in sensitivity or lowering of the threshold.

Second, if a real requirement existed for considerably increased range, for example, to 1,000,000 km, basic changes in configuration would be required and tradeoffs with some of the other requirements would be necessary.

This section constitutes a short review of the design considerations and implementation methods that constitute the present AROD system. Although a detailed mathematical analysis incorporating the measured performance of the present equipment was contemplated, it now appears on review of basic principles that this is unnecessary and that indeed maximum system range performance is being achieved. There may be some interest in making minor changes in future equipment built to the present objectives but these will not result in significant range extension. They may very well be highly desirable for reasons of improved reliability, etc., but are not warranted for range extension reasons.

3.1.1 Constraints

Before evaluating the present system performance, it is well to review the fundamental goals of the present design. The AROD system is designed to simultaneously interrogate up to four unmanned, automatic ground transponder stations and from these interrogations to derive four simultaneous measures of range and range rate.

The time from initial interrogation to full track was to be two seconds. The system range resolution was to be 0.25 meter with an accuracy of 0.5 meter rms over the life expectancy of two years of the vehicle or satellite-borne equipment. A minimum range ambiguity of 2000 km was desired with a system signal dynamic range of 70 db. Range rate resolution and accuracy of 0.015 m/s was desired with rates up to 12,000 m/s. Orbits as low as 50 km should be handled which led to accelerations as high as 450 m/s^2. A data rate of four simultaneous interrogations per second was desired. A maximum protection against multipath and signal dropout was desired.

A 10-watt, 2200-MHz carrier and 12-MHz bandwidth was allocated for the satellite to ground link with a 20-w, 1800 MHz carrier and 20-MHz bandwidth link from ground to satellite. In addition, a control link from satellite to ground at 6 watts and 138 MHz with a 500-kHz bandwidth was allocated. A 6.5 db noise figure for the receivers was specified. There are a number of other stringent requirements such as size, weight, power, etc. which strongly influence the detail circuit design and packaging concepts but which do not directly influence the basic system performance.

These objectives, the theoretical performance, and measured performance are summarized in Table III-1.

The significance of these various factors on the ability of the system to operate at longer ranges must be clearly understood. Given the radiated powers and a ground S-band antenna gain of 16 db (a projected estimate of gain of some antennas under design elsewhere) and incidental path loss of 8 db, a projected maximum range capability of 16,000 km is obtained. This occurs at a signal level of -127 dbm. (See the AROD System Description, Section V.) The thresholds originally predicted for both S-band links and the vhf link all occurred at this same range.

Although there is 3 db less power in the down-link, S-band system, the noise figure is lower with a specified paramp.

What constitutes threshold? A philosophy was adopted at the outset that the AROD system threshold was reached whenever any of the following failed:

TABLE III-1. Summary of Objectives and Performance

	Design Goal	Predicted Performance	Measured Performance to Date
1. No. of Simultaneous Chan. that can be used	4	4	4
2. Acquisition Time (sec.)	2	3.188	3.63
3. Range Ambiguity (km)	2,000	>3,000	>3,000
4. Range Resolution (m)	0.25	0.18	0.18
5. Range Accuracy (equip.) (m)	0.5	0.32	0.6
6. Velocity Range (m/s)	±12,000	±13,000	~13,000
7. Velocity Resolution (m/s)	±0.02	±0.026	±0.026
8. Velocity Accuracy (m/s)	0.015 rms	0.015 rms	0.024 m/sec
9. Dynamic Range (db)	70	67 -60 to -127 dbm	66 -60 to -126 dbm
10. Noise Figure (db)	6.5	7.5	8.3 Vehicle 8.0 Grd.-Including Cable
11. Power Output Ground S-Band Vehicle S-Band Vehicle VHF	 20 10 6	 10 10 6	 10 10 6
12. Range & Vel. Data Rate (per/sec)	4	4	4

TABLE III-1. Summary of Objectives and Performance (cont)

	Design Goal	Predicted Performance	Measured Performance to Date
13. VHF Data Rate (Veh. to Ground B/S)	Not Spec.	800	800
Bit Error Rate	Not Spec.	$<10^{-3}$	$<10^{-3}$
14. Gr. to Veh. Data Rate (B/S)	Not Spec.	50	50
Bit Error Rate			
L Code	Not Spec.	$<10^{-3}$	
H Code	Not Spec.	$<10^{-3}$	
15. Multipath Protection	Not Num. Spec.		
Total Rejection L Code		>160 μs	
Full Track H Code		>156 ns	
16. Drop Out (sec.)	2	>0.25	>0.25
17. Relative Protection Against Interchannel Interference	Not Spec.	>26 db	26-32 db

1. The system could not acquire L-code.

2. The system could not acquire H-code.

3. The system data error rate necessary for system control, acquisition, or determination of system measurement performance became excessive.

4. The system could not track range in L-code.

5. The system could not track range in H-code.

6. Carrier track could not be accomplished in L-code.

7. Carrier track failed in H-code.

8. Range accuracy was lost.

9. Velocity accuracy was lost.

10. VHF control could not be accomplished.

The premise is that as a complete system it is unable to perform its job satisfactorily whenever it failed to perform any of these functions. Quite obviously an inability to track either modulation or carrier constitutes a complete failure.

It did not appear that over the ranges involved it was likely a circumstance would arise where the system could acquire at one range and be required to track to a significantly greater range. Hence the ability to acquire L code was as important as the ability to track.

Only when the H code is acquired can the system obtain highly accurate range tracking, although full accuracy may be obtained in the Doppler measurement. It was decided that for orbital problems, such as could profitably use the AROD system, range was equally as important as Doppler. Hence, the system must acquire H code.

Accuracy of range and Doppler tracking should be reasonable at threshold. What to call ranging and velocity threshold is a subjective matter. In fact, the design predicts a ranging accuracy of the order of 1 to 2 meters and a velocity accuracy of the order of 0.05 m/s at threshold.

In order to achieve rapid acquisition, a cooperative acquisition technique was necessary. This is accomplished by the ground station reversing the Doppler shift during acquisition. Once acquired by the vehicle system, a command is sent to the ground to go to normal Doppler operation. When the translation is completed, the ground transponder tells the vehicle to go to full track. These commands require data transmission over the

S-band link. A command requires from 0.3 to 0.4 second when a data rate of 50 bits/sec. is used. One-eighth of the total signal energy is used for this purpose. The data link threshold occurs at -127 dbm. A slower data rate would increase the acquisition time in proportion to the decrease in rate. More energy in data could be used but this degrades the acquisition thresholds for synch detection. Since this threshold is at -127 dbm, one is led to the conclusion that the code selection and distribution of energy is nearly optimum for the objectives.

Perhaps the most significant thing that could be done would be to exploit the L-code periods in H track for data transmission other than commands.

3.1.2 Conclusions

The most significant conclusion to be drawn is that the present modulation and demodulation technique is essentially optimum for the given set of system objectives.

This conclusion leads naturally to the question of what would one do to significantly increase range and what must be given up. Quite obviously the system threshold is -127 dbm. Therefore, one could reduce this by reducing system noise figure. Unfortunately large improvements cannot be made in this area, particularly since the ground system requires a paramp to match the vehicle performance because of the 3 db less transmitted power and 2 db increased path loss. Obviously, one can increase the output of the power amplifiers. Outside of a review of the diplexers, further redesign would not be required. Increased S-band antenna gain could be used instead, at the transponder. This must be matched by increased vhf power in the vehicle since the vhf antenna should be hemispherical.

These methods preserve the present objectives and extend the range capability. They are, however, expensive and yield only a moderate increase, perhaps a practical limit of a factor of ten, since vehicle power is involved.

One must, therefore, ask if greater range objectives are consistent with high dynamics and rapid acquisition times. Obviously they are not and furthermore multiple simultaneous interrogations are also inconsistent. This seems to be true because the dynamics are occasioned by geometry, not vehicle, maneuverability. Also, the long range case means that earthbound stations have "short" baselines and, consequently, yield poor position accuracy. Finally a station can see such a vehicle for long periods of time negating the need for rapid acquisition. Single-channel operation appears to be a more likely requirement for anything beyond a synchronous orbit.

An upper limit on range for a given amount of power is established by the narrowest bandwidth one can use for the carrier because of oscillator noise. At S-band, a practical limit is 20 cps. The ranging bandwidth can be cut to about the same extent or to 0.4 cps. The data bandwidth must be less than that of the carrier but it need not be greater than the ranging bandwidth. This will yield a factor of about 13 db at most. Inevitably, greater powers and higher gain antennas are required on the ground. This will necessitate high gain vhf antennas, if the vhf link is retained, although this is no longer a necessity.

For long ranges one would like a range ambiguity much larger than 3000 km. In general, one would require less range accuracy, since the speed of light is not known to the accuracy commensurate with the obtainable equipment accuracy. Hence, a lower rate on the coders is probable with a considerably longer L code. The lower code rate reduces multipath protection but this is probably not important on long range tracking stations which will tend to operate nearer the zenith. Longer L codes mean slower acquisition in direct proportion to their length. Hence slower data rates can be tolerated and still represent only a fractional part of the acquisition time.

These changes can be done using exactly the same principles as before. In addition the i-f bandwidth can be reduced at least in proportion to the change in L-code clock frequency. This, in turn, can be reduced in proportion to the carrier loop bandwidth.

In applications requiring longer ranges, there is no reason why the hardware concepts employed and the basic principles of modulation and demodulation cannot be preserved. These have proven to work and work well. However, in all likelihood the basic system objectives will be sufficiently changed that a considerable alteration in detail will be desired.

3.2 UTILIZATION OF THE VHF LINK

The vhf link is used in the present AROD system to provide the following functions:

1. S-band antenna steering
2. S-band frequency preset
3. S-band code preset
4. Control data transmission

The vhf link has additional information capacity and could perform other functions. For example, the ranges and range rate data accumulated by the vehicle could be telemetered to a selected ground station. This requires a data rate of approximately 1200 bps. For some AROD applications, the vehicle may compute the position of a mobile ground terminal and transmit positional information to this terminal. A data rate of 1000 bps is more than adequate. It is also possible to transmit data not directly associated with AROD. This auxiliary data could be in either analog or digital form. In the following paragraphs, the additional data capability of the vhf link will be presented along with the constraints imposed on this data.

3.2.1 Modulation Constraints

The received vhf carrier at the transponder station has a Doppler uncertainty of ±6 kHz and a receiver vco uncertainty of 1.5 kHz. Since the vhf carrier loop bandwidth is 1000 Hz (β_L) during acquisition, the lowest frequency of significant modulation components should be restricted to the order of 15 kHz so that the carrier vco will not lock to a modulation component. The constraint on the higher frequency terms is determined by the out-of-band components generated by the modulation process. All out-of-band modulation components must be 60 db down from the unmodulated carrier level. In paragraph 3.2.2, different modulation techniques will be examined with a view to expanding the vhf data rate subject to these constraints.

3.2.2 Modulation Methods

Since the sensitivity of the vhf receiver is limited by the data threshold, any additional modulation will reduce the sensitivity to some degree.

Digital modulation can be added to the present system in several ways. One direct method is to combine additional bits into the present PCM bit stream and increase the rate proportionally. The present modulation is a return-to-zero modulation with a signalling rate of 800 bits per second (bps). The subcarrier frequency is 18.75 kHz and the modulation spectrum is contained in a bandwidth of approximately 2.4 kHz. This rate can be increased by a factor of three before the modulation components fall below 15 kHz. This will provide an additional signalling rate of 1600 bps with a reduced sensitivity (for the same error rate) of 4.7 db.

For higher data rates, a higher subcarrier frequency is required. As an example, a subcarrier frequency of 37.5 kHz can support a data rate of the order of 10 kHz. The modulation index is limited to 0.4 radian by the out-of-band modulation requirements. This compares with 1.2 radians which is used in the present system. This means that this channel sensitivity will be reduced by 4.7 db over the reduction due to data rate.

3.3 ELIMINATION OF THE VHF LINK

Under some operating conditions, the vhf link can become the limiting factor in system operation. A primary example of this would be operation in a highly ionized medium such as would be encountered near a nuclear blast. The S-band signals would not suffer to the same degree, but acquisition could not be accomplished until the vhf link were re-established.

To examine the acquisition and operation of the AROD System without a vhf link, it is necessary to provide other means of accomplishing the vhf functions. As presently implemented the vhf functions are:

1. Direction finding for the S-band antenna.

2. Frequency preset for the S-band receiver.

3. Coarse code timing for the S-band receiver.

4. Standby alert signals for all stations in range.

5. On, Off, and Track commands.

Of these, the functions of initial antenna direction, standby-alert, and off commands could be accomplished by an operator at the ground station using a prior knowledge of the expected orbit and the approximate time derived from an external source. The functions of TRACK command and OFF commands could be done by appropriate modulation on the S-band signal, but the problem of coarse-code preset and carrier-frequency preset are not so easily accomplished.

If operation is constrained to the same frequency range as now implemented, the downlink tracking signal will be in the frequency band around 2200 MHz. The frequency uncertainty of the carrier received at the station will be as much as ±88 kHz for vehicle velocities up to ±12000 m/sec. Allowing 5 ms for capture of the carrier, there are about 300 frequency cells to search with the present receiver acquisition bandwidth of 565 Hz. These frequency cells, together with the 127 cells of code timing, would result in an acquisition time of about 760 seconds.

Although it is recognized that the number of cells can be reduced to some extent with approximate knowledge of the orbit, such as approaching or receding, the addition of vehicle dynamics could prohibit acquisition under some conditions. This can occur because the cell search pattern and the cell trajectory of the received signal do not necessarily intercept for all dynamic conditions. The present search technique will have to be supplemented to ensure reliable acquisition in reasonable time spans.

3.3.1 Antenna Direction

For most applications a directive antenna will be required in the S-band link to provide signal power gain and as a relatively simple method of discriminating against multipath receptions. As the tracking receiver in the transponder station is phase stable, it has the capability of providing angle tracking information to the antenna drive. The additional hardware needed to add a monopulse tracking capability will be relatively small, as the code generator and acquisition timing circuitry can be shared with the reference channel. This capability can track the received signal once acquisition has been achieved, but does not solve the initial acquisition problems.

An obvious way to obtain initial direction is to use prior knowledge of the orbit. This can be either automatic or operator assisted. Then, when a signal is received, the receiver monopulse function can take over. As the required beamwidths are not small, (on the order of one radian) the initial aiming is certainly not critical, and the tracking accuracy requirements are equally loose.

Another method of providing antenna gain is to install a directive antenna in the vehicle. This could be of great advantage where jamming signals are expected and the ground station is geometrically out of the jamming environment. One configuration which could be used is shown in Figure 3-1 as a fan shaped beam which sweeps across the transponder stations as they come into range.

This implementation of course would not require equipment modifications, but it is doubtful if the multiple access features would be required in the vehicle due to the poor geometry. Multiple fan beams, such as one leading the vehicle and one trailing would help this situation.

3.3.2 Frequency Preset and Code Timing

The received signal at the transponder has been shown to have large frequency and code timing uncertainties. As the signal and its modulation are formed in the vehicle as a product (i.e., balanced modulated-suppressed carrier) the transponder receiver is forced to search the product of code and frequency cells. Possible ways of relieving this are:

1. Transmit a carrier component in the clear.

2. Re-erect a carrier component in the receiver.

Either of these would permit the receiver to quickly capture the carrier without code timing, then perform a code search. The resultant acquisition time would be the sum of the carrier and code acquisition time.

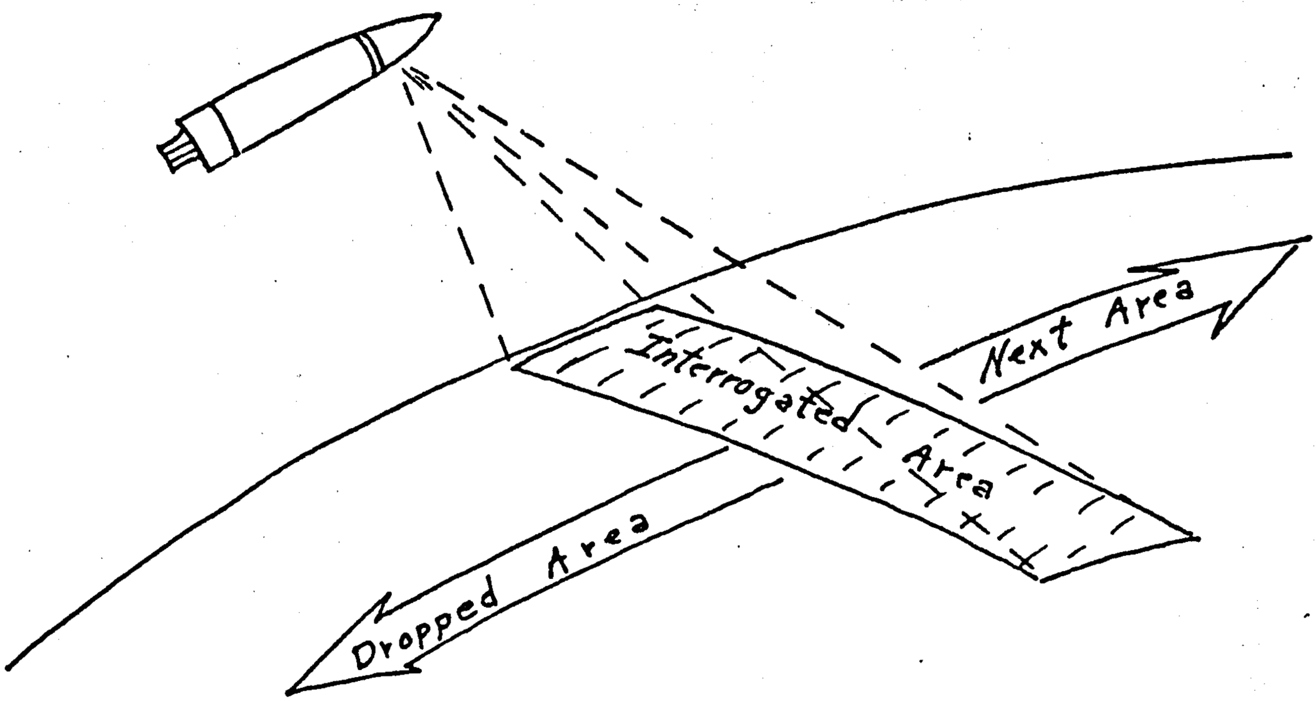


Figure 3-1. Spatial Search with Directive Spacecraft Antenna

A clear carrier component has definite disadvantages from multipath reflections and jamming vulnerability. The situation is, however, not nearly as serious as it would be on the uplink from the transponder to the vehicle. The downlink has no corresponding intermodulation and crosstalk vulnerability, as it is receiving only a single signal at a time. Also, multipath signals can be resolved if the receiver is switched to operate only on the coded part of the signal once code correlation is detected. The acquisition sequence would proceed as follows:

The transmitted signal from the vehicle will contain the normal range coded modulation and a fraction of the total power in a carrier component.

The Transponder Tracking Receiver will normally be energized. The receiver frequency will be swept with a sawtooth waveform to cyclically search the range of possible received signal frequencies. The sweep rate will be slow enough that upon coincidence of the received frequency and the swept frequency carrier capture will occur, automatically disabling the sweep circuitry. The receiver then performs a code search in the same manner as the vehicle does. The receiver is held by the captured carrier by direct coupling of the carrier loop, and code capture is sensed by the present gated A_L detector.

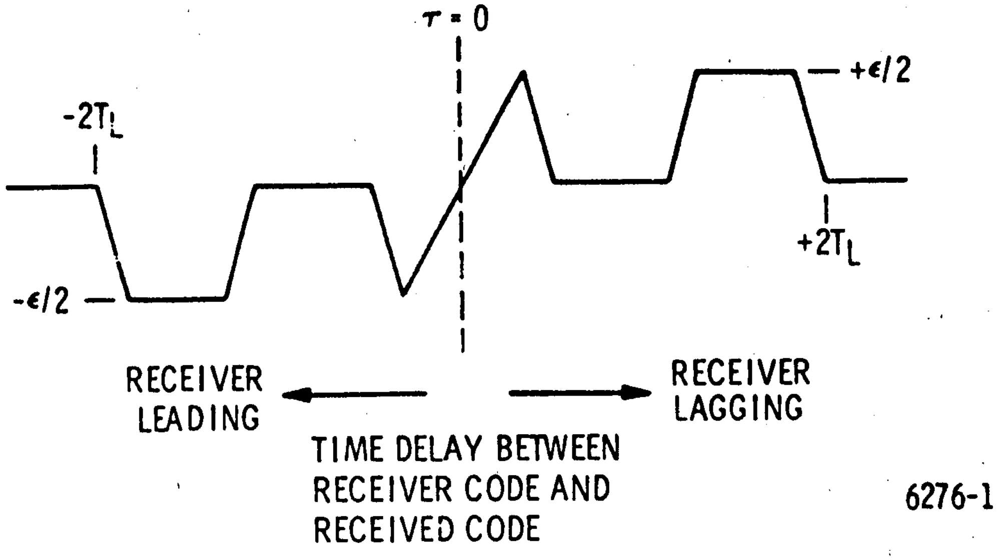


Figure 3-2. L-Code Tracking with H-Code Present

The range loop is continuously closed and will track the received code when correlation is achieved.

The carrier loop then reverts to the normal gated sequence and tracks the coded portion of the received signal. The cw component due to the carrier will be averaged out by the receiver code and will be ignored by the receiver. H-code capture Doppler reverse, and retransmission to the vehicle will be the same as in the present implementation.

The time required for acquisition of the Transponder Station will be longer than that presently needed. This is primarily due to the frequency search which is presently eliminated by the Doppler shift of the vhf carrier, and the low code search which is presently eliminated by the event marker in the vhf transmission.

The frequency search can take place at about 70 kHz/second, which will search the range of potential frequencies in about 2.5 seconds. The code search can take place at the same rate the the vehicle does, for even though less than half of the received power is in the low code the time allocated for carrier capture is no longer required. This will require a maximum time for code capture of about 2 seconds. The transponder acquisition time will total about 7 seconds compared to about 3 seconds with the present implementation.

The tracking receivers would have difficulty acquiring the transmitted signals without modification of the code time sharing method. As derived in Report No. 3065-2-2, the modulation tracking signal would be of the form shown in Figure 3-2.

With the present implementation, the responses at $\pm 2\ T_L$ have no effect upon the system because the code is preset to nearly $T = 0$ by the L-code transmission. Initial acquisition, however, would be quite likely to result in a spurious lock with this correlation curve.

Revision of the receiver code time sharing as shown in Figure 3-3 would eliminate this problem and prohibit the spurious correlation points.

In the course of modeling this code structure, the analysis uncovered an anomaly in the present system. This anomaly is the cause of the difficulty in the range loop which forced the direct coupling of the range gates, and resulted in the inclusion of several sources of range errors which were undesired. The problem can be explained by reference to Figure 3-4 as the amplitude of the correlation in acquisition state V-3.

The delay of these signals in the intermediate frequency amplifiers will change as the point of exact correlation is reached. The average component changing from $-\varepsilon T$ to zero and the total gated signal remaining essentially constant. The a-c coupled gated component will be the difference between these and will have a $+\varepsilon T$ transient as H-code comes into correlation. The magnitude of this effect, if the average component is discarded by a-c coupling, is sufficient to make the desired correlation point unstable. The resultant range loop error signal is shown in Figure 3-5.

In the present system this effect is eliminated by direct coupling of the loop, thus using the entire gated signal with no transient. Shown on Figure 3-2 is a better way to eliminate the problem by alternately adding F_L and $\bar{F}_L$ to the H-code intervals. This will result in removing the H-code influence upon the L-code tracking signal, permitting a-c coupling of the range loop with the attendent reduction of system error.

3.4 INVERTED MODE OPERATION.

The normal AROD operation is in the "Inverted Mode", that in which all station selection, acquisition, and data collection is in the vehicle terminal. One application of AROD is in a partially righted mode. That is the mode of operation in which the vehicle continues to be the central time reference and data

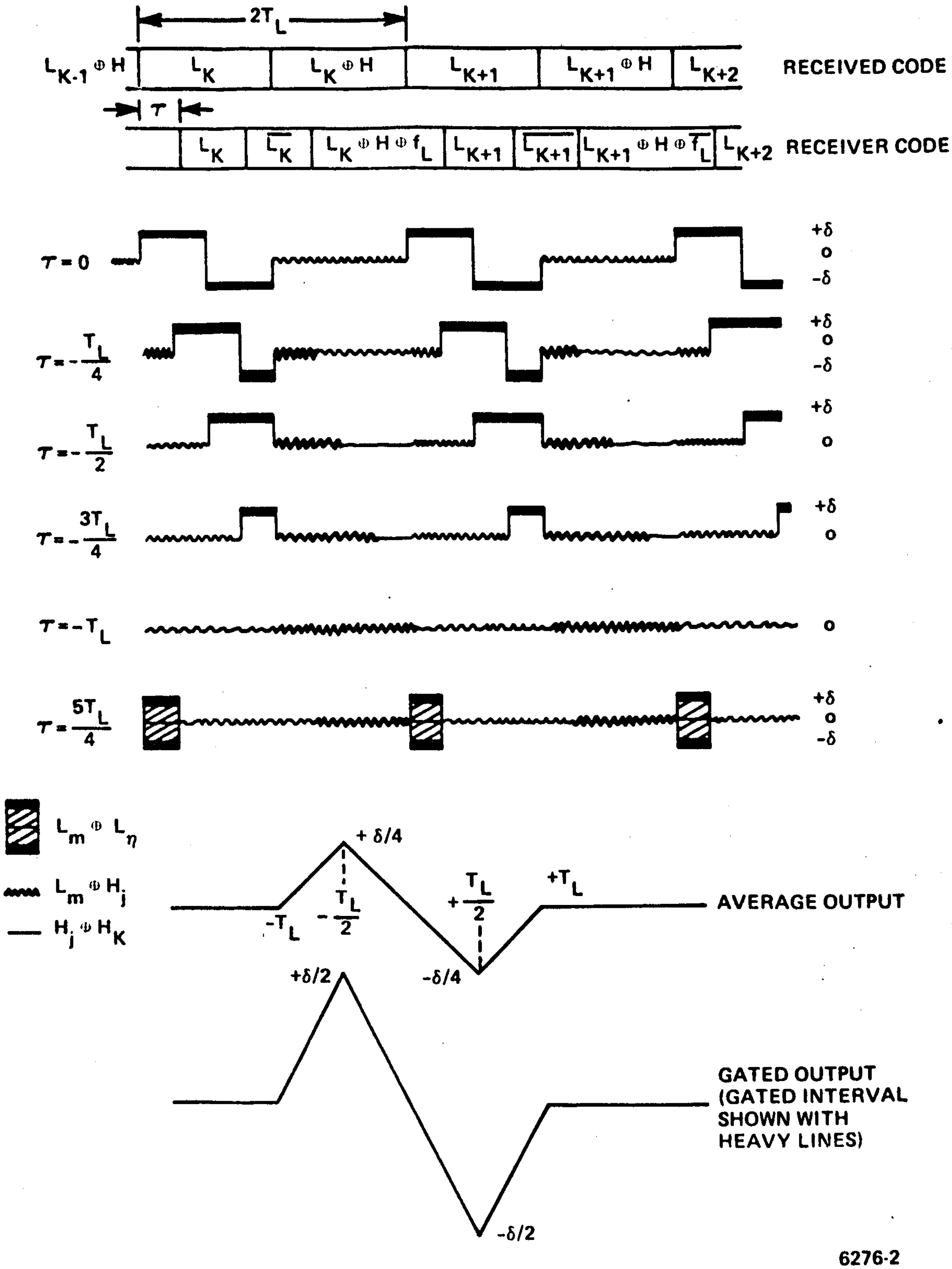


Figure 3-3. Receiver Code Modifications

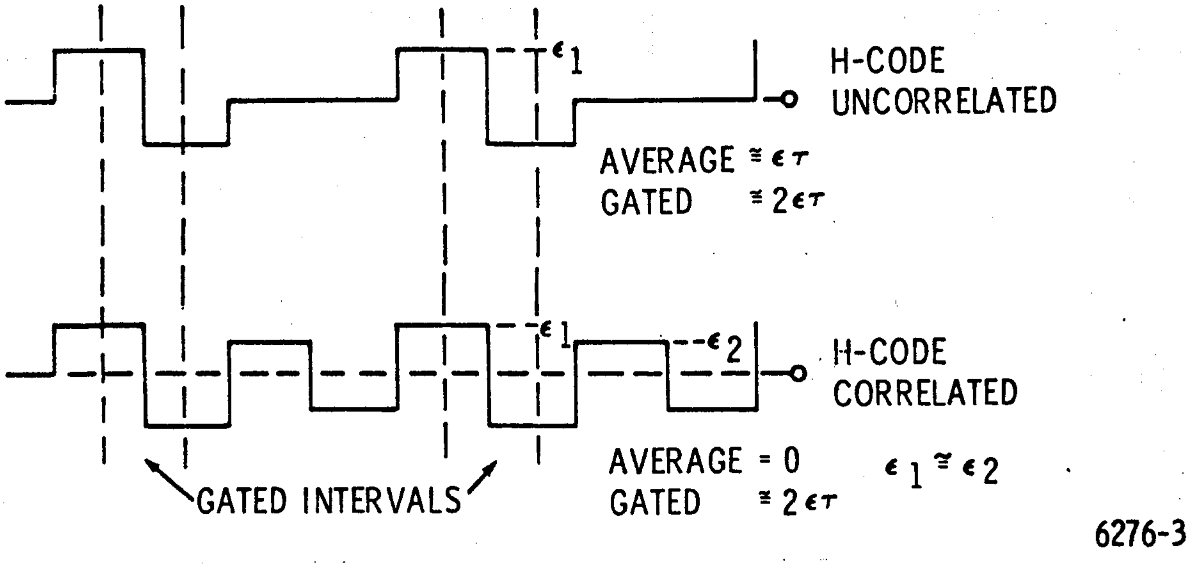


Figure 3-4. V-3 Code Correlation Through Filter Delay

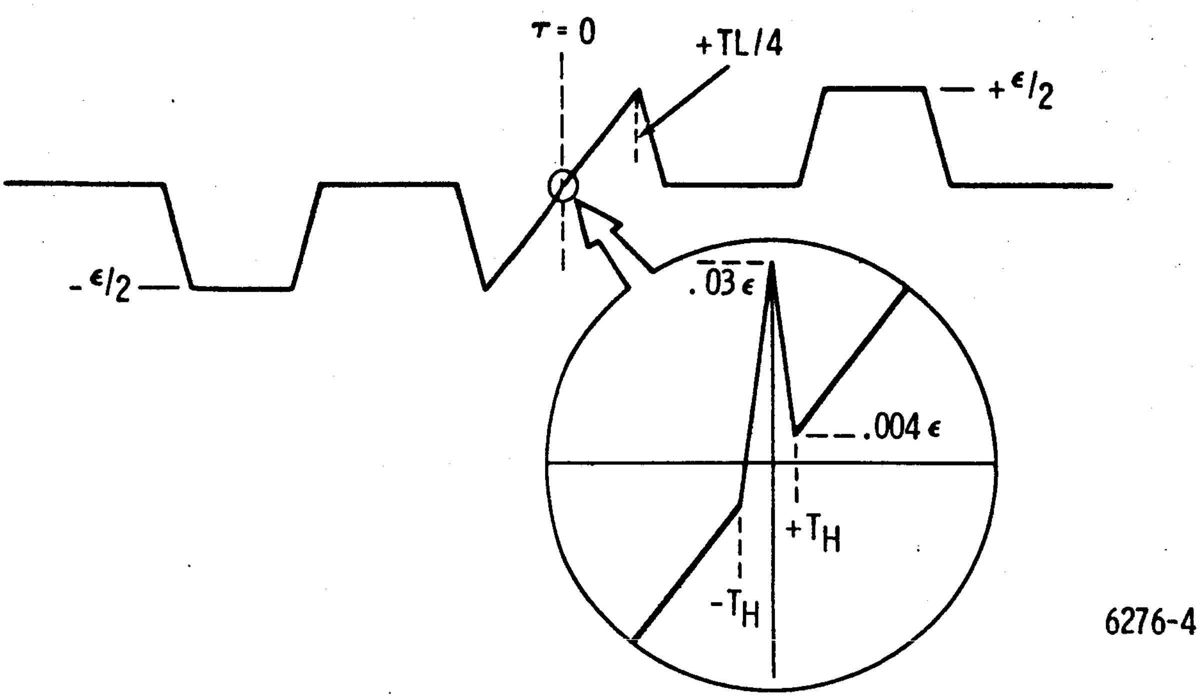


Figure 3-5. V-3 Error Signal AC Coupled

collection point, but an interrogation is initiated by an isolated ground transponder station. This mode lends itself primarily to the geodetic applications in which a station wishes to be the controlling terminal for survey purposes.

As presently implemented, the station "call sequence" is stored in the vehicle memory. There is no way in which an isolated station can break-in other than assuming a legitimate station ID code and suppressing the normal station operation. If the vehicle equipment were designed with this mode as being desired, certain advantages would be obtained. An example follows:

Consider the case in which a complete AROD System is in orbit. By complete is meant an equipment with a data processor capable of resolving slant range and range-rate into vehicle position and velocity in some coordinate system linked to the ground station complex.

An isolated ground station, considered to be perhaps a portable station, wishes to know its coordinates in that coordinate system. The station has no knowledge of when the vehicle pass is due, and no knowledge of its position. The coordinate position, and possibly probable error, is to be known at the station in as short a time as possible.

The station control logic may easily be equipped with an override switch which will enable that station to respond to any legitimate AROD request. This involves the vhf standby instruction and a call for a station which indicates that the vehicle has an empty receiver channel at that time. Normal station response can be prohibited by modifying the station call sequence to call for a nonexistent address for one cycle (4 seconds) prior to calling the next station in sequence. Thus if an overriding station responds with a special "override" identification, the vehicle can recognize this identification to take special action. This action would be to continue to track the already acquired stations, perhaps even disabling the maximum range criteria, while acquiring and tracking the intruding inquirer.

The geometry of the situation is outlined in Figure 3-6. In a linear situation, the position of the intruder can be resolved to lie somewhere on the periphery of a circle in space. The vehicle trajectory is not linear though, but includes the influence of the earth's gravitation field. In addition, the earth's rotation will add a tangential component to the measurement which can resolve the position measurement to a single point on the circle. Once resolved, which will take a succession of measurements by the vehicle, the coordinates of the intruding inquirer can easily be reported via the vhf link (see data capacity of vhf link,

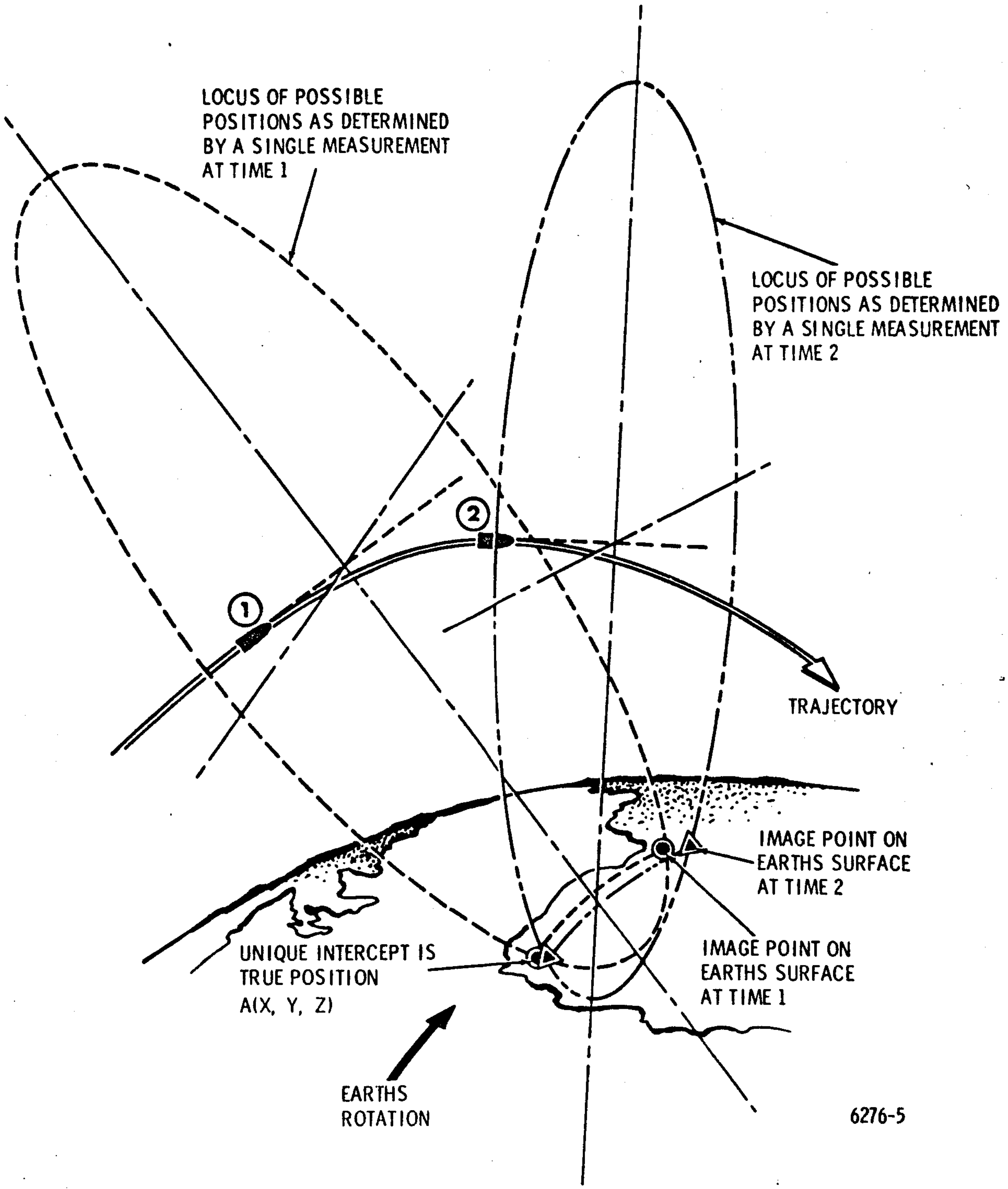


Figure 3-6. Surveying Geometry

subsection 3.2) to the inquiring station. The potential accuracy of the measurement, and the time over which such a measurement must be made, is yet to be analyzed, but the potential for such a measurement and capability exists in the AROD system with no significant changes in hardware.

Operation in this mode will not be affected by the lack of a vhf link. Acquisition will be somewhat slower,but the station call, and the data reporting can be carried equally well by way of the S-band data link (see subsection 3.5).

3.5 S-BAND DATA CHANNEL CAPACITY

The present AROD system requires an S-Band digital data link with a data rate of 100 bits per second for automatic acquisition. Future applications of the AROD system may require the transmission of additional data to satisfy other operational requirements. For example, a bit rate of 625 bps is adequate to report the position and velocity of the vehicle four times per second. This section contains a general description of compatible data modulation techniques and establishes practical limits on data rate for a variety of conditions.

For the purpose of analysis, the present AROD transmitter power and receiver sensitivities are assumed for both terminals. The data channel capacity will be determined as a function of performance degradation and tradeoffs between equipment complexity and data channel performance will be developed.

In the following paragraphs various modulation techniques for data transmissions are examined. The upper bound on data rate for the same receiver sensitivity is on the order of 1,000 bps. This assumes the same transmitter power and antenna gains defined in the AROD System Description Report. Higher data rates can be achieved with a reduced threshold. For example, data rates from 40 kbs to 60 kbs can be achieved with a received power level of -100 dbm. Both analog and digital modulation can be used with some modification of the present system.

A practical analog channel will require a separate i-f channel in order to eliminate the chopping frequency introduced by the "time-sharing" modulation frequency. The analog channel is constrained to a lower frequency limit of the order of 500 Hz during carrier tracking intervals and 25 Hz during range tracking intervals. The upper frequency limit is determined by the i-f bandwidth chosen for the analog channel and would be on the order of 50 to 100 kHz.

Digital signals can be transmitted by using the present technique of balanced bi-phase modulation during selected time intervals. This approach would require less hardware than the analog channel, but would require modification of the code control logic to provide timing signals. In the case of the analog signals transmitted digitally, the A/D and D/A converters must be charged to the link. For voice channels, the A/D and D/A conversion can be performed simply by the use of delta modulation.

The purpose of this study is not to select a technique, since this is very sensitive to specific data requirements. However, some general conclusions can be stated. The AROD range modulation is digital; therefore, digital modulation is more compatible than analog modulation. For the case of digital information, there is little doubt that digital modulation would be selected. For analog information, the modulation technique must absorb the penalties associated with A/D and D/A conversion. Some analog signals can be converted by using delta modulation and would make digital modulation acceptable. For analog signals requiring more accurate conversion, a separate i-f channel for data would probably be the selected approach.

It is possible, in principle, to utilize all the received power for each operation; i.e., carrier tracking, range tracking, and data transfer. The block diagram for an idealized AROD receiver is shown in Figure 3-7.

The data demodulator has an inherent delay of one bit time, T, for digital data and the delay of the processing bandwidth for analog data. If the range and carrier channels use a signal which has been delayed by the same time period, the data can be removed with an accuracy determined by the data bit error rate. The range modulation can then be stripped off leaving all the received power for the carrier loop. Similar cross coupling between the loops also provides all the received power for the other functions.

This technique requires a considerable amount of hardware and is not practical for most space applications. It does, however, provide an upper bound for the channel sensitivity. The practical bounds for AROD data rates in the TRACK mode are presented in Figure 3-8. Curve 1 represents the channel capacity in bits per second as a function of received signal power assuming all power is used for data. Curve 3 corresponds to the channel capacity of the present S-band data channel which uses one-fourth of the range modulation power. Curve 2 is the channel capacity which uses the power presently lost by the G_i gate. These curves provide a bound for data rates based on power considerations alone. In the following selections, various techniques are explored which use this power for data transfer.

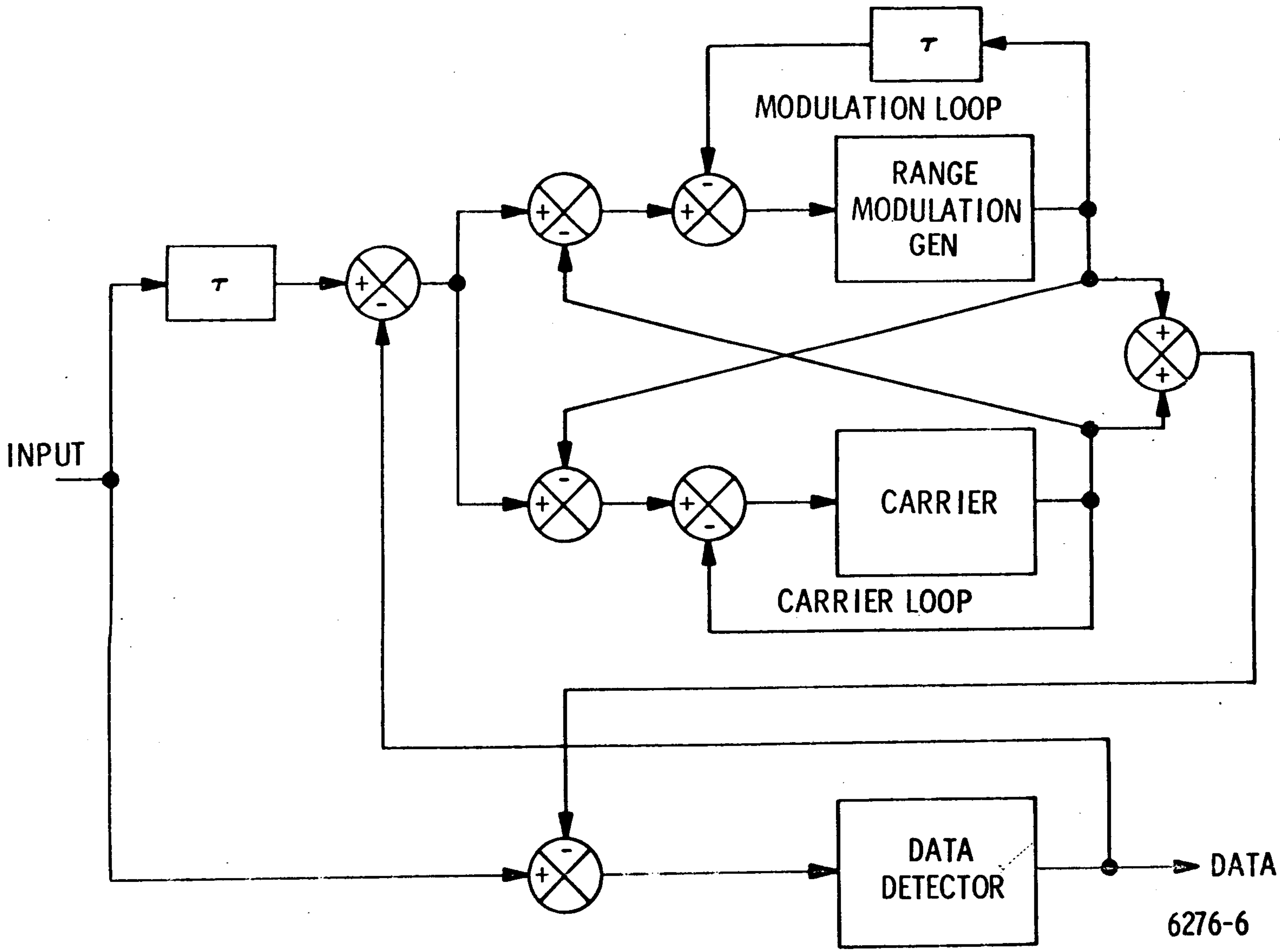


Figure 3-7. Idealized AROD Receiver

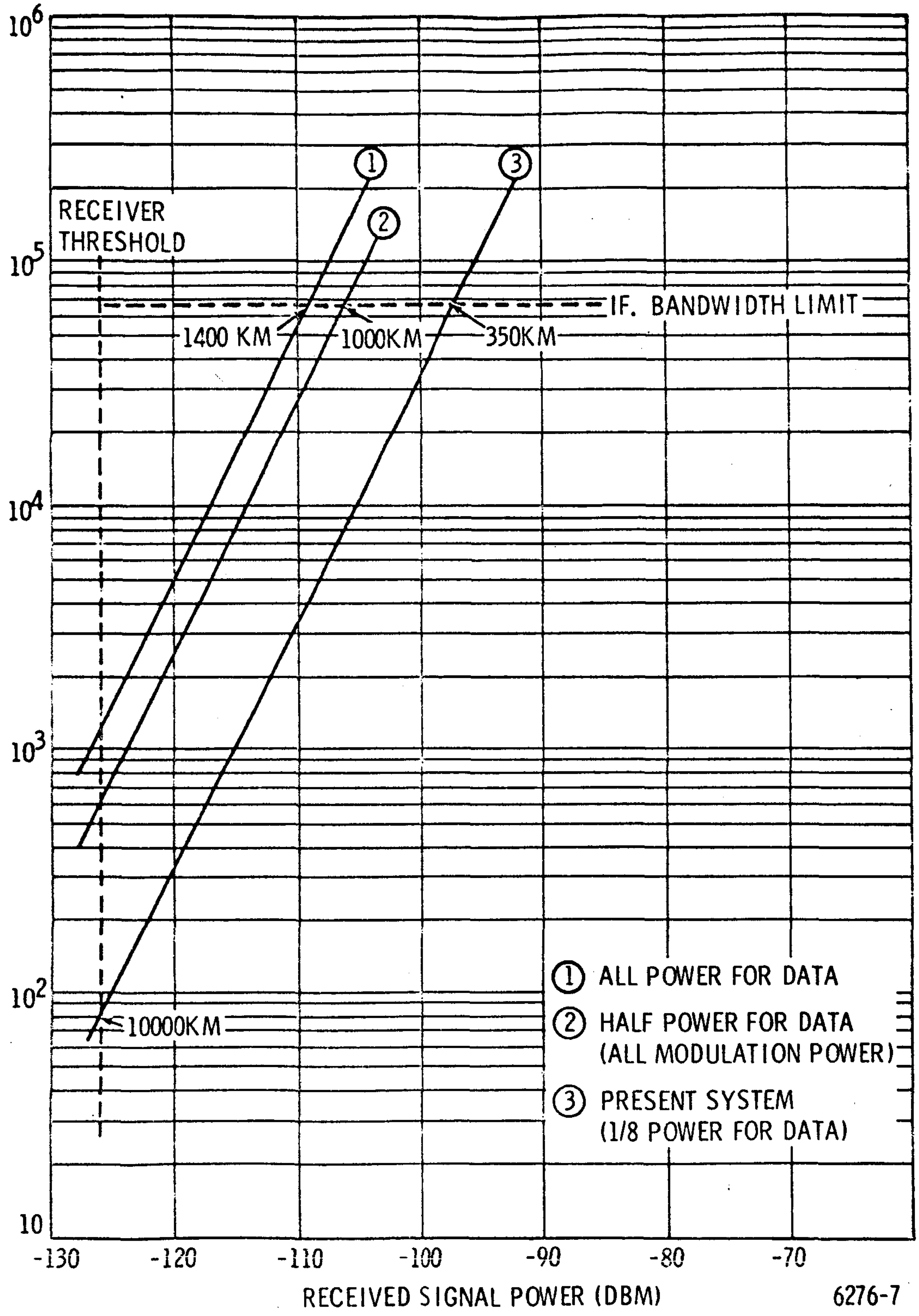


Figure 3-8. AROD Data Channel Capacity For S-Band Link

3.5.1 Analog Modulation

Analog signals can be used to modulate the S-Band signal in three ways:

1. amplitude modulate the carrier
2. phase modulate the carrier
3. phase modulate the range modulation

The constraints imposed on this modulation will be generated by first considering the distortion effects on the analog signals by the AROD modulation and then considering the effects of the analog signals on the AROD range and range rate measurement. All three forms of modulation present almost identical constraints; therefore, it will be possible to develop the detail requirements for the AM case and extend the argument to the other modulation techniques.

Figure 3-9 is a functional block diagram of one vehicle S-band receiver channel. In any form of modulation which contains a significant portion of the total power, the receiver will have to be fully acquired before external modulation is applied therefore, in all cases it is assumed that the receiver is in the TRACK mode.

In the AROD receiver, amplitude modulation can be recovered at the input to the agc amplifier. One problem arises in that the AROD receiver is designed for time-shared modulation and will introduce a chopping frequency of $F_L/2$ or approximately 6.25 Khz. This is caused by the G_i gate (located in the first mixer) which clamps the i-f amplifier off during the L-code interval and by the fact that the i-f filter will not pass the sideband during the ranging interval. It is possible to reconfigure the AROD code structure to eliminate the need for the G_i gate; however, the chopping frequency due to the range tracking interval cannot be easily eliminated. The effect of this chopping frequency is to blank the analog channel for 80 μs every 320 μs. This will limit the upper frequency of the analog channel to the order of 1500 Hz. The lower limit for AM signals is set by the agc bandwidth to the order of 100 Hz.

Similar constraints apply to phase modulation on both the modulation and the carrier. The sampling frequency introduced by the range tracking interval limits the high frequency response of all three forms of modulation. The low frequency response is determined by the loop response of the channel; 100 Hz for the agc loop (AM), 5 Hz for the range loop (PM of the range modulation), and 200 Hz for the carrier loop (PM on carrier). In order that

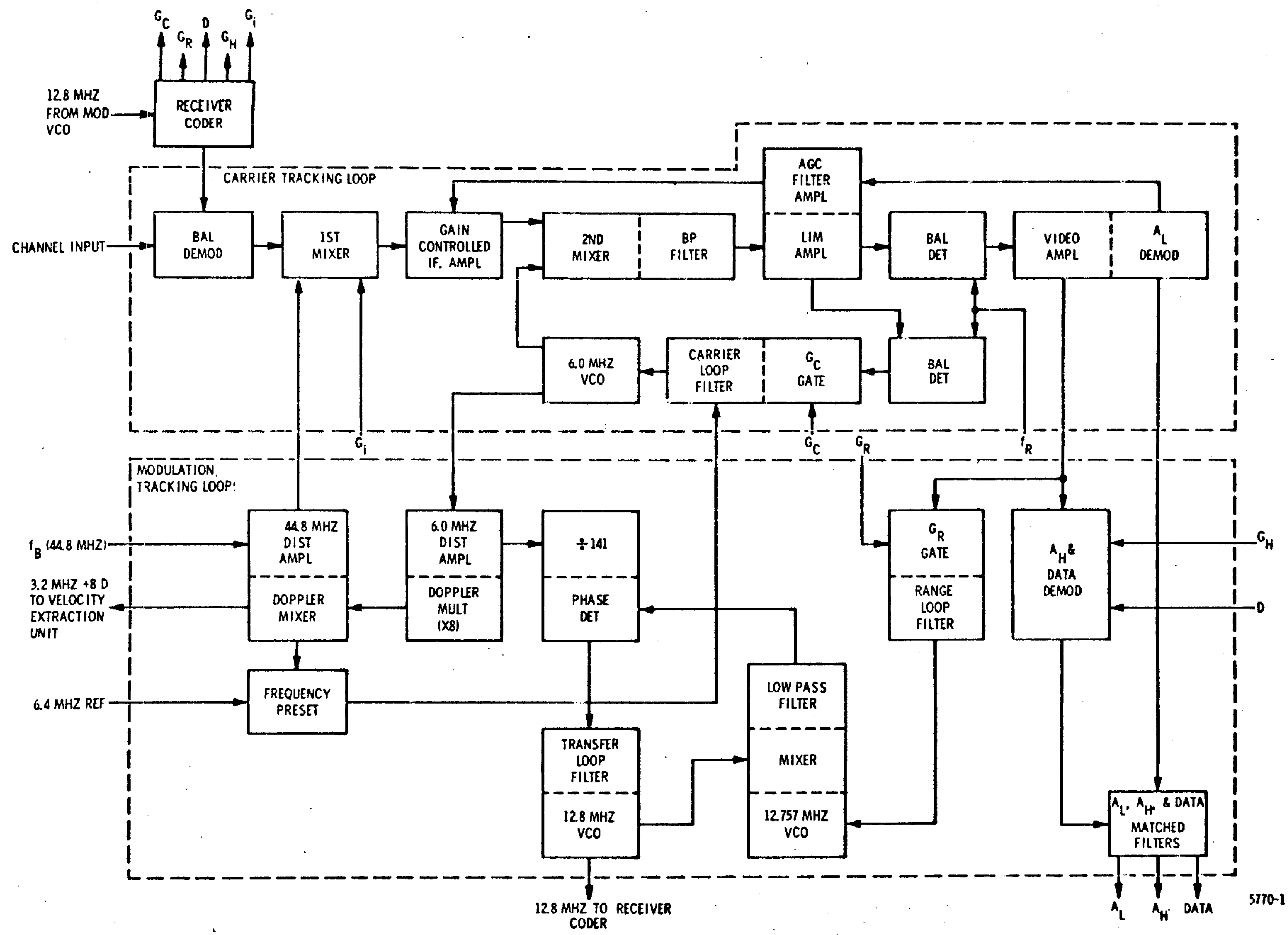


Figure 3-9. Vehicle Tracking Receiver Tracking Subsection

these analog channels not degrade the performance of the AROD system, the low frequency limit on the modulation will be on the order of 20 times the low pass noise bandwidth, β_L. Therefore, the usable channel bandwidth of the present system is limited to the order of 100 to 1500 Hz.

One solution to this problem is to provide another receiver channel which is not sampled. This is shown in Figure 3-10. A separate balanced demodulator can strip range modulation off the carrier and the resultant signal is processed exactly as in the AROD receiver, except for the G_i gate. This will provide a nonsampled channel, except for the S-band data modulation presently on during selected L-bit intervals. This data could be removed from the present range modulation and reinserted into the added data channel. Either carrier AM or carrier PM could be used. The low frequency components interfere with range and velocity measurements. However, the upper modulation frequency would be limited only to the i-f filter bandwidth.

3.5.2 Digital Modulation

Digital signals can be divided into two general categories:

1. real time signals
2. not real time signals

A real time digital signal is one in which the digital symbols must have a specific time relationship with each other. An example is a voice signal (or other band limited analog signal) which has been sampled by an analog-to-digital converter. The receiver must provide a digital-to-analog converter which operates at the same sample rate in order to reconstruct the original signal.

Digital signals which do not require a specific time relationship with each other (except as required by the demodulator) are classified as not real time signals. Ordinary ON-OFF control functions fall in this category.

The constraints on each type of digital signal will be determined by first considering the distortion effects on the digital modulation by the AROD modulation and then considering the effect of the digital modulation on the AROD system.

Digital data which is not "real time" can be transmitted over the S-band link in the form of balanced psk modulation during selected bit times. This technique is presently used to transmit

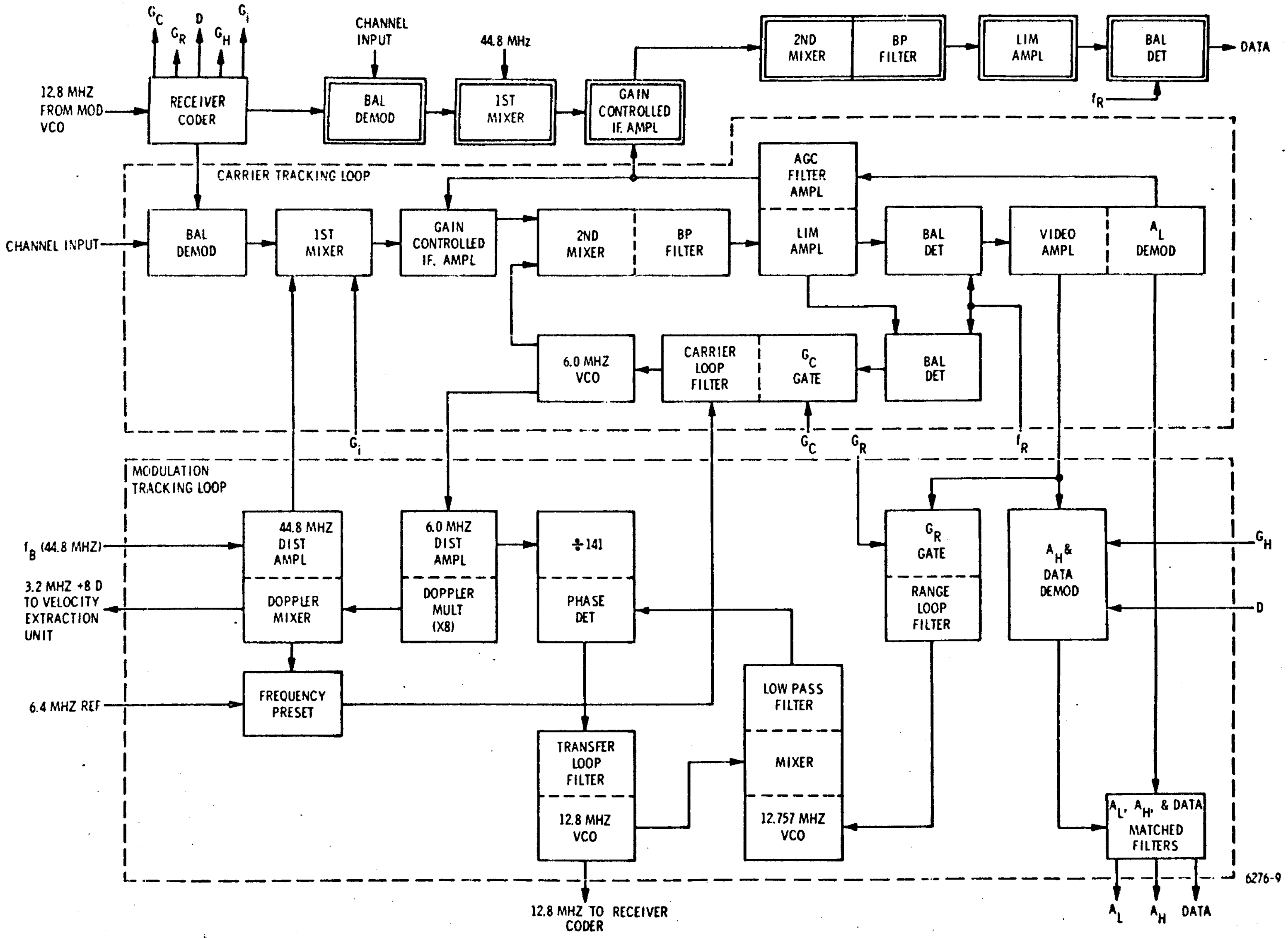


Figure 3-10. Vehicle Tracking Receiver Tracking Subsection with Separate Data Channel

transponder site ID and control status information to the vehicle. Under the constraint that the system is in the TRACK mode, the channel capacity can be increased. The energy required for a communication channel can be extracted from the following sources:

1. blanked interval (G_i clamp time)
2. carrier track intervals
3. range track intervals

At the present time, the i-f amplifier is gated off for one-half the time to insure that the i-f filter does not introduce a bias error in the range measurement due to the Low code portion of the track modulation. It is possible to construct the code so that the i-f amplifier does not have to be gated OFF. This would provide a data rate of 1600 bps for the same threshold. This is a profitable area to explore in future AROD systems. A disadvantage of this source of energy is that it uses energy which has been allocated for dropout protection. Indeed this is a problem for any technique which is allowed only in the TRACK mode, since a loss of lock at one terminal must be recognized at the other terminal so that all external modulation can be removed for reacquisition of the tracking system.

The other sources of energy are the carrier and range tracking loops. The carrier loop can be eliminated for two reasons -- both associated with its relatively wide bandwidth. The first reason is that the carrier loop signal-to-noise ratio is poorer by virtue of a relatively wide carrier loop noise bandwidth. The second reason is that the sample rate (the rate at which the loop received a sample of error) should be on the order of 5 to 10 times the low-pass noise bandwidth. The range loop on the other hand can tolerate a much lower sample rate and has a higher signal-to-noise ratio. The calculated rms range jitter in receive state V-4 as a function of data transmission rate is shown in Figure 3-11. This shows that the range jitter does not increase markedly until the data channel uses virtually all the modulation power.

In summary, additional communication channels can be provided by either utilizing the period of time presently blanked by the G_i gate or additional time periods presently allocated for range track or a combination of both. The rates are limited by amount of degradation in range loop SNR which can be tolerated and the input receiver power.

Real-time digital signals can be transmitted in the same manner as not-real-time digital signals. Any variations in sample separation must be absorbed in a buffer store. In the AROD

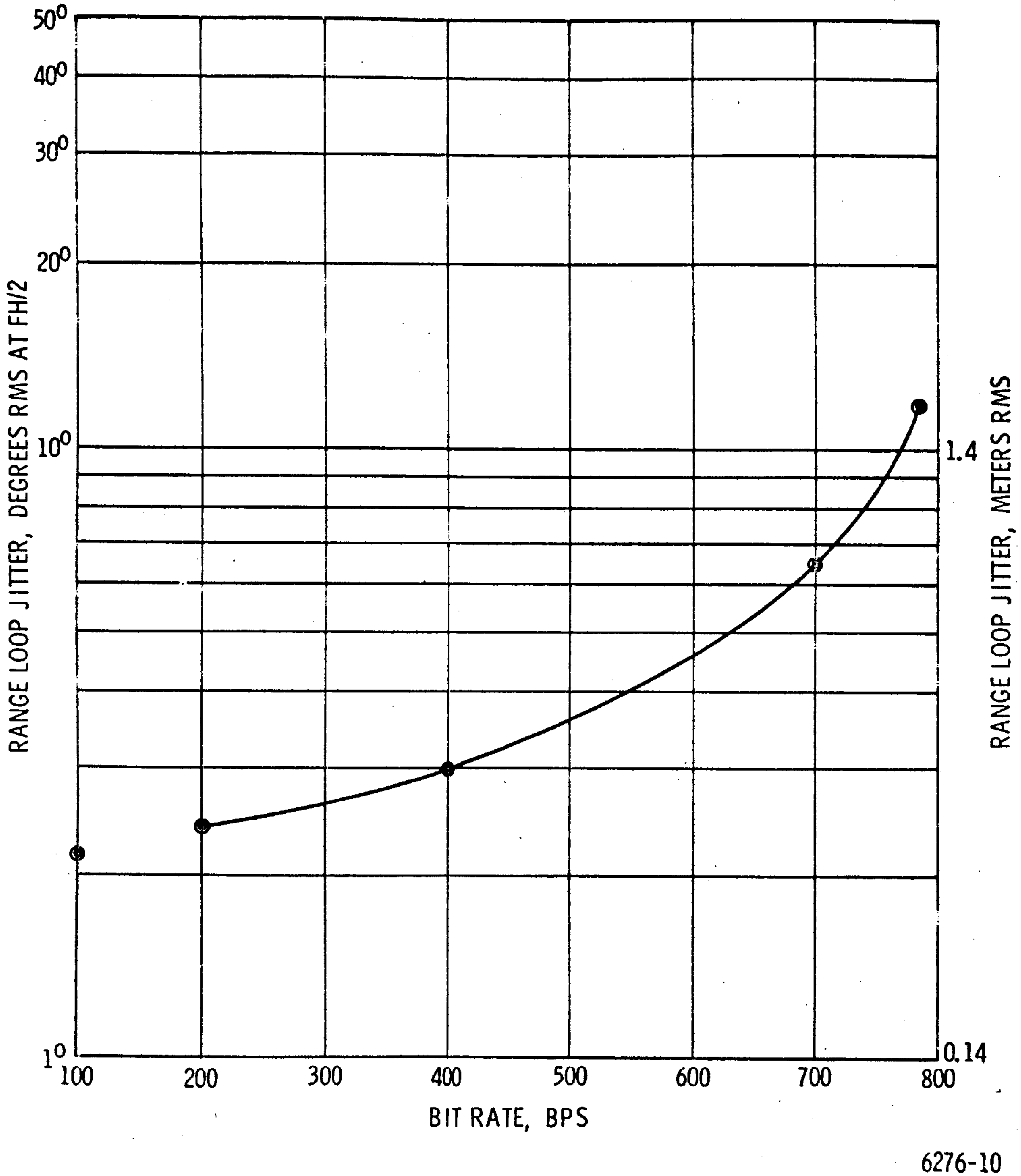


Figure 3-11. Range Jitter Vs S-Band Data Rate at Threshold

system, the encoder sample rate can be synchronized to the range code and eliminate the buffer requirements. This may insert some slight variations in the period between samples; however, this will not affect the data.

The sample rate and quantization levels are determined by the desired link quality. For example, intelligible voice can be transmitted at a nominal bit rate of 18-20kbps with a probability of bit error on the order of 1×10^{-2}. The quantization distortion at this level is of the order of 10 percent and is acceptable for many applications. The threshold for a channel with these rates would be approximately -115 dbm. The range signal-to-noise ratio under these conditions would be on the order of 15 db.

3.6 SUMMARY

The system concepts have been shown to be sufficiently non-restrictive that a large number of applications can be supported. That is:

1. The range capability can be extended many fold, with appropriate tradeoffs with the multiple access and acquisition time features.

2. The acquisition techniques can be applied to ground control, both with and without the vhf link.

3. Sufficient data dapacity is available on both the S-band and the vhf links to support other applications.

SECTION IV

4. SUPPORTING STUDIES

4.1 PROPAGATION CORRECTIONS

In the development of a Test and Demonstration Program for AROD, the problem of real time atmospheric propagation corrections for range was studied. A brief examination of the range rate corrections was also made. This was contained in Appendix A of the final report of that development and is also TM 3065-18, 6 December 1965. This analysis was largely concerned with the corrections necessary for an aircraft flight test; however, it is extendable to super-atmospheric propagation as well, although it does not include ionospheric effects. The proposed method evolved from work done by B. R. Bean and G. D. Thayer of NBS.[6]

No significant effort had been spent in studying the necessary adjustments for ionospheric effects, except to the extent of determining relative magnitude of error involved. It was conjectured that theoretical adjustments as a function of geometry would satisfactorily remove these effects. Indeed it was felt that the adjustments could be incorporated into the same general form of equation as the atmospheric corrections.

Because of the interest in determining the computational requirements for a complete AROD system used for satellite applications, a longer look has been taken at ionospheric propagation corrections. In the process a new report by K. A. Norton of NBS[2] on atmospheric corrections was reviewed.

Paragraph 4.1.1 summarizes Norton's report. The ionospheric studies to date are discussed in paragraph 3.6.2. Two problems have arisen in the latter case. First, the information available is adequate only to indicate the second problem,which is that a proper study is more extensive than first envisioned, and further work is probably not justified at this time.

4.1.1 Atmospheric Corrections

In January 1966 K. A. Norton delivered a paper at the Third Tropospheric Refraction Effects Meeting at the Mitre Corporation.[2] This paper attempted to answer five basic questions:

"(1) The determination of the ultimate limitations imposed by nature on electronic tracking systems;

(2) The determination of optimum methods for correcting data from electronic systems for the effects of tropospheric refraction;

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*See correspondingly numbered References at end of this section.

(3) The estimation of the magnitude of residual errors after using various correction procedures;

(4) The development of methods for forecasting the magnitude of uncorrectable residuals for specific meteorological conditions; and

(5) The development of real-time methods for correcting the effects of tropospheric refraction."

Although by no means complete, Mr. Norton's study did go a considerable way towards answering these questions. Perhaps the most significant conclusion he reached was that the method for range correction proposed in TM-3065-18 was optimum. It certainly is for real-time operation and appears to be for any use.

One of the questions discussed by Norton is the averaging time which should be used to derive the best estimate of surface refractivity, N_S. The averaging time, T, for best results is equal to

$$T = \frac{R_e \cos\theta \cos\beta}{U} = \frac{R_e \cos \alpha}{U}$$

where

R_e = measured range in meters

U = wind velocity in meters/sec

θ = elevation angle

β = angle between the wind velocity vector and the projection of the range vector onto the x, y plane tangent to the earth at the station

$\cos\theta \cos\beta = \cos\alpha$

α = angle between wind vector and range vector.

Unfortunately T is strongly related to geometry. Typical values for T are one hour. The satellite is not in contact with a station for periods anything like this. Furthermore, α is constantly changing.

Hence averaging may be impractical. In the one case where this was analyzed, the improvement by averaging overtime as opposed to one-minute averaging was to reduce the residual variance from 5 parts/million to 3 parts/million. Averaging also requires either prerange measurement or post range measurement averaging times, depending on the wind direction. Consequently, one is led to the belief that averaging N_S measurements is undesirable for real time range corrections and one will have to live with the residuals encountered with no averaging.

A further reason for this conclusion is the fact that the influence of the atmosphere on range exists over the whole of the wave trajectory although a large portion is due to relatively local effects. However, the velocity corrections due to atmospheric effects are a truly local phenomenon. That is, 90 percent of the ray bending, the cause of range rate error, occurs in the first few hundred meters of the path from the ground station. Thus one must conclude that the value of N_S to use here must be a local average. These too are wind velocity dependent but only in an area very near the station.

On this basis, one would conclude that the present surface value of the index of refraction should be used.

Norton also stressed that a regression type of correction can best be made using as data past history at each station taken by itself. This has been done in some instances, notably on the Atlantic Missile Range. The difficulty with this approach is the greatly increased requirements for data transfer from ground to air or the increase storage capacity for a real-time data processor. In addition, a large number of profiles would be required at every station which must be carried out over a fairly large period of time -- months. This is in general impractical. The most important question to be answered is whether or not a ducting situation exists at a station. This cannot be answered readily by any reasonable means in the AROD concept.

In conclusion, it is believed that a single world-wide regression formula should be used for all AROD stations, using averaging periods of the order of minutes at most for all real-time applications.

It would be interesting to know how well, in general, this method would work. Extreme benefits may be estimated from the world-wide regression accuracy and from the Atlantic Missile Range data. An extreme value of mean correction, with an altitude of 1000 km and a range of 3800 km, is 118 meters with a standard deviation of 8 meters, using world-wide data. Using the AMR data, the correction is 121 meters with a standard deviation of 4 meters. The differences are much smaller for better geometry. Consequently, it does not appear to be profitable to use better than a single world-wide regression formula.

The work in this area that remains to be done is to determine the exact regression equations for superatmosphere satellite flights.

4.1.2 Ionospheric Corrections

The ionospheric propagation corrections are a more complex problem. Unlike the tropospheric or atmospheric corrections where group velocity is equal to phase velocity and both are less than the free space velocity of light, the ionospheric phase velocity exceeds the velocity of light. Here $V_g V_p = C^2$. The group velocity must be used to correct the range and the phase velocity must be used to determine the ray bending from which the error in range rate can be determined.

The index of refraction in the ionosphere may be approximated by the relationship

$$\eta(h) = \sqrt{1 - \frac{81\ N_e(h)}{f^2}}$$

for frequencies, f, greater than about 100 Mhz. $N_e(h)$ is the electron density at altitude, h.

$V_p = C/\eta(h)$ the phase velocity.

Apparently only the F layer is significant. Models have been made to represent this layer. However, its height varies as a function of time of day and its density as a function of day, month, and solar sunspot activity. The latter effect can alter N_e by an order of magnitude.[9] This layer is also a function of latitude and longitude.

Because of the strong dependence on frequency, the ionospheric effects vanish at 10 GHz. They may be important at S-band. In order to correct for those effects, one would have to estimate the geometry, know latitude and longitude, time of day (sun time in the ionosphere), the period of the sunspot cycle (11 years), etc. The variability or dependence of $N_e(h)$ on these factors is not available from the documents reviewed by the author.

At the present time it does not seem reasonable to measure the ionospheric electron densities. Thus, if ionospheric effects are to be corrected, theoretical models must be generated.

Fortunately, the magnitude of correction required is small. The AD HOC Committee on Electromagnetic Propagation[8] has computed the effects of both ionospheric and atmospheric corrections for a reasonably severe geometry at 2 GHz.

The geometry is

h = 160 n.m., altitude

R = 660 n.m., range

$\theta = 6^{o}$, elevation angle

V = 10,000 ft/sec, tangential velocity

	AD HOC	AMR	W.W.
Mean Atmospheric Correction	18.3 m 60.0 ft.	19.0 meter	18.0 m.
Standard Deviation	0.097 m 0.3 ft.	0.6 meter	1.3 m.
Atmospheric Velocity Correction	0.0076 m/sec 0.025 ft/sec		
Mean Ionospheric Correction	1.37 m 4.5 ft.		
Standard Deviation	0.009 m 0.03 ft.		
Ionospheric Velocity Correction	0.065 m/sec 0.2 ft/sec		

For comparison the atmospheric corrections using the regression method and surface index of refraction are included. The AMR column is using the Atlantic Missile Range data and the W.W. column using the world-wide data in the regression equations for nearly the same geometry. The AD HOC committee atmospheric corrections use the CRPL Exponential Reference Atmosphere with calculations by Bean and Cahoon in 1957. The standard deviation was based upon estimates of residuals using this method. The subsequent data used in the regression method revealed larger variances.

A test over a 15-km path had standard deviations of 0.03 meter which extrapolated to 1000 km should yield standard deviations closer to 1 meter. (A linear extrapolation is not legitimate, since some of the path is superatmosphere and some is in relatively more stable portions of the atmosphere.)

This particular target is in the ionosphere, in fact, very near the peak of the electron density. Perhaps one-third of the ionospheric retardation has occurred and nearly the maximum velocity error will be seen. The total retardation through the ionosphere vertically can reach as high as an equivalent range correction of about 5 meters.

The maximum range rate error occurs where $\partial N_e(h)/\partial h$ is maximum, since the rate error depends largely on the angular deviation at the vehicle. This will occur on the lower side of the F layer not too far from the peak density level.

4.1.3 Conclusions

On the basis of the review of the readily available literature, it is not possible to adequately define a method of range and range rate corrections in the manner that has been done for atmospheric corrections. It is known that their effect is significantly less and, on range only, of the order of a few times the equipment resolution and of the order of the variation in atmospheric corrections. For vehicles within the F layer, the rate corrections may be important. Here the effect is reversed. The ionosphere contributes an error that can be ten times rate resolution and the atmospheric corrections can be ignored.

The theory of ionospheric effects appears to be well known. A much more exhaustive look at the electron density profiles as a function of position, time of day, year, and solar cycle is required to determine the relative importance of these factors. These same typical missions should be postulated and the errors calculated. This will yield a better understanding of the magnitude of the corrections. It may prove that, in general, ionospheric effects can be neglected or at least ignored for real-time applications.

The proposed atmospheric correction methods for range appear to be the best possible. Rate corrections probably can be ignored.

4.2 GEOMETRICAL DILUTION OF PRECISION -- GDOP

The overall operational accuracy or performance of a position determining system such as AROD is influenced by the following factors:

1. The basic measurement accuracy of the equipment which can be specified in terms of a bias which varies very slowly with respect to the data measurement rate and a random jitter which exists because the system is operating with a finite (S/N) ratio.

2. The propagating media (ionospheric and atmospheric) causes small residual errors in the measurements even after the best available correction techniques have been used.

3. The accuracy to which the ground transponders can be located in the coordinate system being used.

4. The techniques of data analysis used, e.g., fitting a curve defined by orbital mechanics to the data points in a least square sense.

In this section the position accuracy that can be achieved by using AROD is calculated using the following assumptions.

1. The sources of error are grouped into those which are assumed constant over periods of several minutes such as equipment bias errors, transponder coordinate errors and some propagation errors, and those whose errors vary more rapidly, such as thermal noise induced jitter and some types of propagation errors.

2. All of the errors are assumed to be Gaussian distributed which allows all of the short term and all of the long term errors to be combined on an rms basis.

3. The position error produced by the short term variations can be reduced by smoothing (repeated measurements) while the long term ones cannot.

4. In this analysis, no sophisticated data reduction techniques, such as curve fitting to an assumed orbit, are used because they do not lend themselves to obtaining near real time position information; and second, a variety of techniques may be used, each of which will provide a slightly different value.

In all of the analyses which follow, a range error and a ground transponder position uncertainty are assumed for purposes of numerical computations. Since, in many of the cases analyzed, the resulting error is linearly related to the assumed input errors, unity errors were assumed which allows convenient scaling to any value of input error.

4.2.1 Three Station GDOP

In this analysis, a typical range measurement is given by

$$(r_j)^2 = \sum_{i=1}^{3} (X_i - X_{ij})^2 \qquad j = 1, 2, 3 \qquad (1)$$

where

X_i = vehicle coordinates, i = 1, 2, 3

X_{ij} = i^{th} position coordinate of the j^{th} transponder

r_j = slant range between the vehicle and the j^{th} transponder.

This system of equations can be linearized by either

1. Expanding equation 1 in terms of increments and neglecting second order terms, e.g., $r_j \rightarrow (r_j + \Delta r_j)$, $X_i \rightarrow (X_i + \Delta X_i)$ and $X_{ij} \rightarrow (X_{ij} + \Delta X_{ij})$.

2. Using a Maclaurin's series expansion and dropping all the second order and higher terms.*

These two operations are equivalent and produce equation 2

$$\frac{\partial\left[r_j^{2}\right]}{\partial r_j}\,\Delta r_j = \sum_{i=1}^{3}\left\{\frac{\partial\left[\left(X_i - X_{ij}\right)^2\right]}{\partial X_i}\,\Delta X_i + \frac{\partial\left[\left(X_i - X_{ij}\right)^2\right]}{\partial X_{ij}}\,\Delta X_{ij}\right\} \quad (2)$$

By taking the partial differentials indicated, the results can be rearranged so that the unknown ΔX_i (the vehicle position coordinate) can be expressed in terms of the known Δr_j (range measurement uncertainty) and ΔX_{ij} (uncertainty of the coordinates of the ground transponders). This forms a set of three equations and three unknowns which allows solution for the ΔX_i's. The position uncertainty values given in this section are found by

$$\left(\sum_{j=1}^{3} \Delta r_j^{2}\right)^{1/2} .$$

When the input uncertainties are equal to unity, the value calculated gives an indication of the error magnification, or blowup, which is also called the GDOP.

GDOP curves were calculated for the three station system configuration shown in Figure 4-1, which is typical of one flight profile that might be encountered in operation with a low altitude satellite. In this geometry, the path of the vehicle is assumed to be a straight line because the results are nearly the same as for an elliptical path, except at low elevation angles. Figure 4-2 shows the GDOP or position uncertainty when the total range error is equal to one meter and the ground station error is zero.

*VonBun F.O., Analysis of the Range and Range Rate Tracking System IRE Transactions on Space Electronics and Telemetry, June 62, p. 97-107.

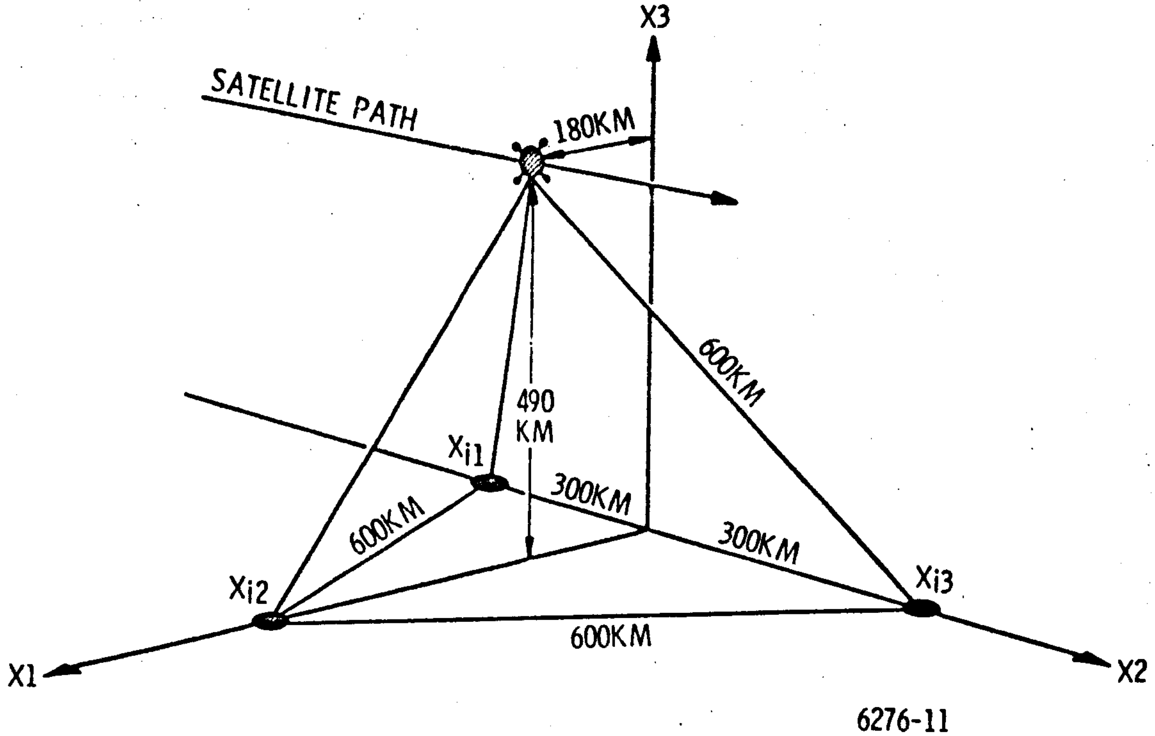


Figure 4-1. Vehicle and Ground Station Geometry

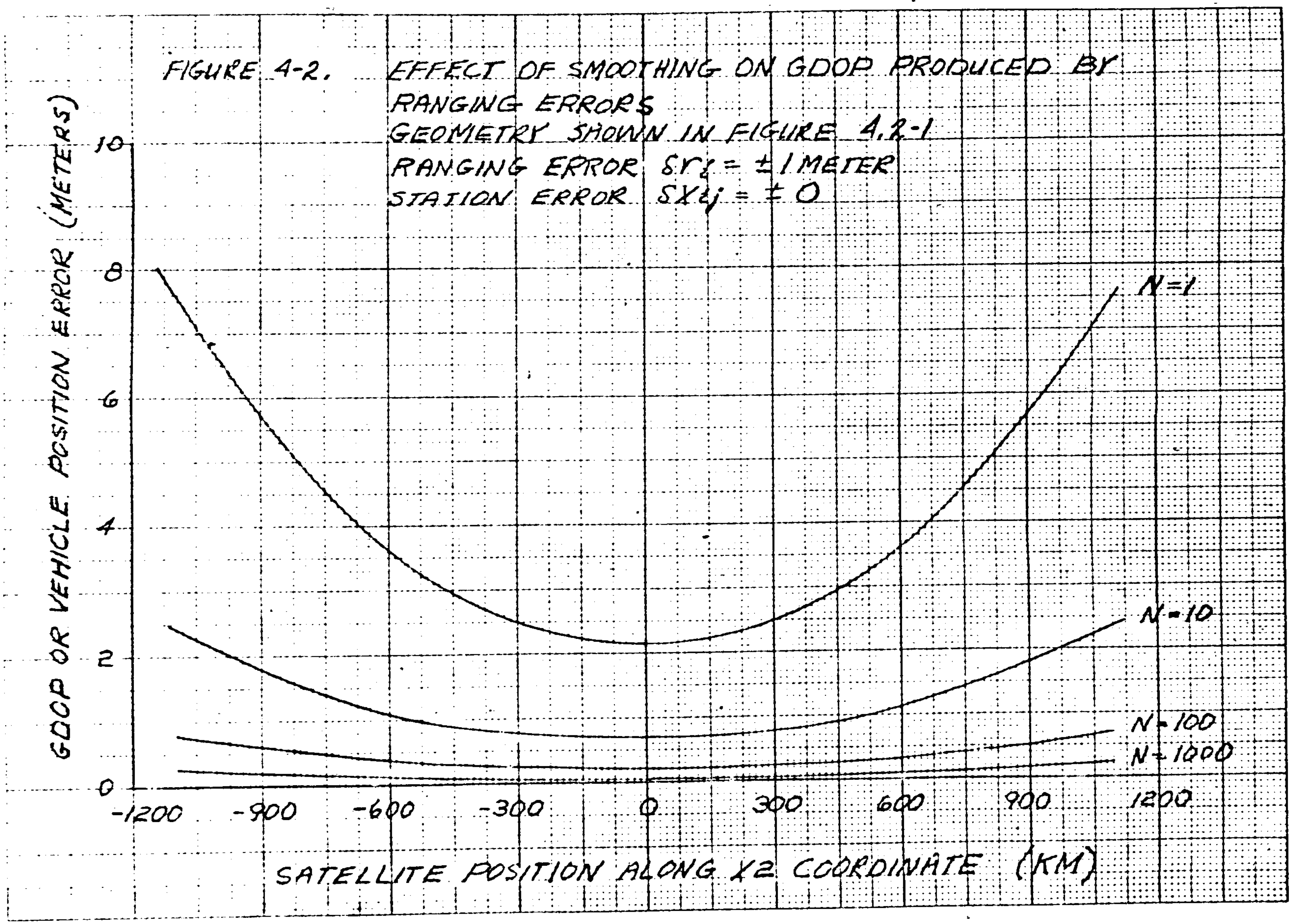


FIGURE 4-2. EFFECT OF SMOOTHING ON GDOP PRODUCED BY RANGING ERRORS
GEOMETRY SHOWN IN FIGURE 4.2-1
RANGING ERROR $\delta r_i = \pm 1$ METER
STATION ERROR $\delta X_{ij} = \pm 0$

In Figure 4-2, several different curves are shown for various values of N where N represents the number of sets of statistically independent range measurements used to compute a given position. For example, when $N > 1$, the GDOP is reduced by a factor equal to $1/\sqrt{N}$. It is important to note that this reduction is possible only when

1. The range errors are short term, with respect to the data measurement interval, and

2. A curve fitting technique is used, when the vehicle is moving.

The curve fitting technique is required because when the vehicle is moving, the values measured are slowly changing, and this variation must be accounted for in the smoothing procedure used. Figure 4-3 shows that, if the ranging is set equal to zero and the transponders have an uncertainty of 1m in each of their coordinates, the GDOP which results is exactly equal to that shown in Figure 4-2 with N = 1.

Figure 4-4 shows that when the ranging uncertainty and the ground station coordinate uncertainty are equal, the GDOP is increased by a factor of $\sqrt{2}$. In this graph it is assumed that smoothing can reduce the range measurement uncertainty but it does not reduce the effect of the ground station uncertainty. Therefore, when N is large (e.g., 1000), the curve approaches the one shown in Figure 4-3, in which ranging uncertainty was zero.

4.2.2 Redundant Station GDOP

When four or more ground sites make simultaneous measurements, redundant equations are obtained which produce multiple solutions. In this analysis, a least squares approach was used to locate the vehicle position and compute the GDOP. Basically, GDOP was calculated by selecting vehicle coordinates which minimized the rms difference between the measured ranges and the range to the "optimum" vehicle position. Figure 4-5 shows a comparison of the GDOP which occurs for a three- and a four-station configuration. When the fourth station, shown by the unfilled circle is added, the GDOP is considerably reduced for regions along the negative X_2 axis; but for regions along the X_2 axis where the vehicle is over the triangle defined by the three original stations, the improvement is approximately 10-15%. Further along the positive X_2 axis, the improvement is in the range of 20-25%. Since AROD normally makes simultaneous ranging measurements from four ground transponders, this feature alone shows it provides reduced GDOP compared to a system which uses only three ground stations.

In summary, the results of this analysis showed that redundant range measurements reduced the mean square ranging error and therefore improved the position accuracy. The degree of improvement is a function of the station geometry. For example, if a three-station configuration has poor geometry and the location of a fourth

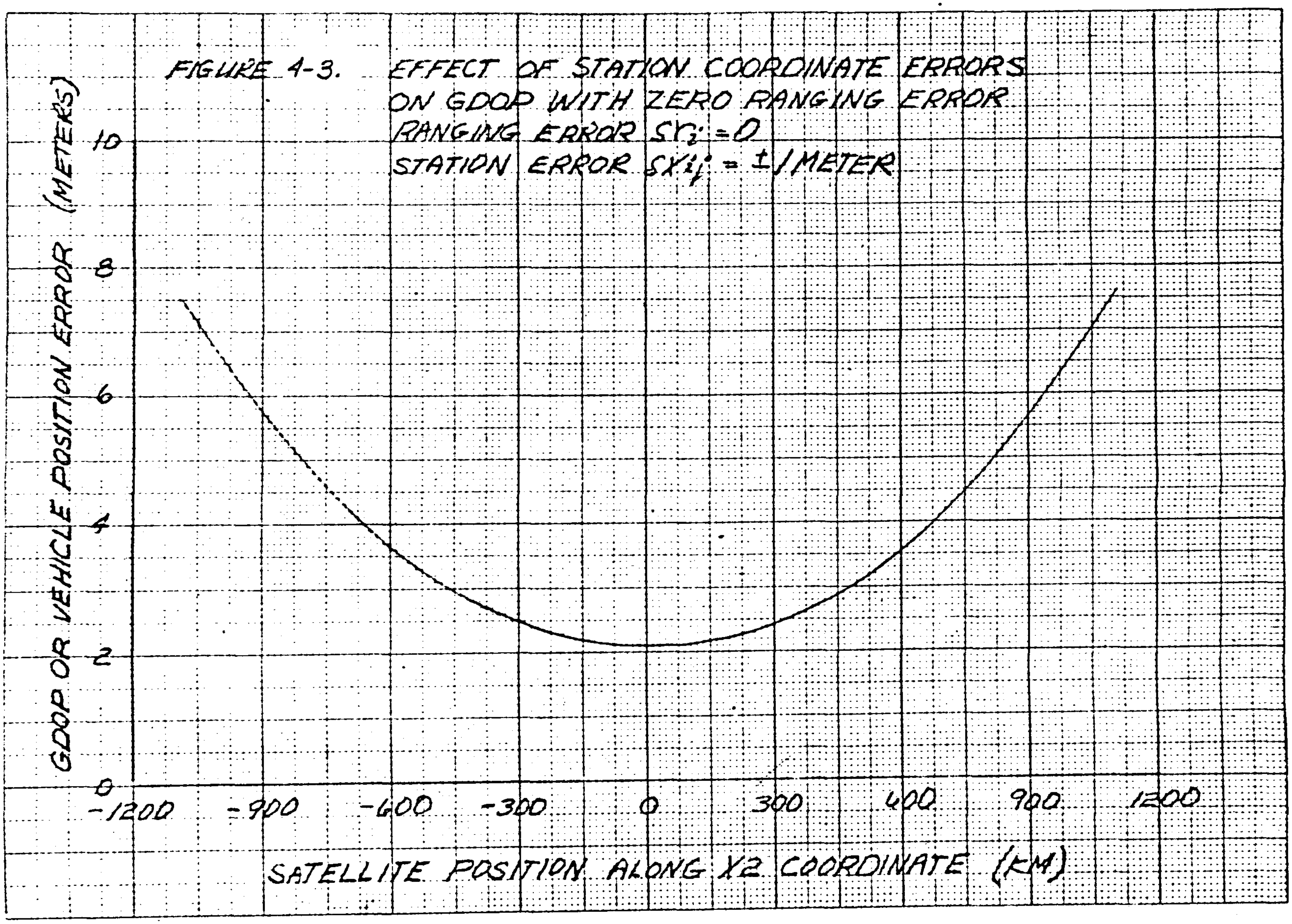


FIGURE 4-3. EFFECT OF STATION COORDINATE ERRORS ON GDOP WITH ZERO RANGING ERROR
RANGING ERROR $\delta Y_i = 0$
STATION ERROR $\delta X_{ij} = \pm 1$ METER

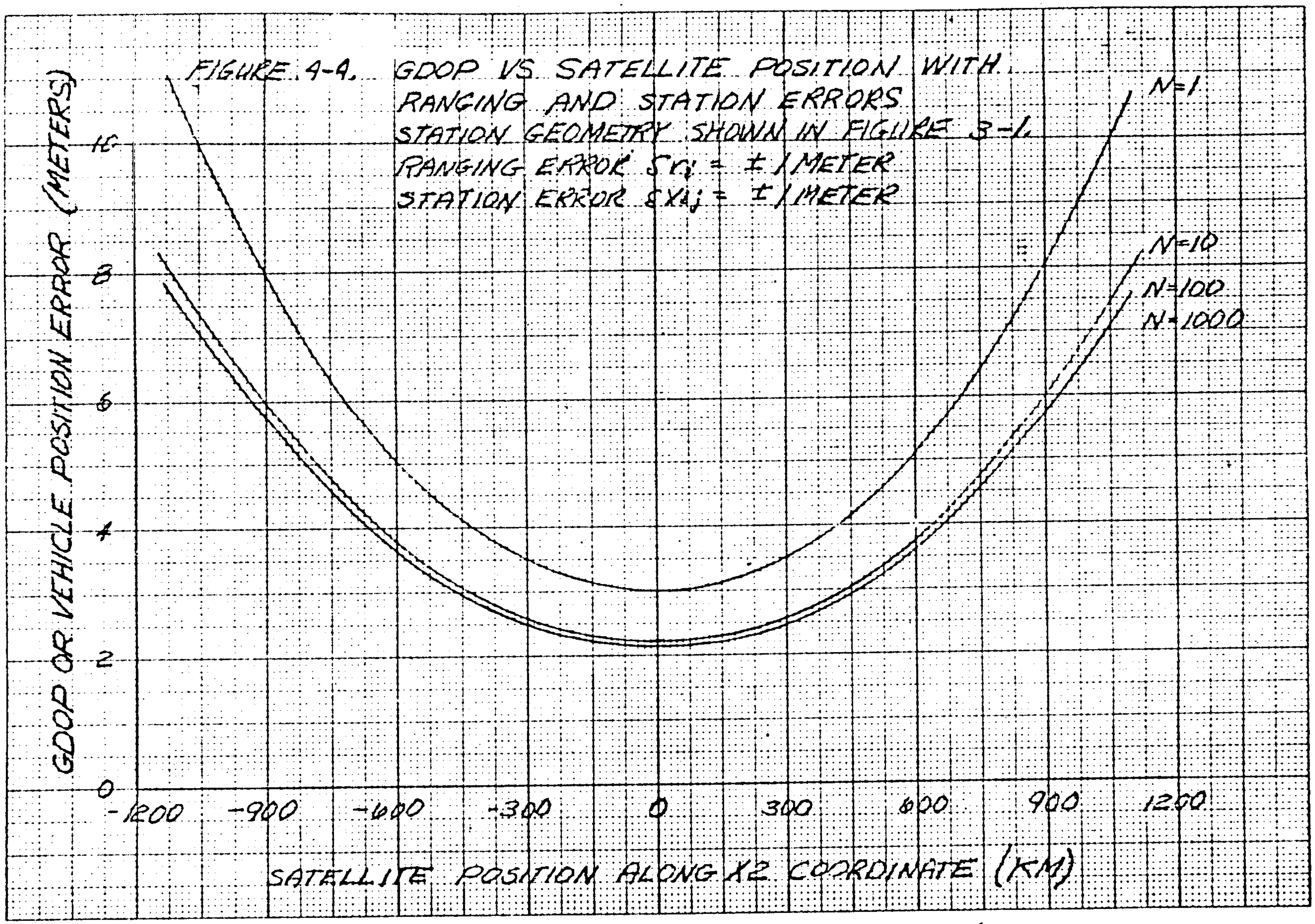


FIGURE 4-4. GDOP VS SATELLITE POSITION WITH RANGING AND STATION ERRORS
STATION GEOMETRY SHOWN IN FIGURE 3-1.
RANGING ERROR $\delta r_i = \pm 1$ METER
STATION ERROR $\delta X_{ij} = \pm 1$ METER

station provides a much improved equivalent three-station geometry, the reduction in GDOP is quite significant; but if a good three-station configuration exists and a fourth station is added which does not greatly improve the geometry, the reduction in GDOP is rather small.

4.2.3 Surveying a New Ground Station

Assume that the vehicle makes a pass over a complex of four ground stations, and the locations of three of the ground stations are known (to a specified accuracy) while the location of the fourth station is known only in very gross terms. Simultaneous range measurements are made to the set of four ground stations at three different vehicle positions. Measurements made using the three ground stations whose positions are known (but including a specified uncertainty) are used to determine the position uncertainty of the vehicle at three locations.

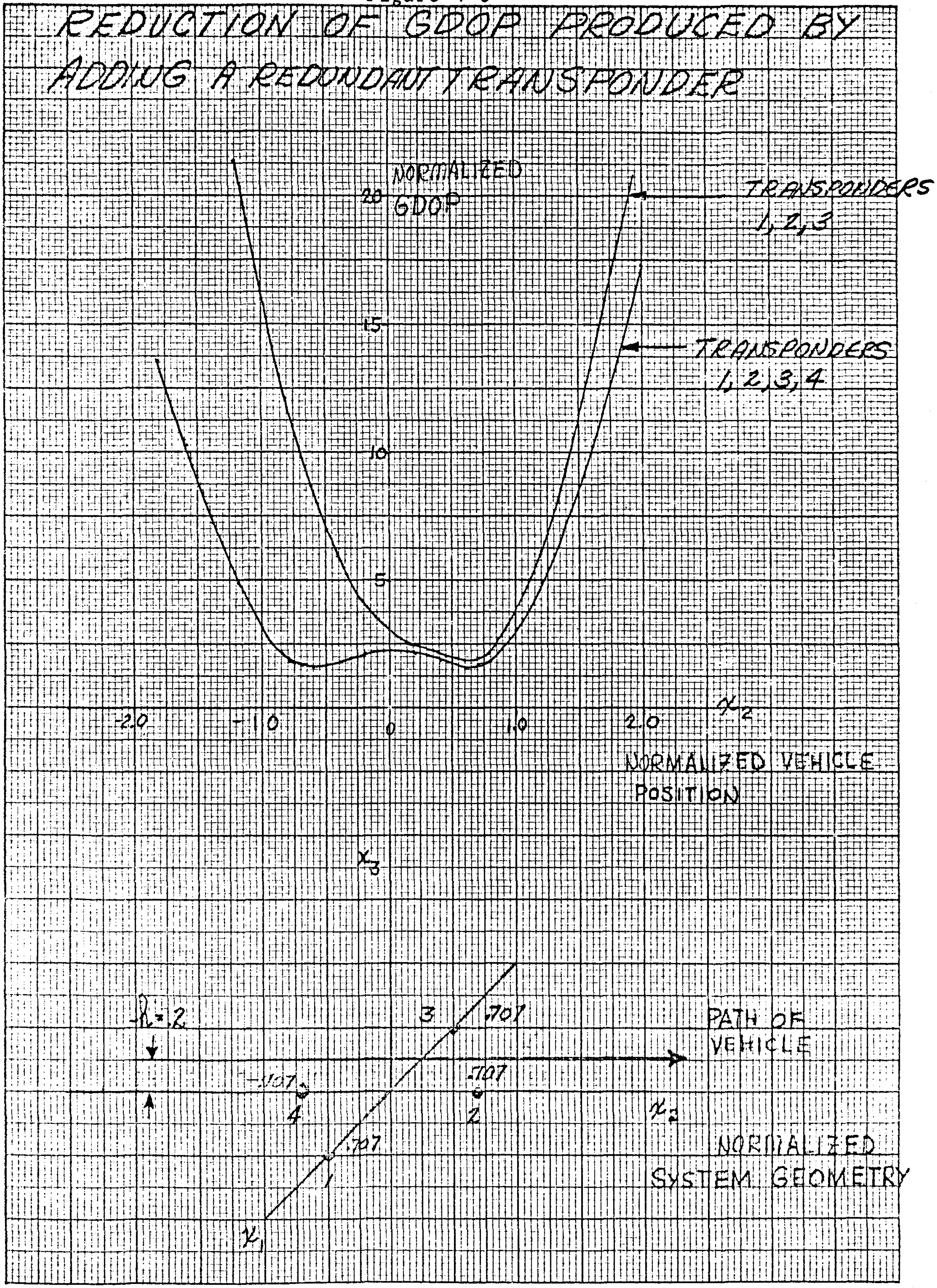
The uncertainty of the vehicle position at these three locations becomes the equivalent of a ground station uncertainty, since these three vehicle positions are used as reference points from which range measurements are made to compute the position of the new ground station. Thus, the GDOP analysis is performed twice. First, it is calculated for three vehicle positions using the three ground stations whose coordinates are known. Then, the computation sequence is repeated using the three vehicle positions assumed above as equivalent ground stations when the unknown ground station is being located. In the second computation, the GDOP calculated the first time becomes the equivalent ground station position uncertainty.

The results of the calculations are presented first and then a brief outline of the mathematical steps used is given. Figure 4-6a shows the geometry of the three known ground stations and the position of the station being surveyed. Figures 4-6b, c, and d show three different vehicle position geometries when the new ground station is being located. In the configurations used, the height (altitude) of the vehicle was set equal to one unit.

Normalized or relative distances can be used in the GDOP calculations because the direction cosines rather than the actual distances influence the results. In Figure 4-6b, c, and d, the numbers in parentheses correspond to the GDOP calculated at each point under the assumption that the three ground stations have no position uncertainty. For the three vehicle position configurations chosen, the GDOP varied from 7.0 to 10.0. Since no technique was developed to find the absolute minimum value, it can be assumed that GDOP values under seven are possible, but it is expected they will not get much smaller because the GDOP in locating the vehicle varies between two and three.

This calculation shows that the GDOP encountered in locating a new ground station is reasonable and, therefore, this represents a useful technique.

Figure 4-5


REDUCTION OF GDOP PRODUCED BY ADDING A REDUNDANT TRANSPONDER
NORMALIZED GDOP
20
15
10
5
TRANSPONDERS 1, 2, 3
TRANSPONDERS 1, 2, 3, 4
-2.0
-1.0
0
1.0
2.0
x_2
NORMALIZED VEHICLE POSITION
x_3
h=2
3
.707
PATH OF VEHICLE
-.707
.707
4
2
x_2
.707
1
x_1
NORMALIZED SYSTEM GEOMETRY

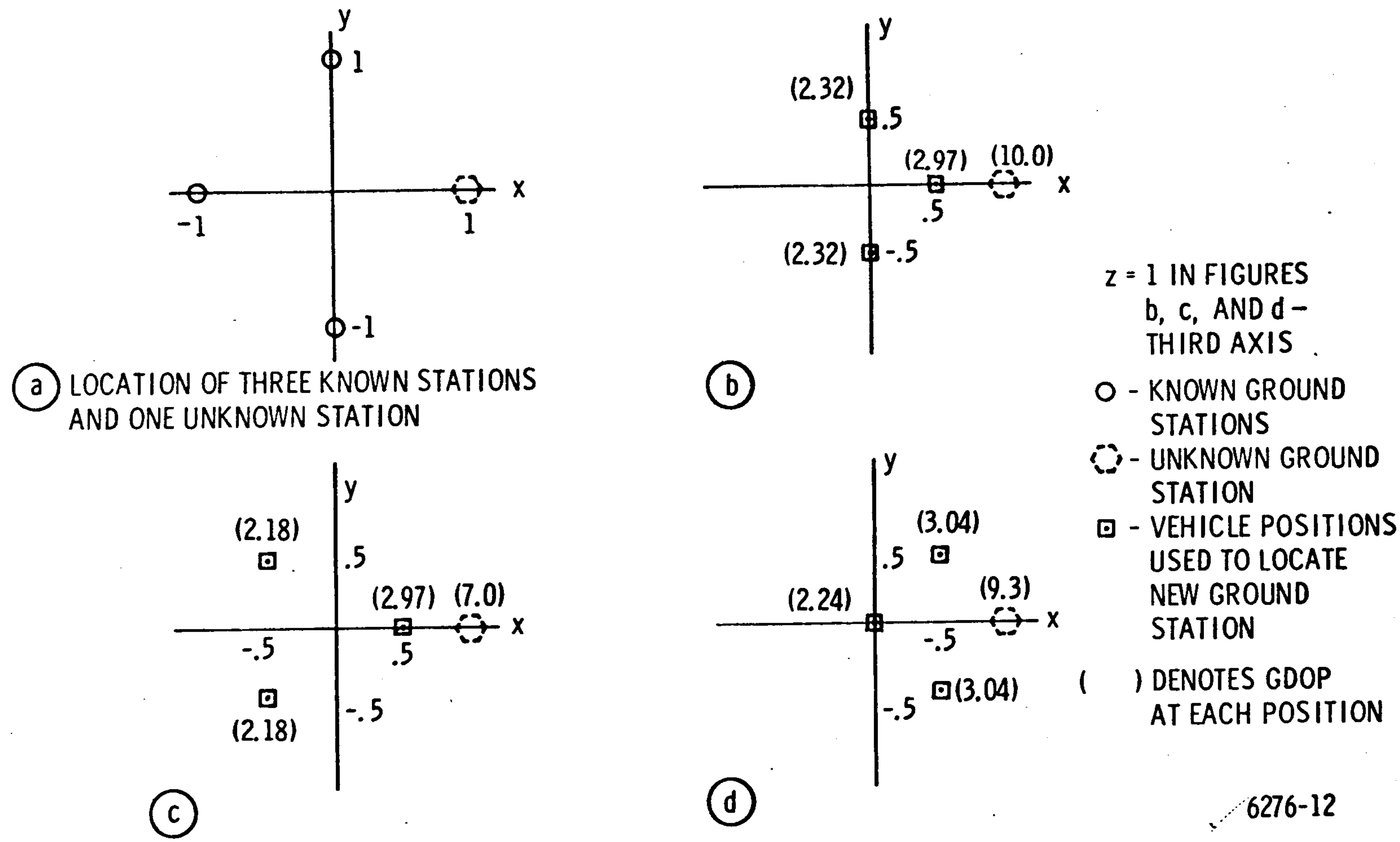


Figure 4-6. Geometries Used For Calculating GDOP Associated With Locating a New Transponder

Now consider the mathematics used in obtaining the above results. The system of equations was linearized as described previously and written in matrix notation as shown below.

$$\underset{\Delta R}{\begin{bmatrix}\Delta R_1\\ \Delta R_2\\ \Delta R_3\end{bmatrix}} + \underset{A_1}{\begin{bmatrix}a_{11} & a_{12} & a_{13}\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}} \underset{\Delta X_1}{\begin{bmatrix}\Delta X_{11}\\ \Delta X_{21}\\ \Delta X_{31}\end{bmatrix}} + \underset{A_2}{\begin{bmatrix}0 & 0 & 0\\ a_{21} & a_{22} & a_{23}\\ 0 & 0 & 0\end{bmatrix}} \underset{\Delta X_2}{\begin{bmatrix}\Delta X_{12}\\ \Delta X_{22}\\ \Delta X_{32}\end{bmatrix}} +$$

$$\underset{A_3}{\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ a_{31} & a_{32} & a_{33}\end{bmatrix}} \underset{\Delta X_3}{\begin{bmatrix}\Delta X_{13}\\ \Delta X_{23}\\ \Delta X_{33}\end{bmatrix}} = \underset{A}{\begin{bmatrix}a_{11} & a_{12} & a_{13}\\ a_{21} & a_{22} & a_{23}\\ a_{31} & a_{32} & a_{33}\end{bmatrix}} \underset{\Delta P}{\begin{bmatrix}\Delta X_1\\ \Delta X_2\\ \Delta X_3\end{bmatrix}}$$

where the a_{ij} elements represent the direction cosines given by

$$\left(\frac{X_i - X_{ij}}{r_j}\right).$$

The above equations can be simplified notationally by representing the actual matrix with the letter shown above each matrix. This equation can be solved for the components of the vehicle position error $[\Delta P]$, as shown by

$$\Delta P = [A^{-1}] \cdot \left\{ [\Delta R] + [A_1] \; [\Delta X_1] + [A_2] \; [\Delta X_2] + [A_3] \; [\Delta X_3] \right\}$$

The covariance matrix of the vehicle position error is given by

$$\mathrm{COV}\ (\Delta P) = [\Delta P] \; [\Delta P^T]$$ where $[\Delta P^T]$ is the transposed $[\Delta P]$ matrix.

Since the variations in the coordinates and the range measurements are assumed to be statistically independent, the covariance of ΔP is given by

$$\mathrm{COV}\ (\Delta P) = [A^{-1}] \cdot \Big\{ [R] \; [R^T] + [A_1] \left([\Delta X_1] \; [\Delta X_1^T] \right) [A_1^T]$$
$$+ [A_2] \left([\Delta X_2] \; [\Delta X_2^T] \right) [A_2^T] + [A_3] \; [\Delta X_3] \left([\Delta X_3^T] \right) [A_3^T] \Big\}$$
$$\cdot \; [A^{-1T}]$$

This equation is very helpful in the survey problem when it is recognized that $\left(\left[\Delta X_i\right] \; \left[\Delta X_i^T\right]\right)$ represents the covariance matrix of the coordinate uncertainties of the i^{th} station. Thus, the above equation can also be written as

$$COV(\Delta P) = \left[A^{-1}\right] \times \Big\{ COV(\Delta R) + A_1 \left[COV(\Delta X_1)\right] A_1^T$$
$$+ A_2 \left[COV(\Delta X_2)\right] A_2^T + A_3 \left[COV(\Delta X_3)\right] A_3^T \Big\} \times (A^{-1})^T$$

In calculating the GDOP for surveying a new station, the following procedure was used.

1. Compute the covariance matrices, COV(ΔP), for three vehicle positions using the three ground stations whose positions are known.

2. Use the three covariance matrices from step 1 as the three-station coordinate covariance matrices and treat the fourth station as the unknown. The matrix A becomes the direction cosines from the fourth station to each of the three vehicle positions, and A_1, A_2, and A_3 are derived from A as before.

A computer program was written to perform these steps and applied to several configurations.

4.2.4 Simplified Two Dimensional Analysis

In the preceding sections, the approach taken was to linearize the system of equations, put them in matrix form and then calculate GDOP values on a computer. While this technique is very effective in arriving at answers to particular geometries, it does not provide much insight on how the GDOP varies with system geometry. Therefore, it was decided to derive equations which express the GDOP as a function of the angles involved. In the analysis that follows, the expressions were simplified by restricting the system to a two-dimensional geometry.

Figure 4-7 shows a diagram of a typical system geometry. The position coordinates of the vehicle are given by

$$x = f_1(a,b) \qquad y = f_2(a,b)$$

By taking partial derivatives, the position error, ΔP, given by the square root of the sum of the squares of the errors x and y, which can be written as

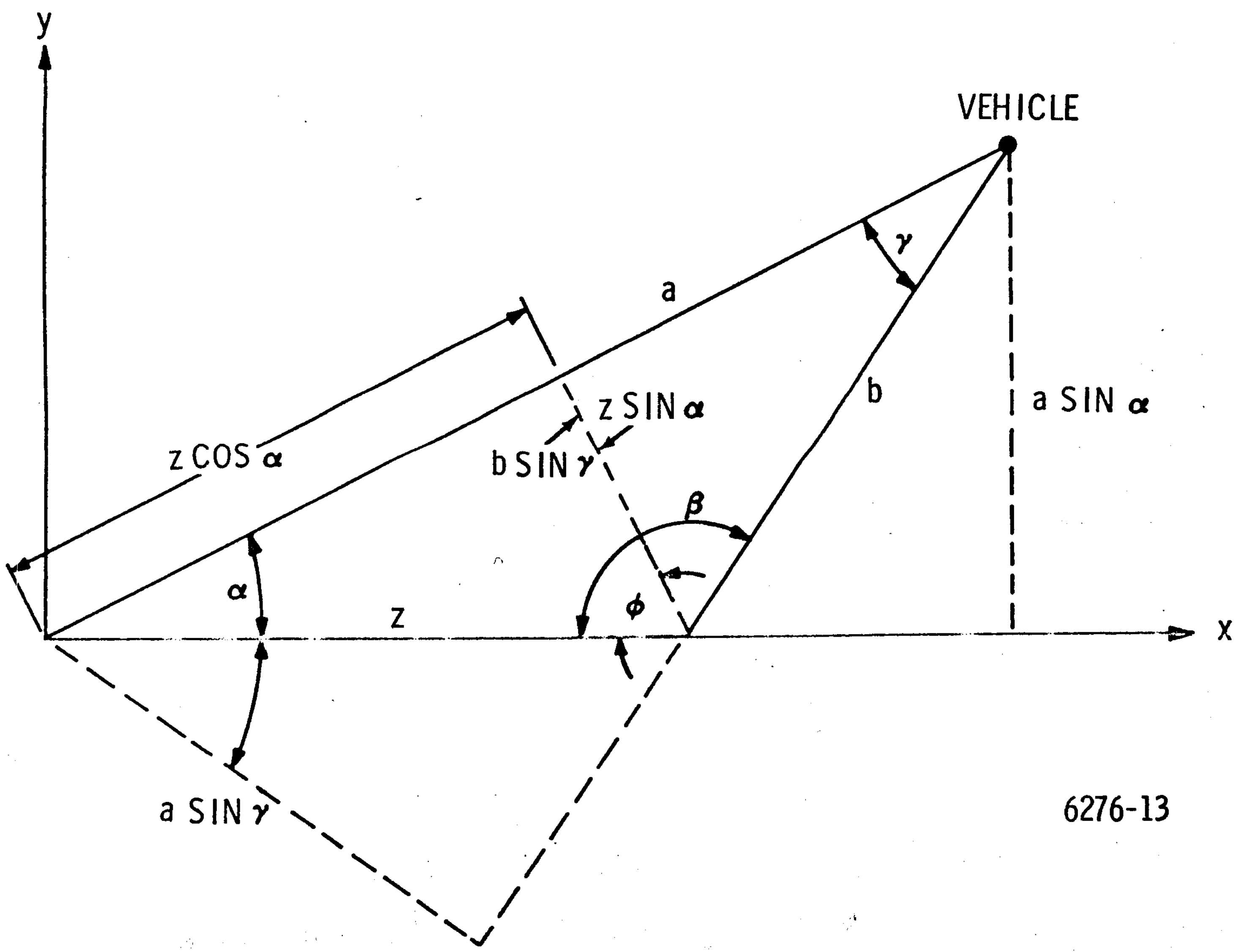


Figure 4-7. Two Dimensional System Geometry

$$\Delta P^2 = \left\{ \sum_{i=1}^{2} \left[\left(\frac{\partial f_i}{\partial a}\right)^2 \Delta a^2 + \left(\frac{\partial f_i}{\partial b}\right)^2 \Delta b^2 \right.\right.$$

$$\left.\left. + 2 \left(\frac{\partial f_i}{\partial a}\right)\left(\frac{\partial f_i}{\partial b}\right) \Delta a \; \Delta b \right] \right\}$$

where Δa and Δb represent incremental variations in the range measurements a and b, respectively.

Taking the temporal averages of the squares of the incremental ranging errors, Δa and Δb, and the incremental position error, ΔP, gives the variance or the standard deviation squared, σ^2, of each of these quantities, since the means are all equal to zero. This produces the following expression:

$$\sigma_{\Delta P}{}^2 = \sum_{i=1}^{2} \left\{ \left(\frac{\partial f_i}{\partial a}\right)^2 \sigma_{\Delta a}{}^2 + \left(\frac{\partial f_i}{\partial b}\right)^2 \sigma_{\Delta b}{}^2 \right.$$

$$\left. + 2p \left(\frac{\partial f_i}{\partial a}\right)\left(\frac{\partial f_i}{\partial b}\right) \sigma_{\Delta a} \sigma_{\Delta b} \right\}$$

where $\sigma_{(\ )}$ denotes the RMS variation of the suscripted variable. The partials with respect to x are readily found as

$$\frac{\partial x}{\partial a} = \frac{a}{z} \qquad \frac{\partial x}{\partial b} = \frac{-b}{z}$$

but the partials with respect to y require considerably more manipulative effort in arriving at the expressions

$$\frac{\partial y}{\partial a} = \frac{\cos \beta}{\sin\gamma} \qquad \frac{\partial y}{\partial b} = \frac{\cos \alpha}{\sin\gamma}$$

When these four partials are substituted back into the equation for $\left(\sigma_{\Delta P}\right)^2$ and appropriate simplifications made, the expression

$$\left(\sigma_{\Delta P}\right)^2 = \left(\frac{1}{\sin^2\gamma}\right)\left\{\sigma_{\Delta a}{}^2 + \sigma_{\Delta b}{}^2 - 2\,\rho\sigma_{\Delta a}\,\sigma_{\Delta b}\cos\gamma\right\}$$

is obtained. This equation shows that the rms error magnification is proportional to $(1/\sin\gamma)$ where γ is the included angle between the ground stations as measured at the vehicle. The equation also shows that the correlation between the range errors affects the position error.

In the AROD system, it is expected that a small degree of correlation may exist in the range errors due to common effects within the vehicle receiver and some correlation of the propagation induced errors. If the correlation coefficient, ρ , is positive as we might normally expect, the effect of the correlation is to reduce the position error when γ is $< 90^{\circ}$. When the sigmas are assumed to be equal and the correlation coefficient, ρ , is set equal to zero, the equation for $\sigma_{\Delta P}$ reduces to

$$\sigma_{\Delta P} = \left(\frac{\sqrt{2}}{\sin\gamma}\right)\sigma_R$$

where $\sigma_R = \sigma_{\Delta a} = \sigma_{\Delta b}$.

For a three-dimensional geometry, the expression becomes

$$\left(\sigma_{\Delta P}\right)^2 = \sum_{i=1}^{3}\left(\frac{\sigma_{Ri}{}^2}{\sin^2\gamma_i}\right)$$

where σ_{Ri} = range measurement from i^{th} ground station

γ_i = included angle defined by

1. line between the vehicle and the i^{th} ground station and

2. plane defined by lines from the vehicle to the remaining two ground stations.

When all sigmas are equal, this equation reduces to

$$\sigma_{\Delta P} = \left(\sum_{i=1}^{3} \frac{1}{\sin^2 \gamma_i} \right)^{1/2} \sigma_R$$

and therefore, the GDOP is equal to

$$\text{GDOP} = \left(\frac{\sigma_{\Delta P}}{\sigma_R} \right) = \left(\sum_{i=1}^{3} \frac{1}{\sin^2 \gamma_i} \right)^{1/2}$$

In the above equations, it was shown that the angle γ, affects the magnitude of the position uncertainty. Therefore, let us derive an expression for the rms value of γ. The angle γ can be represented functionally as

$$\gamma = f\,(a, b)$$

and by taking partials, $\Delta\gamma$ is given by

$$\Delta\gamma = \left(\frac{\partial f}{\partial a} \right) \Delta a + \left(\frac{\partial f}{\partial b} \right) \Delta b.$$

After squaring and taking the expected values, variance of γ is given by

$$\sigma_{\Delta\gamma}^{\;2} = \left(\frac{\partial f}{\partial a} \right)^2 \sigma_{\Delta a}^{\;2} + \left(\frac{\partial f}{\partial b} \right)^2 \sigma_{\Delta b}^{\;2} + 2 \left(\frac{\partial f}{\partial a} \right) \left(\frac{\partial f}{\partial b} \right) \rho\, \sigma_{\Delta a}\, \sigma_{\Delta b}$$

The partials can be simplified to

$$\frac{\partial \gamma}{\partial a} = - \left(\frac{1}{a} \right) \cot \alpha$$

$$\frac{\partial \gamma}{\partial b} = - \left(\frac{\cot \beta}{b} \right)$$

which, when substituted into the equation above results in the following general expression

$$\sigma_{\Delta\gamma}^{2} = \left(\frac{\sigma_{\Delta a}}{a}\right)^{2} \cot^{2}\alpha + \left(\frac{\sigma_{\Delta b}}{b}\right)^{2} \cot^{2}\beta + 2\rho\left(\frac{\sigma_{\Delta a}}{a}\right)\left(\frac{\sigma_{\Delta b}}{b}\right) \cot\alpha \cot\beta$$

For the special case let $\rho = 0$, $\alpha = \beta$ and $\frac{\sigma_{\Delta a}}{a} = \frac{\sigma_{\Delta b}}{b}$, $\sigma_{\Delta\gamma}^{2}$ is given by

$$\sigma_{\Delta\gamma} = \left\{\sqrt{2}\left(\frac{\sigma_{\Delta R}}{R}\right) \tan\left(\frac{\gamma}{2}\right)\right\} \quad \text{RADS.}$$

This expression shows that as γ increases, the rms variation of γ also increases when the ratio $(\sigma_{\Delta R}/R)$ is kept constant. This equation has a singularity at $\gamma = 180^{\circ}$ as does the equation for GDOP. The singularities are caused by the first order approximation used for deriving both of these equations. The equation for $\sigma_{\Delta\gamma}$ shows that for reasonable ranging accuracy, e.g., $(\sigma_{\Delta R}/R) < 10^{-4}$ and $\gamma = 120^{\circ}$, $\sigma_{\Delta\gamma}$ is approximately 0.01°. This is sufficiently small to justify the previous assumption that γ equalled a constant in the previous derivation.

REFERENCES

1. Farmer, Donald J., "Estimates of Ionospheric Guidance Noise When Tracking Objects at Great Heights," STL GM-TN-0165-00152, AD 607698, (Motorola 12680), 26 June 1958.

2. Norton, K. A., "Refraction Corrections to Electrical Range Measurements," Proceedings of the Third Tropospheric Refraction Effects Meeting, Vol. II, AD 628772, (Motorola 20292), January 1966.

3. Newman, S. M., "Tropospheric and Ionospheric Effects on Interferometer Systems," Proceedings of the Third Tropospheric Refraction Effects Meeting, (Motorola 20292), January 1966.

4. "Electromagnetic Propagation, Part I - Refraction Corrections," Applied Physics Department, Electronics Laboratory, STL, AD 607629, (Motorola 11700), 13 December 1958.

5. Bean, B., Cahoon and Thayer, "Tables for the Statistical Prediction of Radio Ray Bending and Elevation Angle Error Using Surface Values of the Refractive Index," Technical Note 44, PB 151403, NBS.

6. Bean, B. and Thayer, "An Analysis of Atmospheric Refraction Errors of Phase Measuring Radio Tracking Systems, Part I - An Analysis of the Refraction Errors to be Expected in a Horizontally Homogeneous Atmosphere and a Method for their Systematic Correction," NBS Report 7254, 5 June 1962.

7. Harris, S. M., "Refraction Compensation in a Spherically Stratified Ionosphere," PGAP, Vol. AP-9, No. 2, March 1961.

8. Report of the AD HOC Panel on Electromagnetic Propagation, Advisory Committee to Air Force Systems Command, National Academy of Sciences, National Research Council, ACAFSC:103,1962, Under AF Contract AF 18(600)-1895, AD 296845.

9. Rosenbaum, "Range Residuals in VHF Radar Tracking," Goddard Space Flight Center, NASA TN D-3560, (Motorola 22278), August 1966.

SECTION V

5. AROD APPLICATIONS

The purpose of the AROD Applications Study was to stimulate applications of the technologies developed in the AROD program. The following procedure was used:

1. Identify potential applications for both operational and experimental uses of AROD;
2. Conduct a preliminary evaluation of the potential application;
3. Make a detailed analysis of those applications which appear particularly promising.

Before these three tasks were undertaken, it was necessary to generate appropriate documents describing the AROD system so that potential users could readily grasp the AROD concept. With this objective in mind, two reports were written. The first was a short, concise description of the AROD system, with simple block diagrams used to describe the basic operation of the system. The material was presented in a manner to stimulate the reader's interest and not bog him down with details. For those who required additional information, a second document was prepared which contained more of the technical details. This report, entitled "AROD Special Technical Report" went into considerable depth on the actual details of the AROD system. It covered the general AROD features; described the operation of the ranging PN code generator, tracking receiver, and Doppler reverse, and outlined the operational sequences used for acquisition, station keeping, data readout, and vhf link.

In addition, an appendix described the type of range code error signals developed in the various acquisition modes.

Some of the diagrams used in these reports were made into overhead cells to facilitate explanation of the AROD concept at conference presentations.

After this information was prepared, a survey was performed to determine potential applications for the AROD technologies. The following areas were initially defined: geodetic, ground and air position location, missile tracking and/or guidance and satellite tracking, and oceanography users.

Before identification of the potential was completed, discussions were held at Huntsville on Dec. 19, 1966 with the contract sponsors and staff personnel at the Astrionics Laboratory of the George C. Marshall Spaceflight Center. At this meeting, the reports prepared were reviewed and several suggestions were made to improve them. These modifications were incorporated before the documents were published. On Jan. 19, 1967 a presentation was made to NASA's Office of Tracking and Data Acquisition (OTDA) which is the office that funded the AROD program through NASA, Huntsville. As a result of these discussions, the approach to be followed during the applications program was finalized.

In this section, the previously mentioned items are grouped into four areas; survey applications, navigation applications, range instrumentation, and oceanography. These items are discussed below in the terms of the contacts made and analyses performed when the application appeared promising.

5.1 SURVEY APPLICATIONS

In this group, the possible applications identified were tactical surveying patterned along the requirements of LRSS and geodetic surveying similar to GEOS-B and SECOR.

5.1.1 Tactical Surveying

AROD as it is presently implemented has the capability of determining the position and velocity of the airborne vehicle and also the capability of surveying or locating the position of a new ground transponder.

The tactical application of AROD was based around a similar system geometry. In this case, the vehicle equipment was located in an aircraft whose position was determined by making ranging measurements with three ground transponders (now called base stations) whose position was known. Three ranging channels provided continuous information on the position of the aircraft while the fourth channel was available to make ranging measurements with the ground transponder (now called forward observer) to be surveyed. Thus by flying the aircraft to three different positions the location of the forward observer could be determined. A large number of forward observers can be accommodated by sequential interrogations.

This application was initially identified in the course of a presentation on Jan. 13, 1967 at the Army Material Command (AMC) in Washington, D.C. From this discussion it was learned that the tactical surveying capability previously described is very similar to the Army's requirements for the Long Range Survey System (LRSS). Contacts were made with personnel from the Office of the Chief of Engineers (OCE) and GIMRADA. Further discussions with these contacts prompted the personnel responsible for the development of the LRSS equipment, at GIMRADA to visit Motorola on Feb. 9, 1967. They were shown the AROD equipment and some of the advantages of using AROD to meet LRSS requirements were explained.

As a result of their interest in applying AROD techniques to their needs, it was decided to model the AROD system around the LRSS requirements. Before this effort was undertaken, these people were contacted on Sept. 28, 1967 to obtain a better appreciation of all of the specified requirements for a LRSS type application. With this information as background, a small document was prepared which describes how the AROD system could be modified to meet the LRSS needs. This effort was continued by revisiting the people at GIMRADA on Oct. 19, 1967 for the purpose of clarifying the techniques used in this system model. It was concluded from these discussions that the personnel at GIMRADA are convinced that an AROD system with slight modifications could meet the LRSS requirements satisfactorily.

From the standpoint of AROD applications, the important questions are: (1) whether or not there is going to be a new equipment development program for a system meeting the LRSS requirements, and (2) the timing of the program. At the present time, the answers to these questions are somewhat tenuous. Initial information indicated that a procurement might be started around February 1968, but at the present time this appears a bit optimistic. In fact, insufficient information is presently available to make an adequate appraisal of the status of the program.

Appendix A is a portion of the material from the AROD model of the LRPDS system. The similarity of the system concepts and requirements to the original AROD system are quite obvious.

5.1.2 Geodetic Applications

The small size and weight of the AROD equipment coupled with its excellent measurement accuracy makes it ideally suited for satellite geodesy. Two programs are active in this area, SECOR and GEOS.

The potential application of AROD to an advanced SECOR was investigated at a meeting held on January 13, 1967 at the Army Material Command facility. This presentation was attended by a large group of people who represented the Geodesy Intelligence Mapping Research and Development Agency (GIMRADA), the Army Map Service (AMS), and the Office of the Chief of Engineers (OCE). The results of this discussion indicated that:

1. The existing SECOR satellites and ground stations are providing position accuracies adequate to meet military requirements.

2. The ground complexes are large, cumbersome and difficult to move from location to location, and

3. Data collection is time consuming and costly.

While the problems indicated in items 2 and 3 could be solved with AROD, the Army personnel indicated they do not have a follow-on program for continuing geodetic surveys. They expect to operate the existing SECOR network until the end of this year, at which time their surveying program will be completed. It is difficult to believe the picture is as bleak as portrayed above but, in any event, the potential for application of AROD to Army geodetic surveys appears dim. As one might expect, there are several groups which are charged with pursuing advanced survey techniques but, at the present time, they have not completely jelled and as a result little progress has been made in defining the requirements for a new system.

NASA is pursuing satellite geodesy under the GEOS program. The GEOS B satellite contains five different types of position locating systems -- SECOR, Goddard Range and Range Rate, C-band radar, flashing lights, and TRANSIT. The objective of this program is two-fold; one is to compare the capabilities of each of the systems and the other is to determine the accuracy with which points on the surface of the earth can be located using combined measurements from all of these systems.

AROD is ideally suited to this type of experiment for the following reasons:

1. The equipment makes all its measurements at the vehicle and, therefore, eliminates the effects of interstation timing errors.

2. The ground transponders may be readily transported from site to site and require no operators.

3. The ranging accuracy possible with the AROD system exceeds that possible with other existing radio ranging systems such as are used on the present GEOS-B satellite.

The objective of the Geodesy branch at NASA is to continually improve the accuracy of the geodetic qualities such as the higher order coefficients of the earth's gravitational field and the accuracy of control points used to tie various local map surveys together. Thus, AROD appears ideally suited to this application.

This area was initially investigated during a conference with personnel from Geonautics on February 22, 1967. At this meeting, it was learned that NASA was interested in having Motorola perform a study to demonstrate analytically the performance of AROD when flying a typical Geos type mission.

The study would contain analyses of the following four areas: AROD equipment accuracy, propagation anomalies, geometrical dilution, and data processing techniques.

This program was discussed at NASA headquarters on July 11, 1967. At this meeting, it was determined that NASA desired the data processing analysis be done by a subcontractor such as D. Brown and Associates, Bissett-Burman, Wolf Research or Computer Usage.

As a result, these companies were contacted and discussions were held relative to their interest in performing the data processing study. All of these companies were interested in the analysis but the limited amount of funding available for this task indicated that subcontracting would be very difficult within the scope of this contract.

Before a final decision was made on this program, another problem developed. Congress severely restricted budgets for most of NASA's agencies in regard to launching new programs. The combination of these two factors has resulted in the exact status of this program remaining undefined at the present time.

5.2 NAVIGATION

AROD was originally designed as an instrument for navigation. Thus, it was only natural this area should be investigated as a potential application for AROD. Two basic areas of interest were identified: the weapon system (WS120A) and several navigation satellite programs.

5.2.1 WS120A

This program has been defined by the Air Force as the next generation of advanced ICBM's. Since this program has not been formally authorized and no approval is anticipated in the near future, work is progressing at a very modest level.

Information concerning this program was learned from contacts with people at the following companies.

1. General Dynamics Electronics, San Diego, on Feb. 21, 1967.
2. Air Force Ballistic Systems Division, Los Angeles, on March 2, 1967.
3. Boeing Aerospace Center, Seattle, Washington, on May 15, 1967.
4. Lockheed Missiles and Space, Sunnyvale, on June 15, 1967.
5. Martin-Marietta, Denver, on July 24, 1967.

Some of the detailed technical information obtained was classified, and therefore, only an unclassified summary of the requirements are given in this report.

There are two potential applications for AROD in this system. First, the system could be used to form a combination radio-inertial-guidance-system for the advanced ICBM. Operationally, the use of any radio system is always faced with the threat of enemy jamming. While the AROD system is capable of a high degree of antijam protection, it is always possible to make pessimistic enough assumptions to show that the system can be jammed. A second problem also arises in this application, involving the modification of the AROD system to handle the simultaneous launch of many missiles. For these reasons the second application appears more attractive.

In this case, the AROD system would be used during initial performance testing of the advanced ICBM. Operation with many missiles simultaneously is not required, since it is assumed that only one or two missiles would be launched at a time for test purposes. For example, the ground stations could use either a dual-channel transponder or a time-sharing process.

For this application, AROD offers three significant advantages.

1. The equipment size is roughly compatible with the volume available in a missile nose cone.

2. The radio system would provide an independent check on the performance of the missile.

3. AROD would provide improved tracking capability for the mid-range portion of flights launched from the Western Test Range (WTR).

These factors make AROD attractive for this application, but presently, this area does not appear promising for the immediate future because no timetable has been established for a program to develop an advanced ICBM. Therefore, most of the effort presently underway is company funded except for a couple of small study contracts.

It is important to remember that once this program becomes officially approved, the potential for applying AROD is excellent.

5.2.1.1 Analysis

For this application, the ranging accuracy of AROD appears adequate but the velocity accuracy needs improvement by a factor of roughly four. The velocity accuracy is affected by the following factors.

f - operating frequency

T - measurement interval

$2\beta_L$ - carrier loop noise bandwidth

S/N_o - received signal to noise power density ratio

The expression for the velocity error can be derived very easily by referring to the waveform shown in Figure 5-1. The velocity can be determined by measuring or counting the number of cycles of carrier frequency (or equivalently at a translated intermediate frequency). The phase jitter of the signal due to noise can be approximated by the equation

$$\phi = 1/\sqrt{2\left(\frac{S}{N}\right)} \qquad \text{Rad}$$

where (S/N) represents the signal-to-noise ratio which, in turn, can be related back to the input (S/N_o) and carrier tracking loop bandwidth as

$$\phi = 1/\sqrt{\left(2\,\frac{S}{N}\right)_i \left(\frac{B_{RF}}{2\beta_L}\right)} = 1/\sqrt{\left(\frac{S}{N_o}\right)\frac{1}{\beta_L}}$$

In terms of a time error, this becomes

$$T_e = \left(\frac{\phi}{2\pi}\right)\left(\frac{1}{f}\right) = \left(\frac{1}{2\pi f}\right)\sqrt{\frac{\beta_L}{\left(\frac{S}{N_o}\right)}}$$

and, since the measurement accuracy is given by (T_e/T), it is proportional to

$$\frac{1}{\pi f}\sqrt{\frac{N_o\beta_L}{(S/N_o)}} =$$

This expression shows that the velocity error can be reduced by increasing the quantities T, f, (S/N_o), and by decreasing β_L. The quantities β_L and f in this expression are not completely independent. For example, consider the effect of increasing "f" on the acquisition time. As the frequency "f" increases, the Doppler frequency shift increases proportionately, which means the sweep rate used for removing the Doppler component must be increased or the acquisition time will be increased. The expression for the maximum sweep rate is given by

$$\Delta\dot{f} < \frac{\beta_L^2}{3}\left(1 - \sqrt{\frac{N}{S}}\right)$$

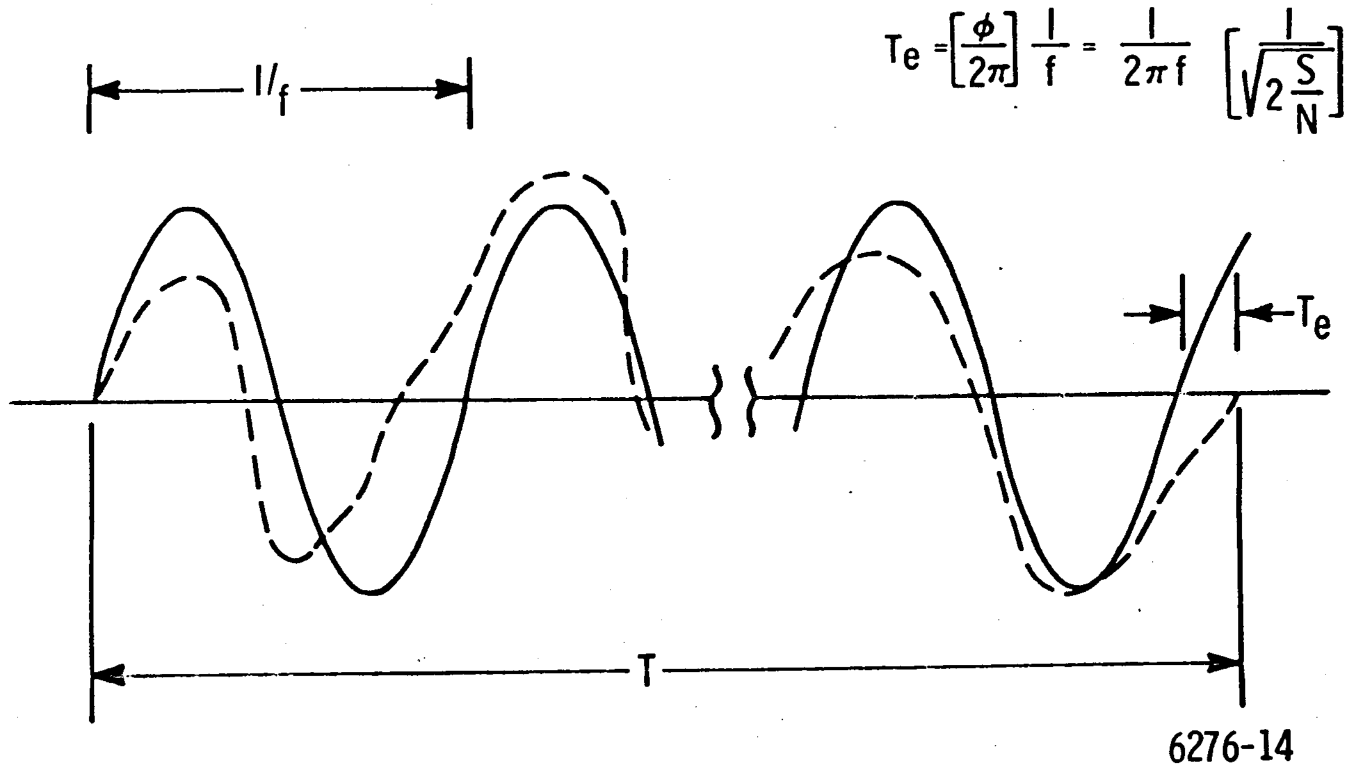


Figure 5-1. Waveform Showing Velocity Measurement Error

This equation shows that if the acquisition time is to remain constant, and the frequency is doubled, the loop bandwidth must be increased by $\sqrt{2}$, which means the rms velocity jitter would be reduced by the factor $\sqrt{2}$ rather than a factor of 2. The purpose of this analysis is to show that the quantities in the first expression are not wholly independent, but in spite of this the expression is still useful to show how the fundamental factors influence the rms velocity uncertainty.

For monitoring the performance of the advanced ICBM, velocity is more important than position for many tests. Therefore, an analysis was made to determine the effect of removing the range measurement capability from AROD. The object of this analysis was to arrive at an estimate of the reduction in size allowed by dropping the range measuring capability. This modification eliminates all of the PN coding functions and most of the code control functions.

Figure 5-2 shows the impact of this modification on the AROD vehicle receiver block diagram. Those blocks which are crossed out could be eliminated in a range-rate only-system. A similar analysis was made for the ground transponders. When the function deleted were related back to the actual hardware required to accomplish the function, it was found that the vehicle equipment was reduced to approximately one-half its original size and the transponder to approximately 60% of its original size.

5.2.2 Navigational Satellites Systems

A large number of approaches and system analyses have been performed in the area of navigation systems using satellites. This broad area can be classified along the following lines:

1. Type of satellite orbit - synchronous, medium altitude, or low altitude.
2. Communication links - one-way, or two-way.
3. Position accuracy required; high - 50 to 100 feet; medium - .1 to .5 mile; or low - approximately 1 mile.
4. Ranging technique used.
   a. CW - PN coding, ranging sidetones, and frequency sweeping
   b. Pulse - coded or uncoded.
5. Measurements made - R, ΔR, $\dot{R}$, or $\Delta\dot{R}$.

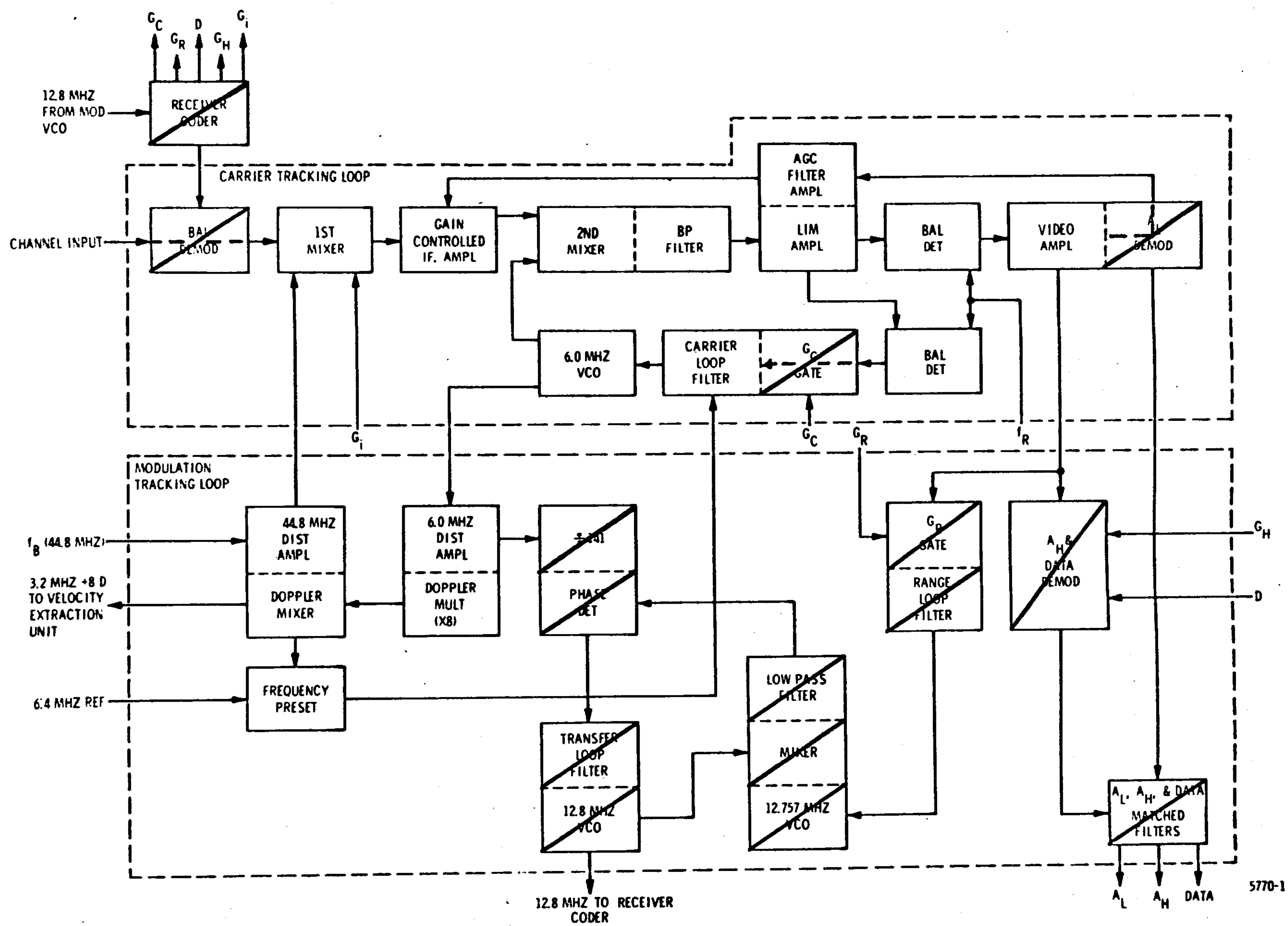


Figure 5-2. Impact of Modification of AROD Vehicle Receiver Diagram

This area was surveyed to determine where AROD techniques appeared most applicable. Since the system is configured around making simultaneous range measurements from up to four transponders whose locations are known, configurations using only a single satellite do not lend themselves to AROD techniques. Similarly, a synchronous or 24-hour satellite orbit is desirable because it provides continuous coverage of a large area which is not possible with a small number of medium or low altitude satellites. One way links (satellite-to-user) are preferred for immediate application of AROD because by eliminating the user-to-satellite link, the typical problem of saturation or interference at the satellite is avoided. Since AROD has demonstrated a highly accurate ranging system, it is desirable to apply AROD to a high accuracy type of navigation system.

With this information as background, the navigation satellite interests of the following agencies were reviewed, NASA's Goddard Space Flight Center, NASA's Electronic Research Laboratory, the Air Force, Navy, and Army. From this survey, it appeared that the Air Force's concept for a navigation satellite system, called 621B was the best area to apply AROD.

More definitive information on this program was obtained through a series of discussions at the following places.

1. Lockheed Missile and Space on July 21, 1967.

2. Litton Guidance and Controls Division on August 2, 1967.

3. Air Force-SAMSO (formerly SSD) on August 30, 1967.

4. Wright-Patterson Air Force Base - ASD on November 11, 1967.

The results of these discussions provided the following information on the 621B program. Now, consider the system geometry suggested for the tactical navigation satellite system which is also called TACNAVSAT.

A cluster of four synchronous satellites is planned; one is placed in a synchronous equatorial orbit such that it remains directly above a single point on the equator, and the remaining three are placed in inclined elliptical orbits with approximately 24-hour periods. These three satellites have their orbital planes inclined approximately 30^{o} with respect to the equatorial plane and have an eccentricity of approximately .25. With this eccentricity, the distance from the center of the earth to the perigee and apogee varies by a factor of two. Since the angular rate of motion of a satellite moving around the earth (conservative central force field) continuously varies, for the typical values given above, the satellite spends approximately 2/3 (12 hours) of its period going from the ascending nodal crossing point to apogee and back and only 1/3 (8 hours) going to perigee and back.

This set of four satellites can be oriented as shown in Figure 5-3. As time increases, the satellites, S_1, S_2, and S_3 appear to rotate around the Satellite M to a viewer lying on his back at the equator directly underneath the satellite M. This orientation allows coverage of an area approximately 1000 miles in diameter. The inclined elliptical orbits allow the area of coverage to be weighted in favor of the northern hemisphere. If the orbital inclination were reversed, coverage of the southern hemisphere would be favored.

Now that the satellite configuration has been explained, it is possible to describe how AROD could be applied to the NAVSAT system.

Assume that a ground based master control station tracks all four satellites and knows their exact position as a function of time. The station can transmit data giving the position of each of the four satellites and their ranges from the master control station in near real time. This data can be combined with PN code transmitted by the master station in a manner similar to that done presently in AROD. The four satellites operate as AROD type transponders, since they all receive a common PN coded signal, demodulate it, and retransmit the signal offset in frequency. Each satellite has a slightly different frequency translation factor. This frequency channelization allows a multichannel AROD type receiver to identify and process the signals from all four satellites simultaneously.

Operationally, the receiver is located at "user" who desires to determine his position, which in the NAVSAT system could be an aircraft, helicopter, ship, submarine, jeep, or man pack.

One difference does occur in this application from the present AROD system. Since the transmitter is located at a fixed station which is removed from the user, a pure range measurement can not be performed at the user because it does not have the transmitted signal available as a reference. Therefore, the receiving system must measure range differences, ΔR_i, which makes this a hyperbolic system rather than a circular one. Four channels are necessary because three linearly independent range differences are required to locate the user.

The major analysis effort was devoted to modeling the system to operate with an aircraft because this represents the most difficult user to obtain high accuracies. Preliminary calculations show that, in order to obtain a position uncertainty between 50 and 100 feet, the ranging data must be smoothed to reduce the rms variations.

With a rapidly moving user, such as a high performance aircraft, near real time data smoothing can be accomplished by adding an inertial measurement unit (IMU).

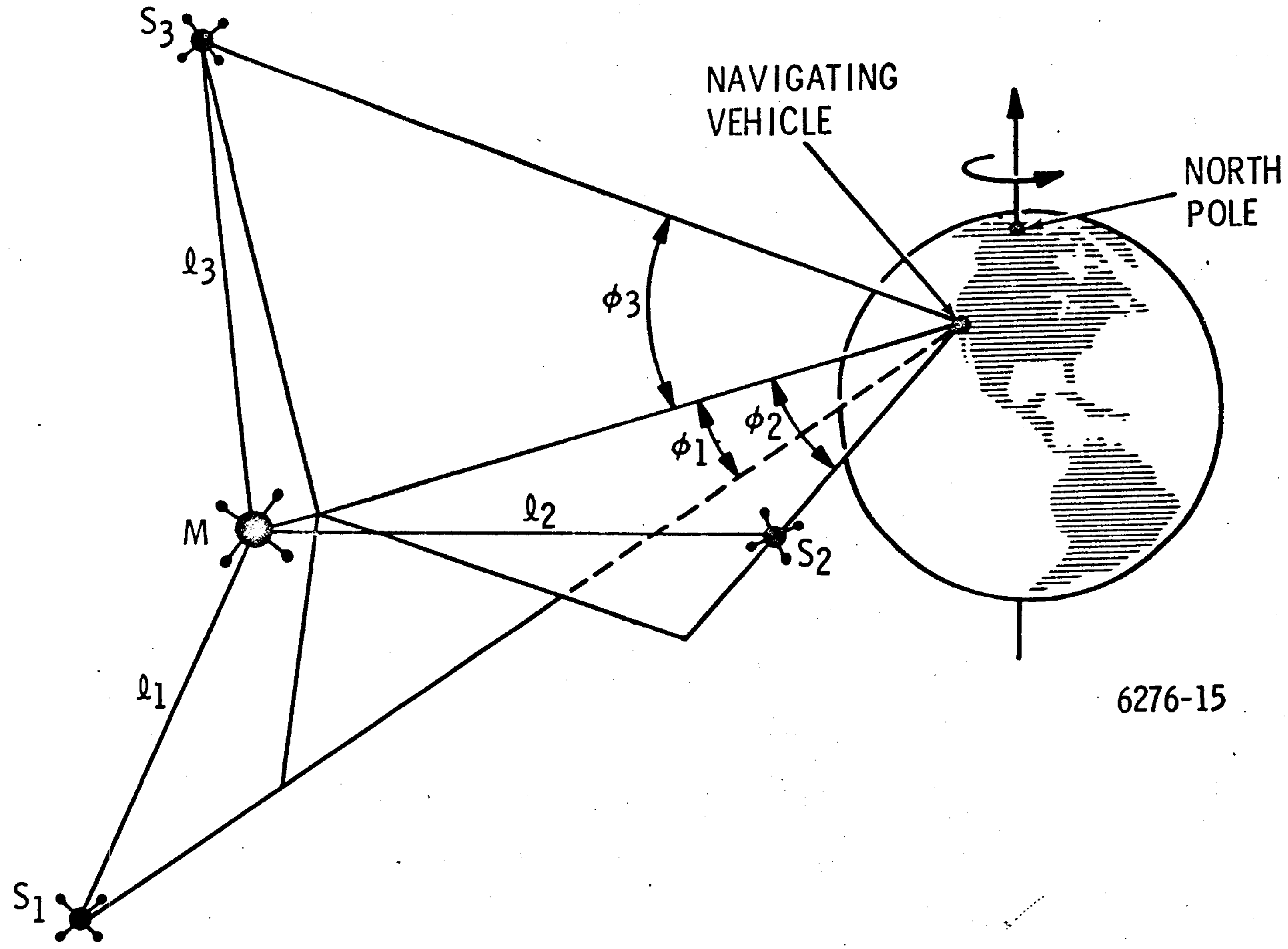


Figure 5-3. Geometry of Four-Satellite Cluster and Navigation Vehicles

This device can provide a very accurate estimate of the velocity and relative position of the user while the radio ranging can greatly reduce the relative uncertainty of the user position. The radio ranging system operating alone can still provide position and velocity information with reduced accuracy.

This particular program represents an excellent opportunity to apply AROD technology. It is anticipated that program 621B will be initiated in the near future.

5.3 RANGE INSTRUMENTATION

AROD was originally designed to track launch vehicles such as the Saturn V. Thus it was only natural that this application should be investigated.

At the present time, the Eastern Test Range (ETR) where launchings occur from Cape Kennedy is rather well instrumented. This is not to say that AROD could not improve their capability but, basically, they have sufficient equipment to adequately handle their present needs and, therefore, there is little incentive for adding new equipment to this range at the present time.

The situation is quite different at the Western Test Range (WTR) where launchings occur from Vandenberg AFB. This range suffers from the natural geography of the area which has no offshore islands such as the Grand Bahamas chain off the ETR. As a result, after most launch vehicles complete their pitch maneuver and head down range, they quickly pass out of line of sight communication with the ground based tracking systems located near Vandenberg AFB. The next tracking station which can be seen is Hawaii, if the launch is programmed to fly near this tracking station. AROD represents a system which could solve this midrange tracking quite easily, since the automatic unattended operation feature of the AROD transponder would allow these units to be located onboard either anchored or drifting buoys.

Discussions regarding this application were held at Aerospace on January 31, 1967 and at Vandenberg AFB on June 14, 1967. These discussions confirmed the fact that the WTR tracking system needs improvement. In fact, Vandenberg AFB personnel are planning to issue an RFP sometime during December 1967 to study the best method of providing tracking capability for the midrange portion of flight. Motorola plans to provide adequate information on AROD to the winner of this study program to ensure that the features and capabilities of the AROD system are fully appreciated by this organization.

AROD's capabilities have been thoroughly demonstrated in the laboratory test program. Since the equipment has performed excellently, it is only natural to extend this testing to an actual flight test program. A program for flight testing of the AROD system on board a KC135 aircraft which is presently operating out of Cape Kennedy was discussed on December 12, 1967 with Air Force personnel representing the National Range Division and advisors from the Mitre Corp. at Bolling AFB. The Mitre Personnel are contemplating a flight test of the AROD system at Cape Kennedy and are going to prepare a program plan for approval of the Air Force. It is anticipated that it will take 60 to 90 days to obtain approval for a flight test program. At this point in time, it appears that the probability of approving a flight test are better than 50/50. The motivation for proceeding with a flight test is that AROD represents a system that could eventually be used to instrument the mid-range portion of the Western Test Range (WTR).

5.4 OCEANOGRAPHY

Oceanography initially appeared as an area of potential application for AROD techniques. For example, accurate position information is required for such applications as surveying offshore oil territories to locate drilling sites, and conducting orderly searches with a minimum overlap, e.g., the Thresher and atomic bomb searches.

Battelle Memorial Institute, located in Columbus, Ohio, was visited on March 2, 1967, since they are considered as a focal point for oceanographic work, e.g., in September, 1966, Battelle held the "First Marine Geodesy Symposium."

Discussions with Battelle personnel indicated that the area of oceanography was expanding very rapidly. Interest was expressed in the accuracy of AROD but when this system is compared with the cost and performance of existing systems, it does not appear that the mission requirements justify AROD accuracies. Therefore, AROD does not represent a cost effective solution to today's needs for commercial applications. If, in the future, a mission develops that requires AROD type accuracies, the entire picture for AROD applications will change drastically.

The conclusion drawn from these discussions is that oceanography does not look promising for AROD applications in the near future. Therefore, no additional effort was expended in this area.

APPENDIX

AN ABSTRACT FROM A SYSTEM MODEL FOR THE LRPDS SYSTEM

1. INTRODUCTION

This appendix summarizes the analyses and observations concerning the system requirements of the Long Range Position Determining System (LRPDS). The extrapolation of these requirements into a basic system design is largely based upon the experience gained with the AROD (Advanced Range and Orbit Determining) system in which there is a marked similarity to the LRPDS requirements.

The AROD system design, in turn, stemmed from a series of programs which have developed capability in the areas of tracking and position locating systems. The most significant steps in this series are the Goddard Range and Range Rate system, the Jet Propulsion Laboratory Deep Space Instrumentation Facility (DSIF) ranging system, the Air Forces Space Ground Link System (SGLS), and the NASA Marshall Space Flight Center AROD system. In this report, the AROD system will be stressed for two reasons: first, it is the most recent and most advanced ranging system; and second, its operating characteristics are very similar to the requirements of the LRPDS system.

The similarities of the AROD system to the LRPDS requirements are examined below.

1. The system geometry is similar as is shown in Figure A-1. In AROD, simultaneous ranging measurements are made between an airborne vehicle unit which may be mounted on a satellite or a launch vehicle and four ground transponder stations whereas, in the LRPDS system, ranging measurements are made between a relay aircraft and three base stations and each of the 24 forward observers.

2. Both systems require at least a four-channel receiver at the airborne terminal. This allows simultaneous range measurements between the relay aircraft and the three base stations from which the aircraft position can be uniquely determined without the need for curve fitting between the data points. This is an important consideration because, in the interval of time between four range measurements when a single channel receiver is used, an aircraft in turbulent weather can undergo violent position changes.

3. AROD uses a pseudonoise (PN) range tracking code. In the LRPDS system, the type of PN code used will be modified slightly because this system must be designed for antijam

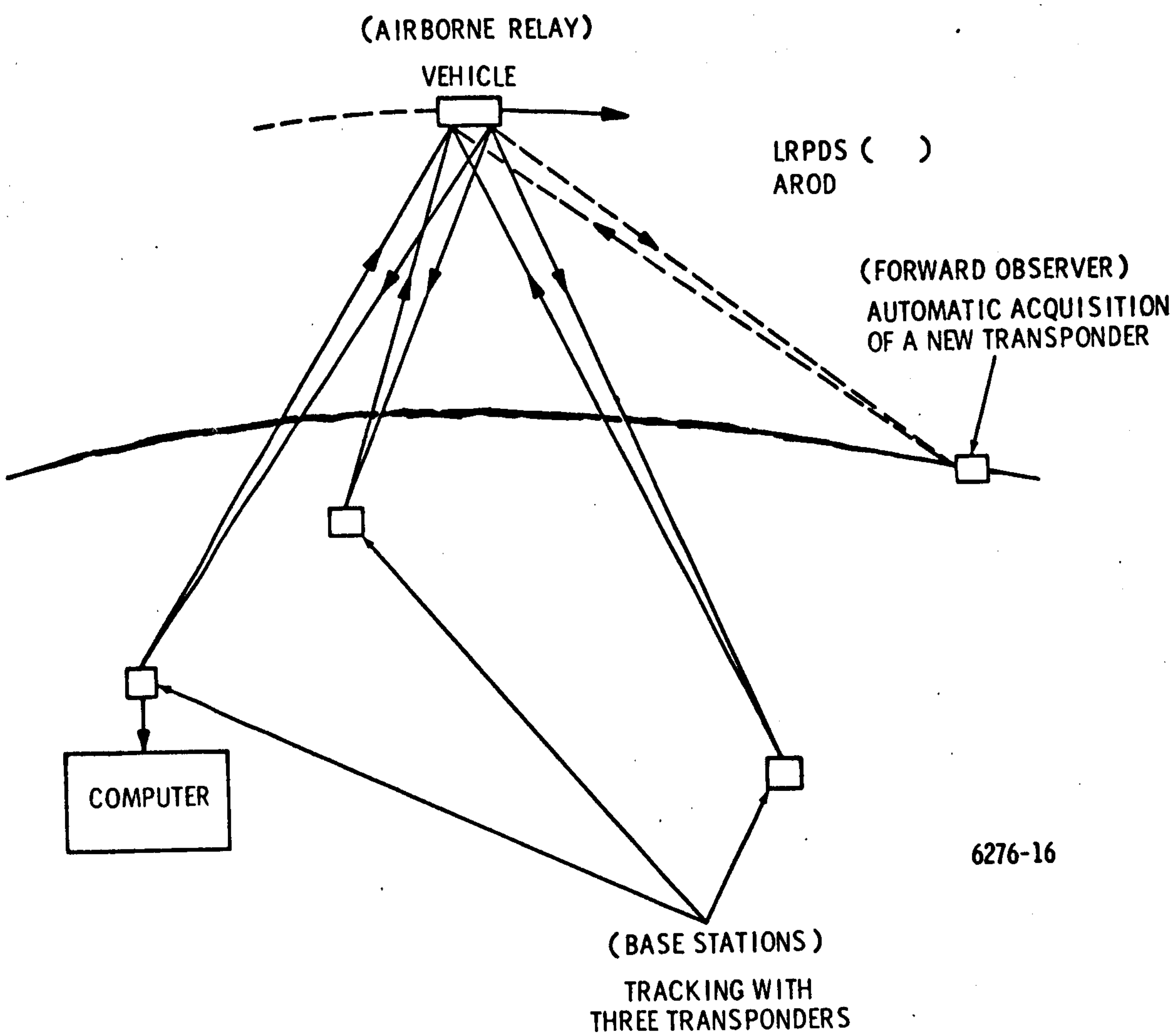


Figure A-1. Similarity of System Geometry requirements that were not necessary for AROD system. Use of a PN code in the AROD system provided Motorola with unique experience concerning the design considerations necessary to facilitate automatic code acquisition which is necessary for the LRPDS system.

4. AROD uses a compact frequency synthesizer which allows the selection of a large number of different frequency channels within a given operating band. Channel selection is a desirable feature for the LRPDS system.

5. Size, weight, power, and reliability estimates can be given with a high degree of confidence based on extrapolation from the AROD equipment. On the basis of our past experience with this equipment, no particular problems are anticipated in meeting the reliability specification.

6. State-of-the-art packaging techniques which involve the optimum combination of monolithic and hybrid integrated circuits demonstrate that it is possible to package the equipment required for the airborne unit within a small, compact piece of equipment. The modular technique used allows repairs to be done on a module replacement basis, which is important to the field repair requirement specified for the LRPDS system.

Thus, it is seen that the AROD system has provided a solid technological base for the design and development of the LRPDS system. In addition, since the equipment has been built and tested in the laboratory to the NASA environmental specifications, Motorola is able to quote attainable performance characteristics of the LRPDS equipment with a high degree of confidence.

2. ANALYSIS

In the following paragraphs, the critical areas of the Long Range Position Determining System are explained for their impact upon thc system design. Particular attention has been applied to those areas where requirements differ from the corresponding constraints in the existing AROD System Design. The common requirements have been analyzed previously and the solutions verified in the operating equipment.

2.1 SYSTEM ACCURACY

The specification requires that the rms position error (excluding the vertical error component) of the forward observer shall be less than $(3.5 \times 10^{-4})R$ or 10 meters depending on which is greatest. In order to determine the accuracy requirements needed for this equipment, a calculation was performed to determine the GDOP (geometrical dilution of precision) that occurs for the geometry used in LRPDS system. Figure A-2 shows the coordinate system used, the position of the three base stations, and the location of the airborne vehicle at three different times. The locations of the base stations are denoted by circles and the approximate location of the aircraft at the three measurement intervals is denoted by the squares. Aircraft altitudes of 5 and 10 km were used in these calculations. According to the ground rules defined, the base station positions were assumed to contain no errors.

The calculation was performed in the following manner. First, the rms position error of the aircraft at the three measurement intervals was calculated, where $\Delta RMS = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}$. The result of this calculation was used as the position uncertainty of the aircraft during the next calculation. In the second computation, the position of the forward observer was verified between 10 to 550 km and the GDOP resulting from the ranging errors and aircraft position error were determined.

Curves showing the (N-E) position error for 1.0 meter and 10 meter error in range measurement are given in Figure A-3. It is seen from this graph that for a 1-meter measurement accuracy, the position error is well below the required limit.

With ΔR equal to 10 meters, the position error is below the limit for ranges greater than 90 km and is slightly above the limit for ranges less than 90 km.

Rather than drawing a family of curves for various values of ΔR, Figure A-4 shows a curve of the range measurement accuracy required to meet the position accuracy requirements. The reverse curvature at short ranges occurs because the maximum range error is defined as a constant (10 M) rather than as a linear function of R. From this curve, it can be seen that the maximum range error that will allow meeting the specification at short ranges is approximately 4.8 meters.

The equipment modeled for this system will have a calibration bias, or drift, of less than 1 meter. Since each ranging link uses a ground transponder and the vehicle equipment, the total ranging error introduced by the equipment is approximately $\sqrt{2}$ * meters.

If the range accuracy of the equipment is combined with the worst case residual propagation error, shown in Figure A-5, the position accuracy of the model system is given by the dashed line shown in Figure A-3. This shows that the accuracy is much better than that required by the specification.

*This value assumes that the ranging bias errors are uncorrelated.

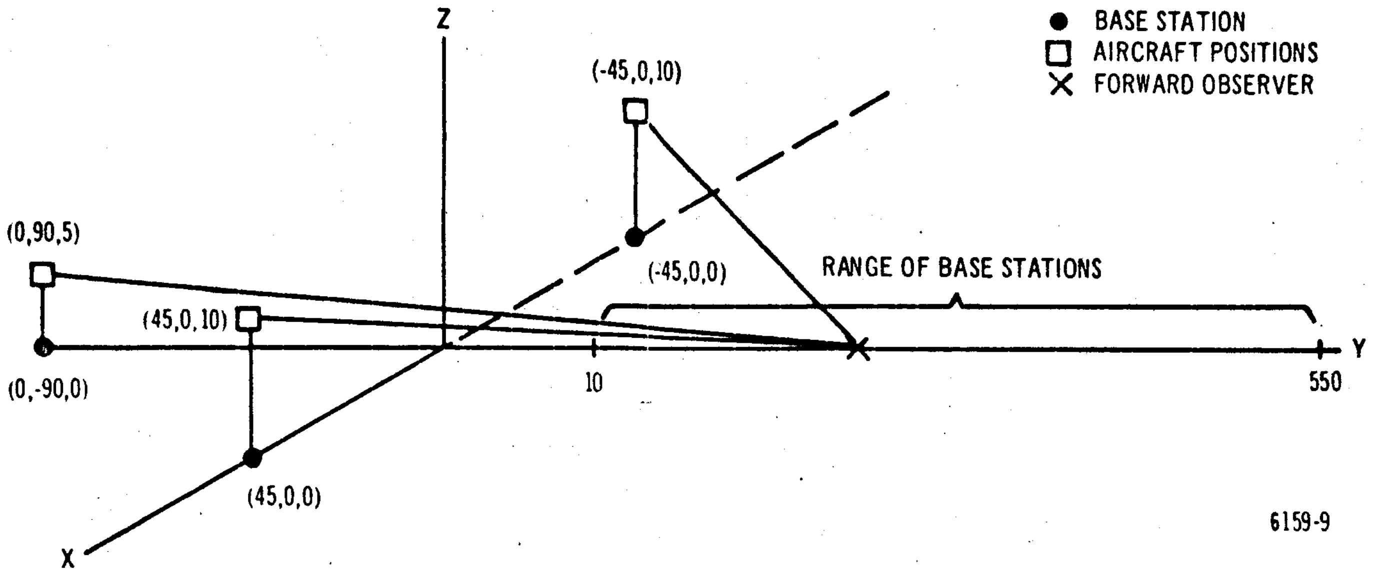


Figure A-2. System Geometry Used for GDOP Analysis

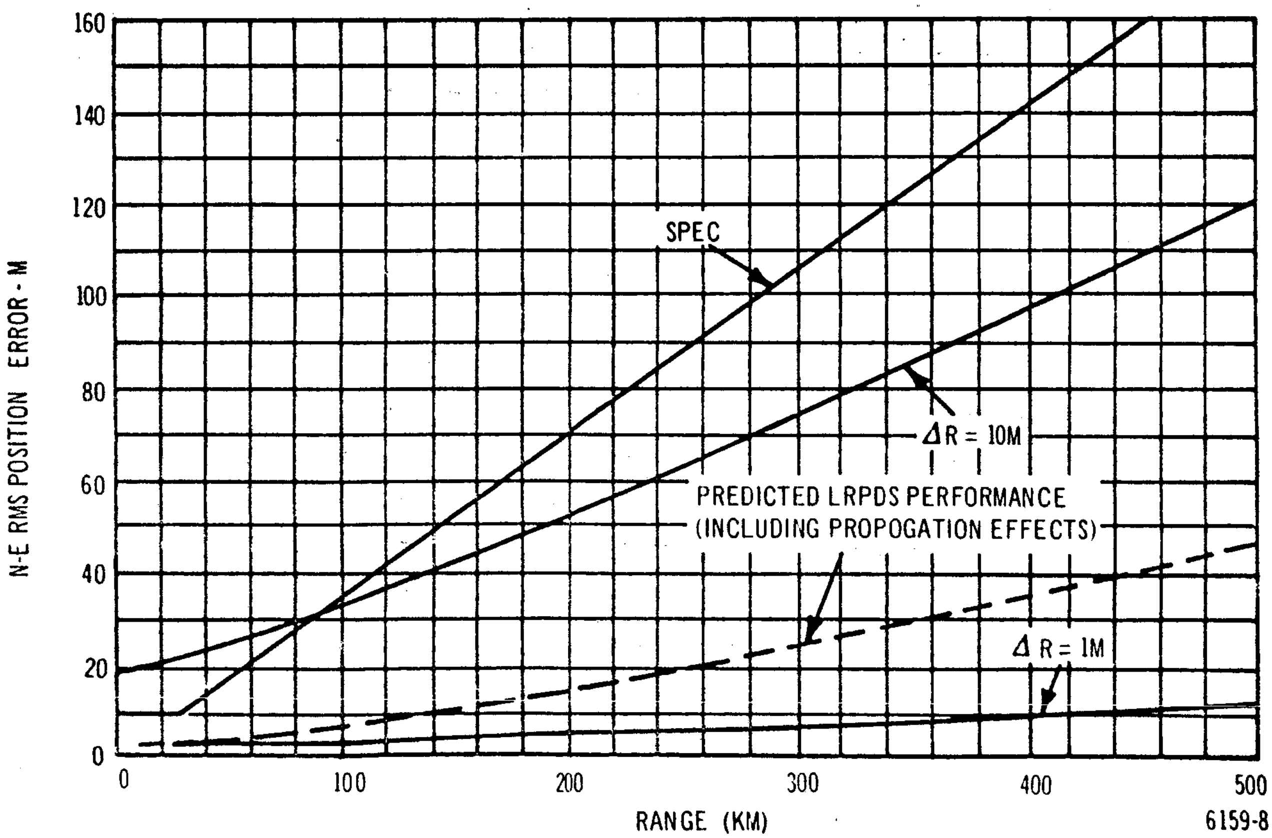


Figure A-3. N-E Position Error vs Range
For Various Ranging Errors

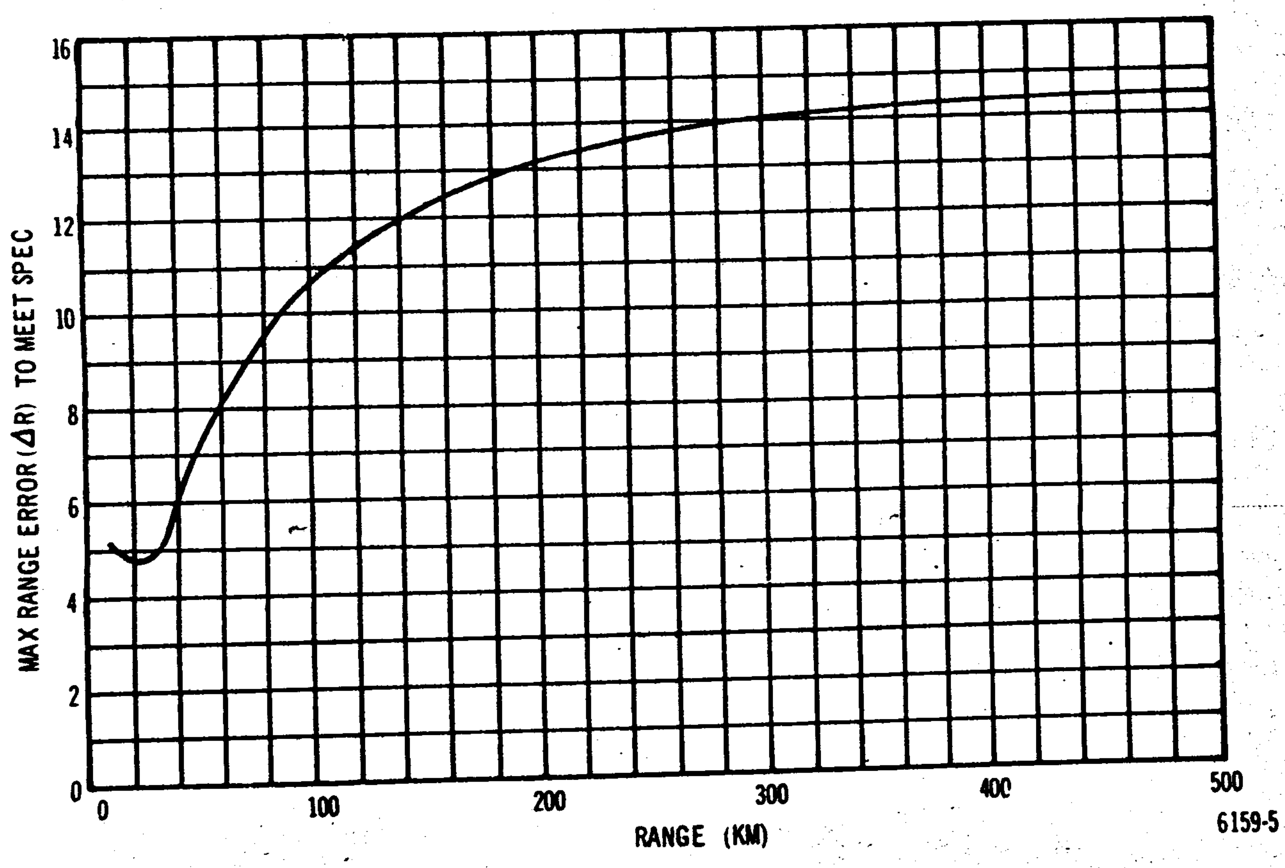


Figure A-4. Max Range Error to Meet Spec vs Range

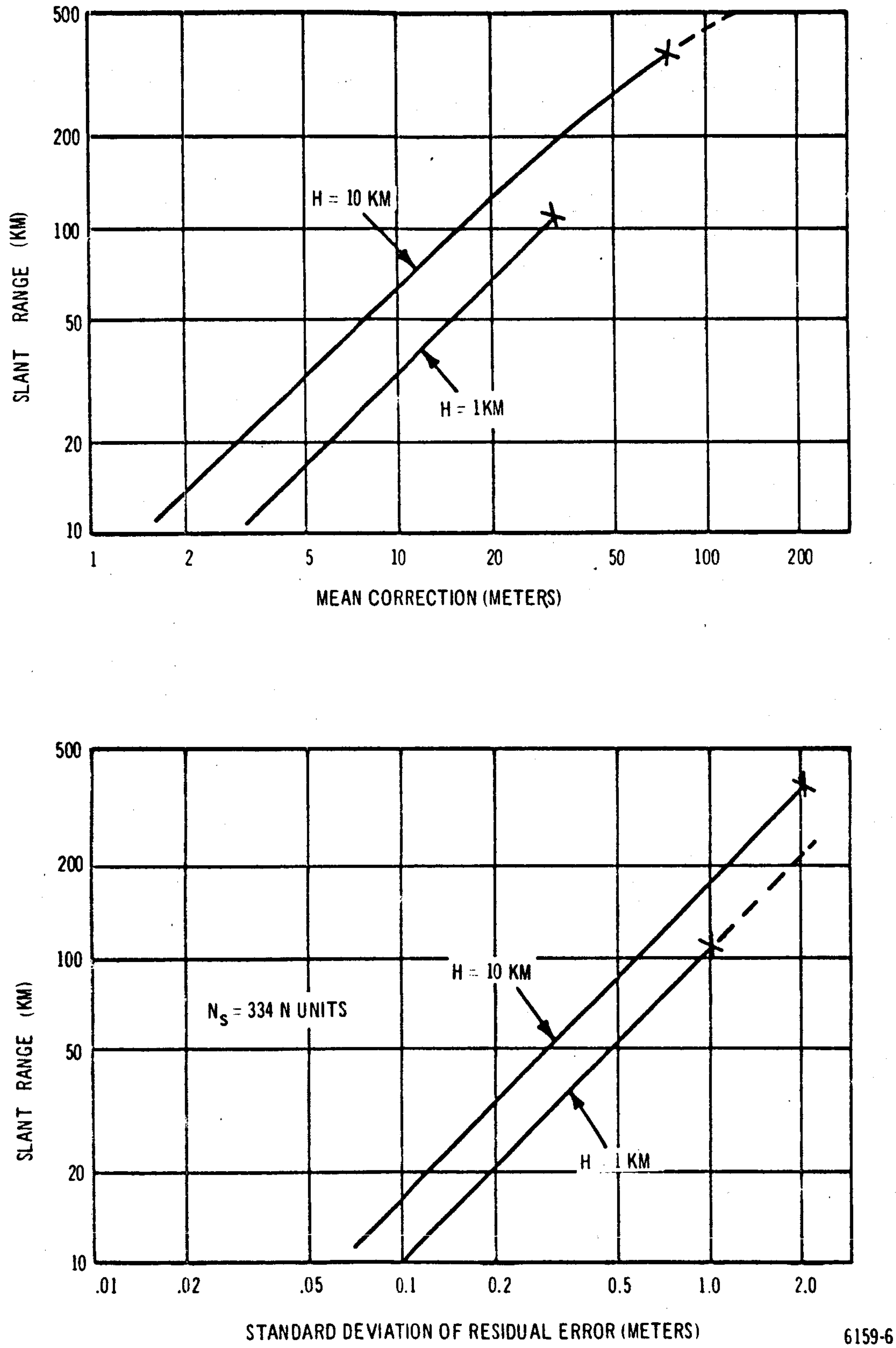


Figure A-5. Typical Tropospheric Range Correction

2.2 PROPAGATION CORRECTIONS

Figure A-5A is a plot of the range correction that is required due to the effect of the troposphere. Figure A-5B shows that residual error to be expected. The method of correction is that suggested by Thayer and Bean of NBS. (G.D. Thayer and B.R. Bean, "An Analysis of Atmospheric Refraction Errors of Phase Measuring Radio Tracking Systems," Part I, NBS Report 7254, U.S. Dept. of Commerce, NBS, Boulder, Colo., 5 June 1962.) The method is as good or better than any other in use.

The magnitudes as shown in Figure A-5 are the corrections and residual errors for a mean surface index of refraction of 334 N units and is the result of 77 profiles measured under a variety of conditions at 13 stations in the United States.

The range correction term, R_c (R, H) is given by

$$R_c(R,H) = A(R, H) + B(R, H)\ N_s$$

Where H is the altitude difference between the two terminals, R is the slant range and N_s is the surface index of refraction. More complicated functions for R_c can be used which use not only surface index but also station height above sea level, h_s, or h_s plus the change in index of refraction, and ΔN, over the first kilometer of altitude above the station. The latter is probably not readily available for the LRPDS application, but by using h_s, the residual range error can be reduced by a factor of about 2/3.

Of prime concern is the value of N_s to use in making the range corrections. Ideally, this correction would use the surface value of each ground station to correct the range to that station. However, this entails measuring N_s at every location and telemetering this value to the aircraft. This is probably not necessary as N_s is highly correlated over very large areas. In general, it takes a change in ground position on the order of 500 km to make the same change as moving vertically 1 km. The value of N_s at any height is essentially

$$N(h) = N_s\ e^{-h/K}$$

Where K is a scale factor equal to about 9 km. The change in H(h) for a change of height of 1 km (equivalent to a range of 500 km) is approximately

$$N(k = 1\text{ km}) - N_s = N_s \left(1 - e^{-h/K}\right) = 334\ N\left(1 - e^{-1.1}\right) =$$
35 N units

The maximum value of B(R, H) for LRPDS geometries is approximately 0.2 which indicates that the error in N_s would produce a range error on the order of 7 meters. While this value seems large, it must be remembered that this occurs at the maximum range at which point the GDOP (see Figure A-3) increases the position uncertainty to 84 meters rms which is well within the specification limit of 175 meters rms.

Since N_s can vary from mean values by as much as ±30 N units for given locations on a day-to-day basis, hourly samples of N_s from the base stations will be adequate.

2.3 LINK CALCULATIONS

The LRPDS system utilizes two-way radio links between the airborne vehicle and both the base stations and forward observer equipments. The received power, P_R, is given by

$$P_R = \frac{P_T \ G_T}{4\pi \ R^2} \left(\frac{G_R \ \lambda^2}{4\pi}\right)$$

Where P_T = transmitted power - watts

G_T = transmitting antenna gain

G_R = receiving antenna gain

R = range, meters

λ = wavelength, meters

Before values are calculated using this equation, it is desirable to discuss the values which affect the received power, P_R.

The extreme values for R vary from a maximum of 558 km, $\left[(550)^2 + (90)^2\right]^{1/2}$, to an assumed minimum range of 3 km (≈10,00C ft) when the vehicle is directly over a base station. This range variation produces a signal dynamic range of 45.4 db.

The transmitting antenna located on the vehicle must be suitable for use with an aircraft. For operation in the 400-MHz region with a propeller driven aircraft, a quarter-wavelength monopole antenna is recommended. It will be approximately 7.4 inches long and can be shaped to minimize the drag on the aircraft. This type of antenna is vertically polarized which is desirable because it tends to reduce the multipath reflections. A monopole antenna, normally has a small, residual, horizontally polarized component.

This is important when the vehicle is directly over a base station because it eliminates the requirement to reorient the base station antenna so that the polarization axes are parallel. When the vehicle is nearly overhead, the range is sufficiently small ($3 < R < 10$ km) so that the base stations can operate satisfactorily with the power received from the residual horizontally polarized component. By mounting the antenna on the bottom of the fuselage, an essentially hemispherical pattern is produced. In the final design, the antenna should be tailored to produce a pattern which tends to reduce the power radiated directly below the aircraft and which helps to direct more power to the distant forward observers and can provide an antenna gain of a few db. In modeling this system, the conservative figure of 0 db was used for the transmitting antenna.

The base stations require hemispherical coverage which can be provided by a vertically polarized 1/4-wave monopole stub similar to that used in the aircraft.

For the forward observers, it is desirable to provide an antenna with more directivity, mainly to reduce reflections and to supply discrimination against interfering signals. The elevation angle varies between approximately 0° and 45° and the included azimuth angle between approximately 78° and 156°. It is desirable that the forward observer should be able to orient the antenna with sufficient accuracy, using only a compass. Thus the antenna is designed with a 3 db beamwidth of 30° in elevation and 140° in azimuth, which provides an antenna gain of approximately 7 db.

The antenna used by the forward observer must be compact, lightweight, and readily assembled in the field. A vertical monopole or stub with a parasitic reflector will provide the desired antenna pattern. Figure A-6 shows the physical dimensions of the antenna. By making the elements telescoping, the antenna may be packaged so that it is compatible with the rest of the system.

The following factors influence the choice of the operating frequency. Higher frequencies are desirable because of

1. Easier frequency allocations.

2. Reduced specular multipath reflections.

Lower frequencies are desirable because of

1. Increased transmitter efficiency.

2. Transmitter is easier to design and build.

3. Reduced frequency uncertainty due to Doppler shift.

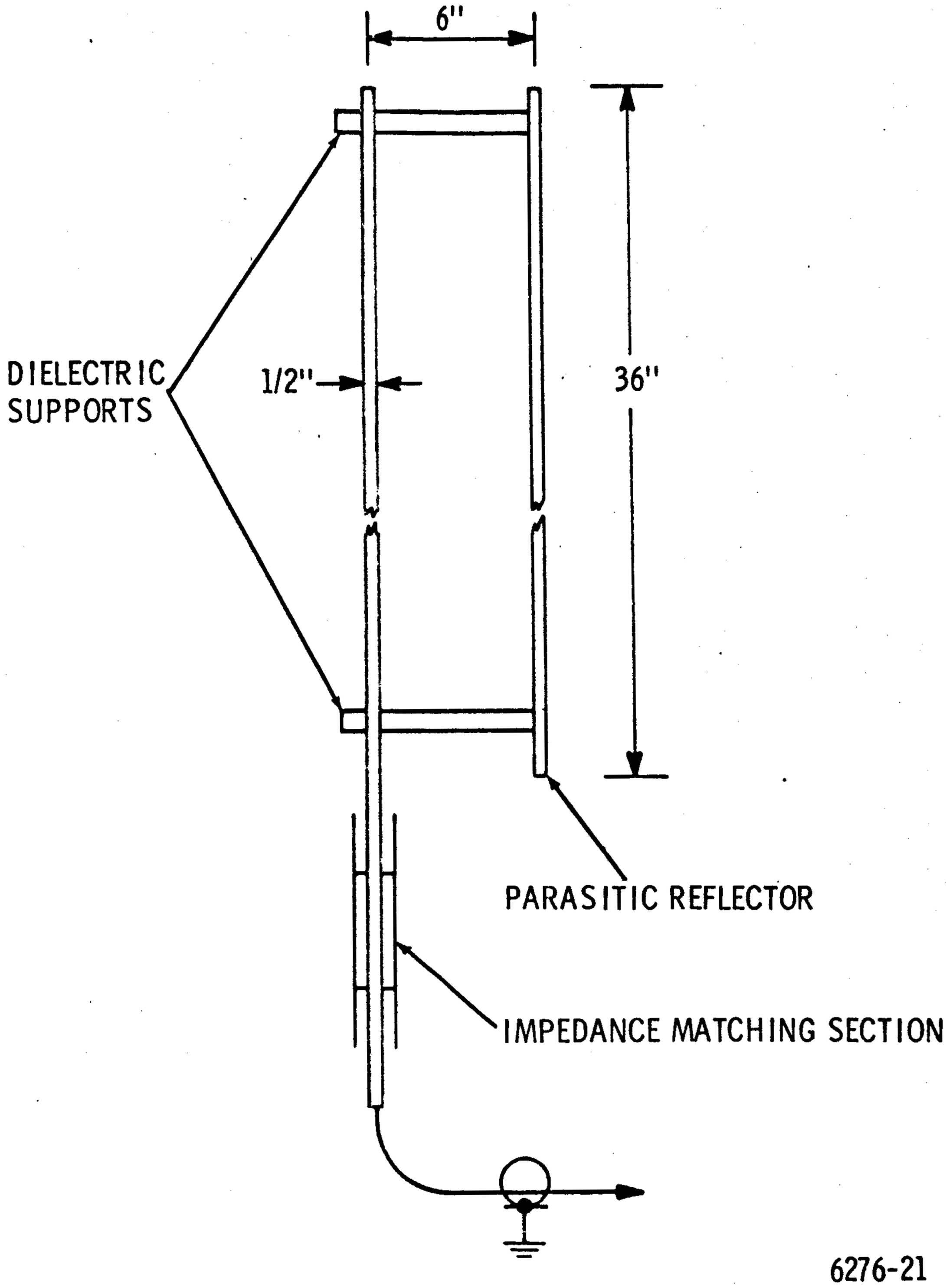


Figure A-6. Base Station Antenna

Since at the present time no frequency band has been assigned, a nominal frequency of 400 MHz was picked as the frequency band of the model, for analysis purposes. It is important to note that the system could be modeled and built for higher or lower frequency operation with approximately the same performance if the available frequency bands required a change.

Using the parameters described above, Figure A-7 shows a curve of received power versus range. The received signal varies from -57 to -102 dbm which produces a 45 db dynamic range.

Both the ground and vehicle use 8 db NF receivers. Assume the forward observer equipment has a 2.0 db line loss and the vehicle equipment has a 0.0 db line loss. The right-hand scale in Figure A-7 shows the SNR (thermal noise) for a 2-kHz bandwidth. At maximum range, a 30 db pure carrier SNR occurs in 2 kHz which indicates that good voice communications are possible even at the maximum range in a 3.5-kHz bandwidth.

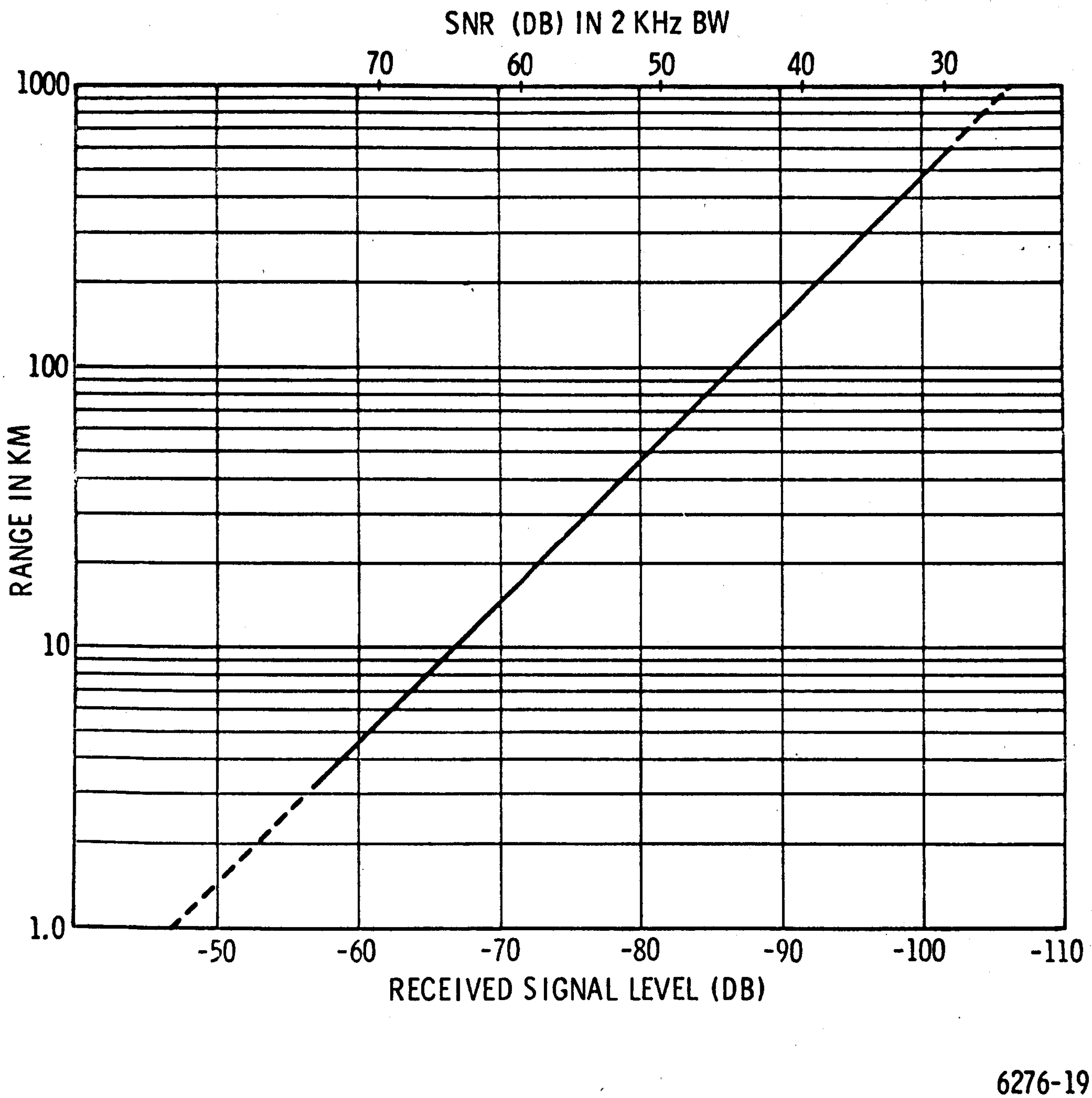


Figure A-7. Received Power vs Range