AD/COM

Final Report

SPECIAL STUDIES OF AROD SYSTEMS, CONCEPTS AND DESIGNS

Contract NAS8-~~20128~~ 20128

October 1967

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

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G-69-F

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1. Scope of the Report

This report constitutes the Final Report on the results of a program of investigations carried out by ADCOM, Inc. under Contract No. NAS 8-20128 for George C. Marshall Space Flight Center, Huntsville, Alabama. The work covered in this program was conducted in close coordination with, and in direct support of, the Astrionics Division, George C. Marshall Space Flight Center in its development of the AROD System.

In view of the timeliness and, sometimes, the urgent need for these investigations, an effort was made to incorporate all the details and results in a series of informal Technical Memoranda so that they would be available for immediate utilization by the cognizant MSFC/NASA personnel. Subsequently, these memoranda were organized and edited into four Technical Reports according to broad subject categories.

The Technical Reports constitute a complete record of all the studies conducted under this contract. The purpose of this final report is then to summarize the accomplishments of the investigations, to show to what extent the objectives were met, and to draw final conclusions and recommendations.

2. Objectives of the Studies

The objectives of the studies were established under Contract No. NAS 8-20128 to be:

> Perform analyses and evaluations of AROD System concepts and of the design of AROD System Test Model hardware, and present analyses, findings, conclusions, and recommendations in the form of technical reports. These studies shall cover the conceptual design, preliminary design, final design, test procedures, and test results of the Test Model hardware, as contained in drawings, specifications, descriptions, and reports. These shall be evaluated with regard to reasonableness of assumptions, soundness of conclusions, completeness, feasibility, efficiency, etc. Particular attention shall be given to multipath and propagation problems, signal design, signal acquisition techniques, and equipment error sources.

The basic approach adopted to achieve the objectives was to investigate signaling and signal processing techniques for the AROD system that will most simply and effectively yield unambiguous range and range rate measurements, within the limitations of existing sources of error, and in harmony with other vehicle and ground station instrumentation functions. The results of the investigations were to aid NASA in the planning, design, and implementation of the AROD tracking system.

3. Summary of First Technical Report

In accordance with the overall technical plan of the AROD program, the main objectives of the work covered in the first Technical Report were to provide analytical evaluations and studies in support of the AROD development effort conducted by Motorola, Inc. Accordingly, this report deals with certain aspects of the system analysis and models presented by Motorola, Inc., in their reports on the AROD system, and presents further investigations of a number of critical system areas.

The second section of this report contains computations of signal and noise levels in the AROD system. The necessary system parameters such as noise temperatures and antenna gains, etc., are explicitly noted and the expressions for computation of the signal and noise levels are given. The signal-to-noise ratios are presented for the Vehicle Tracking Receiver, the Station Control Receiver and its Data Demodulator, at all important locations in these systems. The computations show that the system has sufficient signal-to-noise ratio margin at the maximum range of 2000 km.

Section 3 includes various analyses of the performance of the VTR carrier loop. In Sec. 3.2 the carrier loop model is derived and shown to be similar to a second-order phase-locked loop with different ac and dc gains. In Sec. 3.3 the design relations and performance of an RC-integrator type memory are studied. Finally, Sec. 3.4 covers the effects of switching of the S-band transponder antenna on the VTR. This switching of the antenna causes amplitude and phase steps on the uplink S-band signal. The phase error in the VTR carrier loop due to these effects is obtained.

The range loop performance analyses are contained in Sec. 4. In Sec. 4.2 the effect of uplink data on L-code acquisition is investigated. It is shown in this section that the uplink data can reduce the correlation level of the code nearly 25%. This means that uplink data reduces the system threshold during acquisition. In Sec. 4.3 the combined carrier and range processing scheme used in AROD is analyzed. First the basic model of the processing used in AROD is derived, and the next expressions for variance of the range-measurement noise are obtained. Also derived is an analytical expression showing the bandwidth advantage of the range loop with and without rate aiding.

Section 5 is a noise analysis of the coherent AGC for the VTR carrier loop IF amplifier. An estimate of the amplitude jitter resulting from input noise is presented. This analysis takes into account both the phase error due to noise in the carrier loop and the nonlinear transformation of the Gaussian IF noise by the AGC amplifier.

4. Summary of Second Technical Report

The primary objectives of the Second Technical Report were:

(a) To analyze the performance of the proposed Ground Station Antenna and D/F System, particularly with respect to system noise and hardware limitations.

(b) To identify any deficiencies in the proposed design which would prohibit the system from meeting any of its performance objectives, and

(c) To propose, wherever practicable, design modifications or changes which would result in improved system performance, reduced complexity, etc.

An analysis of Direction-Finding (D/F) System accuracy as related to gain and phase irregularities in one of the system preamplifiers is undertaken in Sec. 2. The equations for system derivation of the signals representing the angular direction of the VHF transmission are first reviewed.

A gain error is then applied to one of the preamplifier channels in the D/F system Z ring, and the resulting system phase measurement error determined. (The phase measurement error ultimately affects the accuracy of S-band antenna steering.) The simplifying approximation is made that the VHF antenna mutual impedances are zero, and graphs are plotted showing the system phase measurement error as a function of the assumed preamplifier gain error.

An assumed phase error is then inserted in one of the Z ring preamplifiers and the analysis process repeated: the system phase measurement error is computed as a function of the assumed phase error in the Z ring preamplifier. Again the simplifying assumption is made that the mutual impedances in the VHF antenna are zero, and graphs are plotted showing the relationship between system phase measurement error and the phase error in one Z ring preamplifier.

In Sec. 3, estimates of signal and noise levels in the D/F system are computed. The minimum input signal level required for proper operation of the D/F system, and the maximum distance over which the initial design D/F system will operate, are first calculated. The amplitude detectors facilitating selection of either Z or XY rings are then examined, and their inadequacy discussed.

Continuing in Sec. 3, the phase meter "threshold" is examined, the threshold being defined as that input signal-to-noise ratio at which the phase meter output becomes unreliable due to noise. A test is described which was performed on the phase meter to be used in the system, and a graph interpreting the test results is presented.

The results of the investigation of two other subsystem components are also reported in Sec. 3. Tests are described for each of these equipments, and the test results interpreted. In tests performed on the proposed amplifier-limiters, the differential phase characteristics were found to vary widely, both as a function of the absolute signal level into the two amplifier-limiters, and as a function of the difference in input signal level between the two devices, one input being held constant. The absence of any limiting was found to occur over most of the input dynamic range of the amplifier-limiters. The test results pointed toward the questionable suitability of these components for the use intended. Tests on reactive (passive) multicouplers showed them to be suitable as signal splitting and summing devices. Isolation between ports of the multicouplers was found to be adequate, and provided the multi-couplers can be included in the calibration scheme, little error is expected to be introduced into the system through their use.

In Sec. 4, various direction-finding receiver techniques are discussed which are intended to overcome some of the basic shortcomings of the D/F receiver undergoing development. Two fundamental receiver designs are presented, both of which utilize local oscillator signals from the Station Control Receiver for removal of doppler. Several methods of achieving the narrow noise bandwidth required of the D/F receiver are presented, included in which are phase-locked loops used as filters, and conventional filters. Acquisition time of phase-locked loops (including both frequency and phase-lock times) is considered, as is derivation of AGC voltages. A brief survey of the various types of conventional filters considered for use in the system is included.

5. Summary of Third Technical Report

Some of the weaknesses in the original AROD ground station direction-finding (D/F) receiver design were discussed in Technical Report No. 2. As a result, the need for a more sophisticated D/F receiver design approach was recognized, and alternate designs, intended to overcome the problem areas characteristic of the original receiver, were presented in that Technical

Report. The alternate designs proposed encompassed the RF section of the D/F receiver.

It is clear that because of the threshold differences between the Station Control Receiver and the Direction-Finding receiver, the D/F receiver design undergoing development is not adequate. Presented therefore, in the Third Technical Report are several alternate D/F receiver designs which will provide the required thresholds, as well as other features highly desirable due to the requirement for long-term stability and other unique requirements characteristic of the D/F system under development.

The Third Technical Report concludes ADCOM's proposed VHF derection-finding receiver design, covering the remaining sections of the receiver requiring definition: phase metering circuits, methods of selection and switching of RF signals, and generation of timing and other control signals. The RF design documented in Technical Report No. 2 is updated and included in this consolidated report on proposed AROD D/F receiver designs.

The following guidelines were adhered to in the development of alternate VHF direction-finding (D/F) receiver designs:

(a) The D/F receiver must function over the operating dynamic range of the AROD Station Control Receiver.

(b) Alternate designs must provide for direct substitution of the new D/F receiver in the presently conceived VHF antenna system.

(c) The requirement for high reliability dictates minimum circuitry consistent with required performance; circuits employed must be within the current state-of-the-art.

(d) Alternate D/F receiver designs must provide for sufficient stability to maintain antenna-pointing position accuracy for long periods of time without the necessity for equipment adjustments or calibration.

Various direction-finding receiver techniques are discussed in Sec. 2 which are intended to overcome some of the basic shortcomings of the original D/F receiver. Two fundamental receiver designs are presented, both of which utilize local oscillator signals from the Station Control Receiver for removal of doppler.

In Sec. 3, several methods of achieving the narrow noise bandwidth required of the D/F receiver are presented, included in which are phase-locked loops used as filters, and conventional filters. Acquisition time of phase-locked loops (including both frequency and phase lock times) is considered, as is derivation of AGC voltages. A brief survey of the various types of conventional filters considered for use in the system is included.

Phase meters with linear sawtooth characteristics are considered in Sec. 4 for use in the D/F receiver. The design of two such phase meters is developed: one utilizing analog integration techniques, and the other employing a type of digital integration. Noise immunity and other requirements of the phase meter zero-crossing detectors is discussed.

In Sec. 5 the criteria and circuits for selection of RF and AGC signals is developed, as is the generation of gating signals to control their routing. Two methods for effecting antenna ring selection are presented, one involving the amplitude comparison of AGC signals from the two rings, and the other, a somewhat more involved technique, utilizing cascaded limiters with different noise bandwidths.

Timing and control signals necessary for the proper functioning of each of the D/F receiver sub-sections are discussed in Sec. 6. The design of a clock signal generation circuit is first presented. Functional control signals required for operation of the digital-type phase meter are next developed. Finally, the logic connections and circuitry for generation of RF routing control signals are shown.

6. Summary of Fourth Technical Report

The specific subjects of the Fourth Technical Report are three:

(a) Evaluation of the signal acquisition procedure employed in the AROD Vehicle Tracking Receiver (VTR).

(b) Evaluation of the ranging errors incurred by propagation through the atmosphere, and of the possibility of correcting them in subsequent data processing.

(c) Consideration of some geodetic aspects relating to position determination with the AROD system, including ground station coordinate system translation and fixing computations required of a vehicle-borne computer.

In Sec. 2 some correlation properties of the AROD ranging code are derived. These properties are central to the discussion of VTR signal acquisition, which is presented in Sec. 3. Here, the emphasis is to explain test results obtained by Motorola, Inc., and to suggest techniques for improving critical phases of the acquisition procedure.

The range errors incurred by propagation through the atmosphere are evaluated in Sec. 4. Both tropospheric and ionospheric error sources are considered. Only simple and approximate bounds to these errors are derived, in order to indicate the magnitude of the problem. The possibility and merits of gross range corrections are then explored.

The AROD vehicle-borne system will include a computer which transforms the tracking measurements into parameters representing the vehicle velocity and position in space, utilizing geodetic information about the location of the transponders. This computation function is considered in detail in Sec. 5. First, geodetic terminology and the basis and meaning of geodetic measurements as related to AROD system fixing are discussed. Next, the mathematics for translation of ground station coordinates to the vehicle-borne computer coordinate system is treated. Finally, the mathematical process of vehicle position determination from station coordinates and AROD system measurements are covered, with a qualitative discussion of expected errors.

7. Conclusions

The investigations summarized in this report indicate that the existing development model of the AROD system performs its functions essentially successfully, with the probable exception of the D/F receiver. Its quantitative achieved performance remains to be evaluated, however, so that comparison with the original system specifications or analytical predictions is not possible at this stage.

It can be seen from the Fourth Technical Report that, in many cases, the theoretical accuracy of the AROD system (possibly even including propagation errors) is at least an order of magnitude better than that with which it is possible to locate ground stations, one with respect to the other. This observation suggests two conclusions:

(a) More accurate ground station surveys may be required in order to employ the full accuracy capabilities of the AROD system, and

(b) It may be possible with the use of the AROD system to perform to the required accuracy these ground station surveys.

This latter possibility offers promise to the geodesist of a powerful new surveying instrument with which it may be possible to connect major datums with considerably better accuracy than present geodetic instrumentation permits.

The problem of the D/F receiver can be solved by development of a new model utilizing some of the techniques described in the Third Technical Report. Alternatively, it may be possible to eliminate the VHF station control link entirely, absorbing its functions into the S-band links. We turn our attention to this possiblity in the remainder of this section.

The desirability of AROD system acquisition, tracking, and ground station control utilizing only two links--a 2.3 GHz downlink and a 1.7 GHz uplink--has been recognized since the outset of the AROD development program. Unfortunately, the problems involved in embodying all of the required AROD system functions in these two links were of such a magnitude when the system was initially conceived that a third link was deemed necessary. This link, operating at a carrier frequency of 138 MHz, has been incorporated in the present system to provide the following three functions:

(a) Direction-finding for angular steering of the ground station S-band antennas.

(b) Coarse doppler extraction at the ground station transponder to aid in tracking link signal acquisition.

(c) Functional control from the vehicle of the ground station transponder.

Recent technological advances suggest that the above three functions could now be absorbed practically into the two S-band links in the present AROD system. Some of the possible approaches for accomplishing this are described below.

7.1 Direction-Finding

The direction-finding function is perhaps the single most important reason for the existance of the VHF station control link. The present method of derivation of the direction-finding signal in the AROD system is that of extraction of phase information from an array of VHF antenna elements. At least three alternative methods suggest themselves for transfer of this D/F function to the 2.3 GHz link:

(a) Provided the AROD system mission can be restricted to vehicles appearing on the horizon always from the same azimuth sector (which may be a reasonable assumption, depending on the station), the electronically steered S-band array could be directed initially toward this azimuth sector. As signal acquisition occurs, monopulse techniques are used for tracking the vehicle transmitting source. Rate memory could also be employed to prevent interruption of angle tracking in the event of temporary loss of signal. An automatic trip mechanism is employed to reset antenna steering to the initial azimuth sector once the vehicle is out of ground station range.

(b) Automatic antenna scanning techniques could be employed--similar to those used in some radar systems--to effect signal acquisition. Thereafter, monopulse tracking techniques would be used.

(c) One of the most attractive S-band D/F techniques involves a minor change in the transmitted modulation of the 2.3 GHz link when all four ground stations are not acquired. For a period of several seconds the down tracking link modulation would remain as it is designed in the present system. Then for a very short period all modulation is removed and only a carrier is transmitted. This sequence is repeated periodically until acquisition of all four stations is achieved, at which time a continuously modulated signal is transmitted. In the absence of modulation the receiver bandwidth can be narrowed to provide sufficient SNR even though the ground station S-band antenna, in its initial state, is omnidirectional. After acquisition, this antenna switches to an electronically steered mode and monopulse techniques are employed for angle tracking.

7.2 Coarse Doppler Extraction

A second function which has been relegated to the VHF link is that of coarse doppler extraction from the VHF received signal to decrease the frequency uncertainty of phase-locked loops in the tracking system. Such a technique enhances greatly the acquisition time of the S-band carrier loop. ADCOM, Inc. has been conducting independent studies on phase-locked loops with rapid acquisition characteristics. A two-speed phase-locked loop with a superior acquisition time characteristic has been developed which appears to have merit for the AROD system, and would permit sufficiently rapid S-band link acquisition when subjected to the doppler offsets normally encountered in the AROD system.

7.3 Ground Station Control

Functional control of the ground station transponder (to STANDBY, OFF, etc.) is presently accomplished by modulation on the VHF link. This function could be transferred to the 2.3 GHz link with relative ease, using the present data-transmission capability of that link.

8. Recommendations

It is recommended that the D/F receiver problems be tackled along one of the two lines described in the previous section, viz. either by development of a new model utilizing the techniques of the Third Technical Report, or by eliminating the VHF station control link entirely, absorbing its functions into the S-band links. In the latter case, a comprehensive investigation is required of the techniques described in the preceding section, and of the system modifications necessary to implement them.

The investigation of geodesic aspects presented in the Fourth Technical Report reveals the need for specific further study concerning the ultimate development of the vehicle-borne computer. Necessary steps in this development process are the following recommended studies, listed in the suggested chronological order of completion:

(1) Exhaustive analysis of errors in the AROD system. As envisioned, this analysis would include all range and range rate errors contributed by delivered AROD equipment, as well as signal propagation errors.

(2) Analysis of the probable error in vehicle position due to AROD system errors (including both equipment and propagation errors), ground station location errors, and geometrical dilution.

(3) Expansion of the analysis presented in Sec. 5.5 of the Fourth Technical Report to include the correction of vehicle position for movement of the vehicle during the signal transit time.

(4) Development of a methodology for obtaining the four-station vehicle solution suggested in the footnote to Sec. 5.5 of the Fourth Technical Report.

(5) An appropriate analysis to develop the methodology for in-flight computation of the vehicle velocity vector.

(6) Development of a coordinate system for in-flight translation of the vehicle position in cartesian coordinates to earth-center form.

(7) Finally, determination of an optimum system design of a special-purpose, vehicle-borne computer whose function is to compute the vehicle velocity vector and vehicle position corrected for vehicle movement during the signal transit time, then translate this information in cartesian form to earth-center polar form.