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GUIDANCE SUBSYSTEMS WITH POSITION MEASUREMENT FOR GLIDING AIRDROP SYSTEMS

C. F. Olenberger

THE RAYTHEON COMPANY
MISSILE SYSTEMS DIVISION
HARTWELL ROAD,
BEDFORD, MASSACHUSETTS

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AUGUST 1978

UNITED STATES ARMY
NATICK RESEARCH and DEVELOPMENT COMMAND
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The objective of this work has been to assess guidance techniques and available hardware which are suitable for gliding airdrop systems. Information presented indicates the suitability of available hardware for measuring required flight data, processing these data according to one of several alternative guidance schemes and activating control lines as required to guide a gliding airdrop system.

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PREFACE

This report was prepared by Raytheon Company, Missile Systems Division, Hartwell Road, Bedford, Massachusetts, under Contract No. DAAK60-78-C-0022 with the USA Natick Research and Development Command, Natick Massachusetts. It is submitted to satisfy the contractual requirement for a Technical Final Report covering the Phase I and Phase II efforts (January 13, 1978 to August 25, 1978), as specified in the Contract Data Requirements List, Sequence No. A003 (DD1423, 24 June 1977).

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1. INTRODUCTION

The parachute provides the conventional means for delivering payloads from an aircraft to a ground site where the aircraft cannot or would rather not land. One problem with a parachute is that, given a ground target to which the payload must be delivered, there is only one point (for a given altitude and wind profile) from which the parachute can be deployed. This problem is a consequence of the parachute's lack of maneuverability.

A gliding airdrop system provides another means for delivering payloads from an aircraft to a ground site. These systems are deployed from an aircraft in flight in the same manner as conventional parachute systems are deployed. The payload is extracted from the aircraft and a canopy is drawn out of a pack and inflated. The payload then rides suspended below the canopy until landing. Unlike the parachute, however, the gliding canopy is specially constructed to produce forward motion as it descends and to execute controlled turns. This capability to maneuver gives rise to a large area (or "deployment window") from which the gliding airdrop system can be deployed with the stated goal of reaching a given ground target.

Given the maneuverability of the gliding airdrop system, we would like not only to steer it to a designated landing site, but also to have it heading into the wind upon landing, so as to reduce the landing speed. To achieve these goals, we need:

1) A guidance law

2) Techniques and hardware for acquiring and processing the data required by the guidance law, and

3) A method and hardware for actuating control lines in response to a signal derived by the guidance law.

The U.S. Army Natick R&D command has developed several guidance laws which are discussed in detail in the literature.[1,2] Briefly, these are as follows:

1) "Radial homing", in which the gliding system's airspeed vector is continuously aligned with the line of sight to the target. In the fixed-wind coordinate system, this is analogous to "pursuit navigation" in the missile-guidance field.[3] This method requires the least amount and sophistication of peripheral equipment.

2) "Azimuth Homing",[4] in which the gliding system's airspeed vector is maintained at some fixed angle with respect to the line of sight to the target. This method encompasses the specific case of radial homing, and, in the wind-fixed coordinate system, this method is analogous to "deviated-pursuit" in the missile-guidance field.[3]

3) "Cone-of-silence homing", which is basically radial homing, modified by a cone of silence over a target-based beacon.

---

[1] Goodrick, Pearson, and Murphy, "Analysis of Various Automatic Homing Techniques for Gliding Airdrop Systems with Comparitive Performance in Adverse Winds," AIAA Paper No. 73-462, AIAA Aerodynamic Deceleration Systems Conference, 1973.

[2] NARADCOM RFP No. DAAK60-78-C-0022, 22 August 1977.

[3] A.S. Locke, Ed., Guidance, Princeton, N.J.: Van Nostrand, 1955.

[4] A.L. Murphy, Jr., "Azimuth Homing in a Planar Uniform Wind," TR74-42-AD, AD780-015, U.S. Army Natick Laboratories, 1973.

4) "Conical homing," which uses radial homing with the addition of elevation angle.

5) "Direct homing", which results in a straight, wind-compensated flight to the target. In the wind-fixed coordinate system, this is analogous to "lead-collision navigation" in the missile guidance field.[3]

6) "CHM5", which uses a completely described mathematical path from a wide range of initial positions down to a landing at the target facing into the wind.

7) "Directed Radial Homing", which accommodates such factors as irregular landing zones and nearby hills or towers.

NARADCOM has also developed a computer simulation for evaluating the performance of these guidance laws in terms of miss distance and landing groundspeed. The results of this simulation are discussed in Reference 1.

Many techniques for trajectory instrumentation[5] and remote control, along with the associated hardware, have been developed, but have never been applied to the automatic control of gliding airdrop systems.

The objective of this contract has been to assess guidance techniques and available hardware which are suitable for gliding airdrop systems. Information resulting from this contract will indicate the suitability of available hardware for measuring required flight data, processing these data according to one of several guidance schemes, and activating control lines as required to guide a gliding airdrop system.

---

[5] See, for example, N. Lawhead, "Position Location Systems Technology," IEEE Position Location and Navigation Symposium, 1976.

The program comprised two phases of 14 weeks each: Phase I, from January 13 to April 21, and Phase II, from May 12 to August 25.

Phase I, or the preliminary study, was intended for the consideration of a wide range of techniques and related devices in limited detail. Here, we identified readily available components for signal generation, signal acquisition, data processing, steering, and control actuation. Particular attention was directed at methods of acquiring any set of parameters that would specify the gliding airdrop system's position vector (relative to the target), its airspeed vector, and its inertial velocity vector.

Phase II, or the system design study, produced a detailed equipment list and specifications for five guidance subsystems selected by NARADCOM during their three-week interim review. Table 1-1 lists the selected subsystems and the characteristics of each. The subsystem designations (3a, 3b, 1b, 2c, or 4) are carried on from the Phase I report.

This technical final report describes these subsystems in detail. Sections 2, 3, 4, 5, and 6 describe subsystems 3a, 3b, 1b, 2c, and 4, respectively. Section 7 describes airborne sensors for measuring heading, altitude, airspeed, and sideslip. Section 8 describes the command link, which allows a ground-based operator to override the computed steering commands at close ranges. Section 9 describes a single-board computer for airborne computation. Section 10 discusses pneumatic and electric actuators for operating the control lines. Section 11 gives conclusions and recommendations for follow-on work.

TABLE 1-1 CHARACTERISTICS OF SELECTED GUIDANCE SUBSYSTEMS

Guidance Subsystem	Plan-Position Fixing Scheme	Measurement Site	Computation Site
3a	rho-rho	ground-based	ground-based
3b	rho-rho	airborne	airborne
1b	rho-theta	ground-based	ground-based*
2c	theta-theta	airborne	airborne
4	(homing)	airborne	airborne

* Section 4 discusses an alternative in which steering commands are computed on the vehicle (airborne).

2. GUIDANCE SUBSYSTEM 3a

2.1 General Description

An airdrop vehicle's position can be determined by measuring the three ranges between that vehicle and three known ground sites. Each range measurement defines a hemisphere around the corresponding site. The intersection of three such hemispheres provides a fix. This trilateration concept is basis for guidance subsystem 3(a), a deployed version of which is depicted in Figure 2-1.

Guidance subsystem 3(a) uses a C-band Motorola MR-III (Mini-Ranger III) Tracking System to

1) measure the three ranges;
2) provide a data link from the vehicle to the ground;
3) compute steering commands, based on this information, at one of the ground sites according to a particular guidance law; and
4) transmit these commands back to the vehicle.

Vehicles are interrogated individually, with each assigned a unique address, allowing the system to control several vehicles simultaneously. The command link allows a manual command override, permitting remote control by an observer on the landing zone.

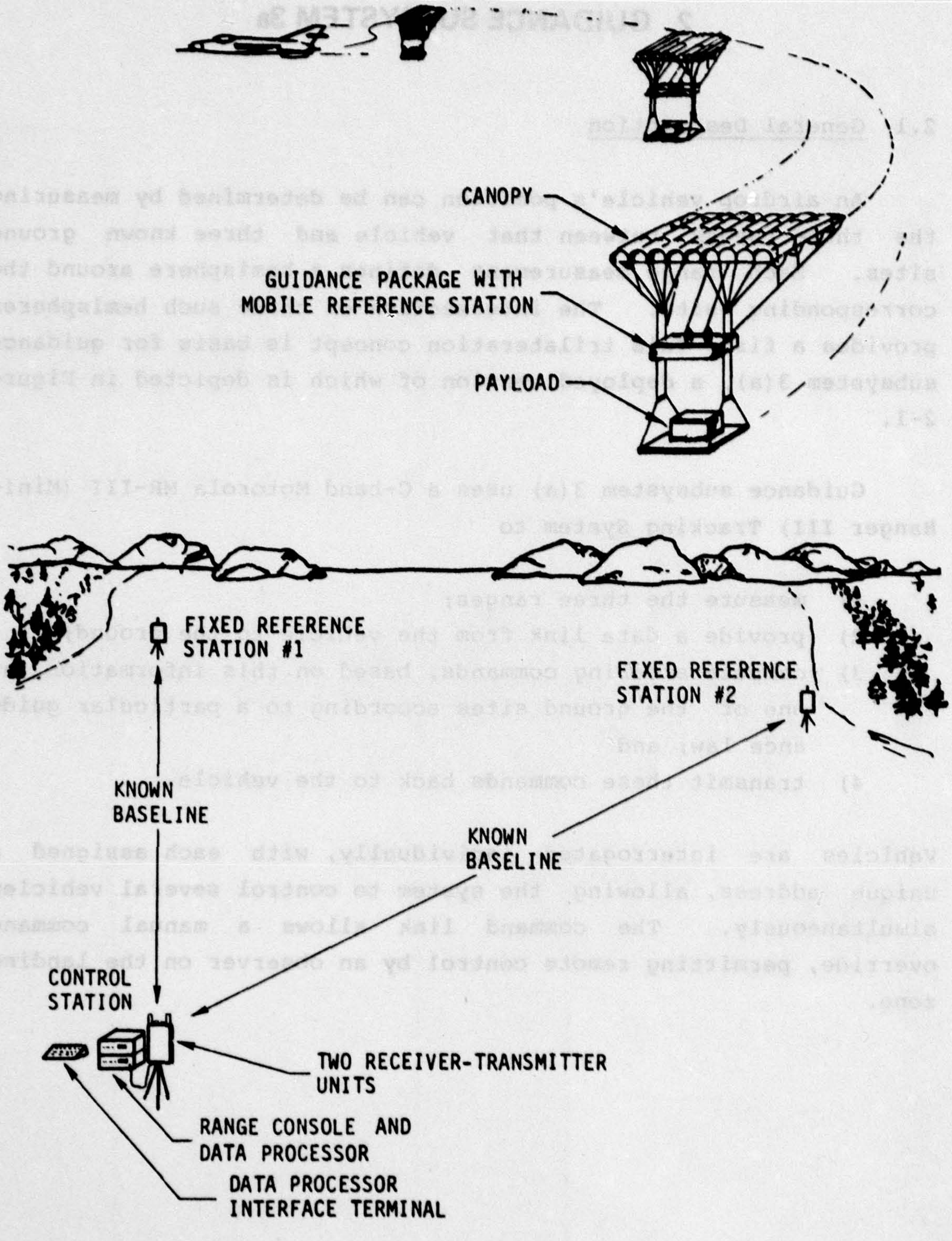

CANOPY
GUIDANCE PACKAGE WITH
MOBILE REFERENCE STATION
PAYLOAD
FIXED REFERENCE
STATION #1
FIXED REFERENCE
STATION #2
KNOWN
BASELINE
KNOWN
BASELINE
CONTROL
STATION
TWO RECEIVER-TRANSMITTER
UNITS
RANGE CONSOLE AND
DATA PROCESSOR
DATA PROCESSOR
INTERFACE TERMINAL

Figure 2-1 - A Deployed System Using Guidance Subsystem 3(a)

The airborne guidance package consists of the following:

1) a compass (section 7.1)
2) an altimeter* (section 7.2)
3) an airspeed and direction indicator (section 7.4)
4) an MR-III mobile reference station with two-way data link capability
5) an actuator with a follow-up potentiometer (section 10), and
6) a power supply.

The ground equipment consists of

7) an MR-III range console
8) two MR-III coded fixed reference stations
9) an MR-III data processor
10) a data processor interface terminal, and
11) a power supply.

The MR-III tracking system comprises the special equipment, which will be discussed in the following sections.

2.2 Special Equipment

2.2.1 MR-III Tracking System

The basic MR-III Tracking System, shown in Figure 2-2, uses pulse radar to locate the position of a vehicle with respect to a known baseline. (The present application requires the system's multiple baseline capability, which will be discussed later.) At one end of the baseline is a "control station" consisting of a range console and two receiver-transmitter units. At the other end is a "fixed reference station". The vehicle carries a "mobile reference station". Line-of-sight contact between the control station and each reference station, and between the reference stations themselves, must be maintained.

---

*Although altitude can be computed through trilateration, the resulting accuracy can be quite poor due to the so-called "geometric degradation of precision". This, along with the need for a rate-of-descent indication, dictates the need for an altimeter.

One of the receiver-transmitter units at the control station interrogates the mobile unit. When the mobile unit receives the interrogation, it transmits a reply. The control station receives the reply, and computes a range to the vehicle based on the elapsed time betwen the interrogation and the reply. This range is displayed on channel A of the range console, and is made available for data processing at the console's back panel.

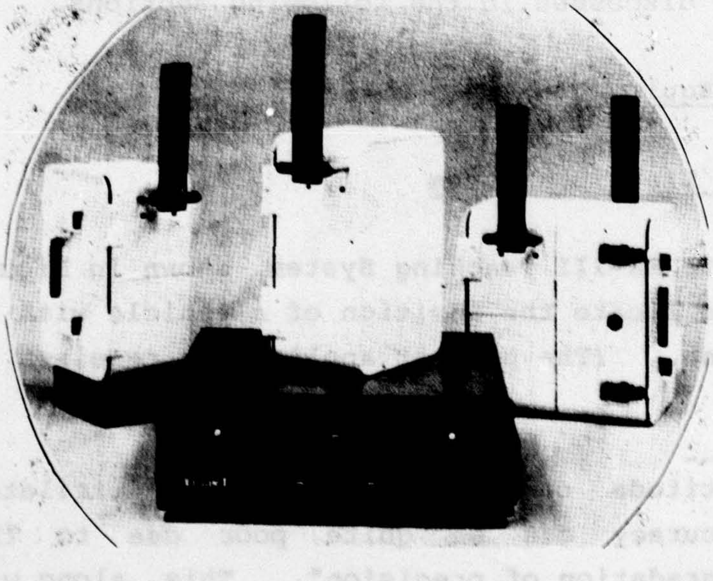


Figure 2-2 - The Basic MR-III Tracking System

The mobile unit's reply to a second interrogation is received by the fixed station which retransmits it to the control station. The control station's other receiver-transmitter receives the fixed station's reply, and the control station computes a loop range from the elapsed time. The display on channel B of the range console is one-half the distance around the loop; this information is also made available for data processing at the console's back panel.

The distance from the fixed station to the mobile station is computed as the loop range, minus the baseline range, minus the range from the control station to the mobile station. If the vehicle's position is confined to a known plane (for example, the surface of the earth), then this system will determine that position, with an ambiguity concerning to which side of the baseline the vehicle lies. This ambiguity is normally resolved by an observer at the control station, or by previous knowledge of the vehicle's position.

In the present application, the "known plane" is established by a barometric altimeter on board the gliding airdrop vehicle. The plane is at the measured altitude above the desired landing point, and parallel to the earth's surface. Furthermore, the two-point ambiquity is resolved by a second baseline. One might argue that the second baseline provides a three-dimensional fix without the need for an altimeter; how ever, the errors inherent in deriving altitude through trilateration can be unacceptably large.

In addition to resolving the ambiguity, the second baseline provides two other benefits:

1) Once the ambiguity is resolved, the system will be able to track the vehicle using a single baseline, should measurements relative to the other baseline be lost (e.g., should the line-of-sight between a fixed station and the mobile station become obscured).

2) Two baselines reduce the uncertainty resulting from "geometric degradation of precision". This is demonstrated in Figure 2-3.

A second fixed reference station provides the second baseline, which shares the control station with the first baseline as a common endpoint. To distinguish one from the other, the two fixed reference stations are coded; by addressing the proper fixed reference station, the control station can measure the corresponding loop range. The choice of the baseline can be dialed into the front panel of the range console, but in the present application, the baseline selection would alternate under computer control through the back panel.

The same approach is used to track multiple vehicles. To distinguish one vehicle from another, each mobile reference station is coded; the control station can then locate any vehicle by encoding the interrogation with the proper address. A choice of one of up to 16 vehicles can be dialed into the front panel of the range console, but in the present application, the vehicle selection would be commutated under computer control through the back panel.

In addition to tracking each vehicle, the MR-III in this guidance subsystem provides a data link to acquire data (compass heading, airspeed, sideslip, altitude, altitude rate, and actuator follow-up from each vehicle) for guidance computation, and a command link to transmit guidance commands back to each vehicle. The system has the capability of encoding four bits of vehicle data onto each reply, and of encoding four bits of command onto each interrogation. The control station normally averages five interrogations to obtain a range measurement, and three range measurements are required for a fix; therefore, 60 bits of information can be transmitted and received per fix. Actually, there is some overhead involved; 12 of these bits are used for framing and error checking, so that only 48 bits are available

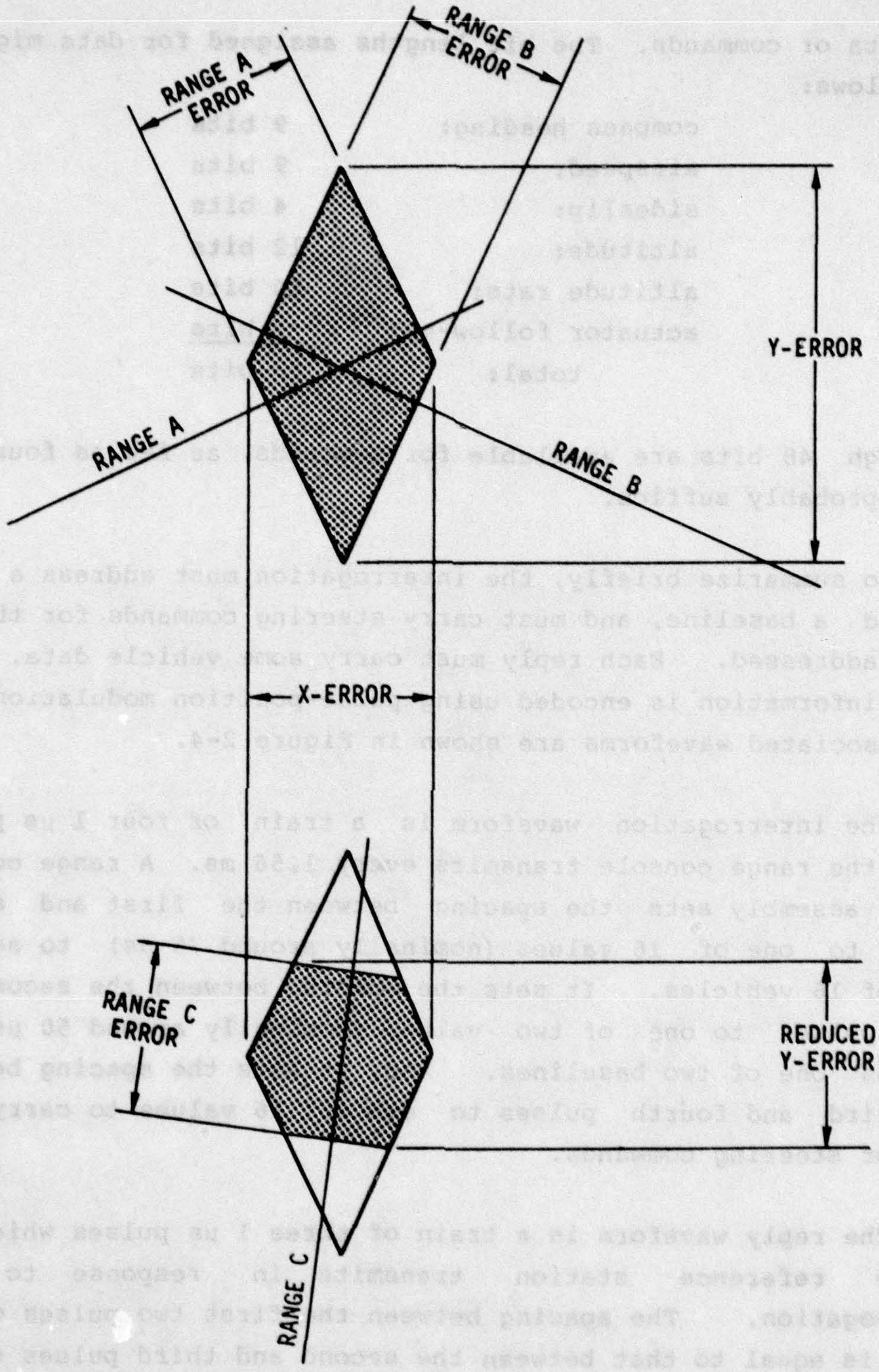

RANGE B ERROR
RANGE A ERROR
Y-ERROR
RANGE A
RANGE B
X-ERROR
RANGE C ERROR
REDUCED Y-ERROR
RANGE C

Figure 2-3 - Geometric Degradation of Precision and How it is Reduced with a Second Baseline

for data or commands. The bit lengths assigned for data might be as follows:

compass heading:	9 bits
airspeed:	9 bits
sideslip:	4 bits
altitude:	12 bits
altitude rate:	10 bits
actuator follow-up:	4 bits
total:	48 bits

Although 48 bits are available for commands, as few as four bits would probably suffice.

To summarize briefly, the interrogation must address a vehicle and a baseline, and must carry steering commands for the vehicle addressed. Each reply must carry some vehicle data. All this information is encoded using pulse-position modulation, and the associated waveforms are shown in Figure 2-4.

The interrogation waveform is a train of four 1 μs pulses which the range console transmits every 1.56 ms. A range console coder assembly sets the spacing between the first and second pulses to one of 16 values (nominally around 75 μs) to address one of 16 vehicles. It sets the spacing between the second and third pulses to one of two values (nominally around 50 μs) to address one of two baselines. And, it sets the spacing between the third and fourth pulses to one of 16 values to carry four bits of steering commands.

The reply waveform is a train of three 1 μs pulses which the mobile reference station transmits in response to the interrogation. The spacing between the first two pulses of the reply is equal to that between the second and third pulses of the interrogation. The mobile reference station coder sets the spacing between the second and third pulses of the reply to one of 16 values to carry four bits of data back to the range console.

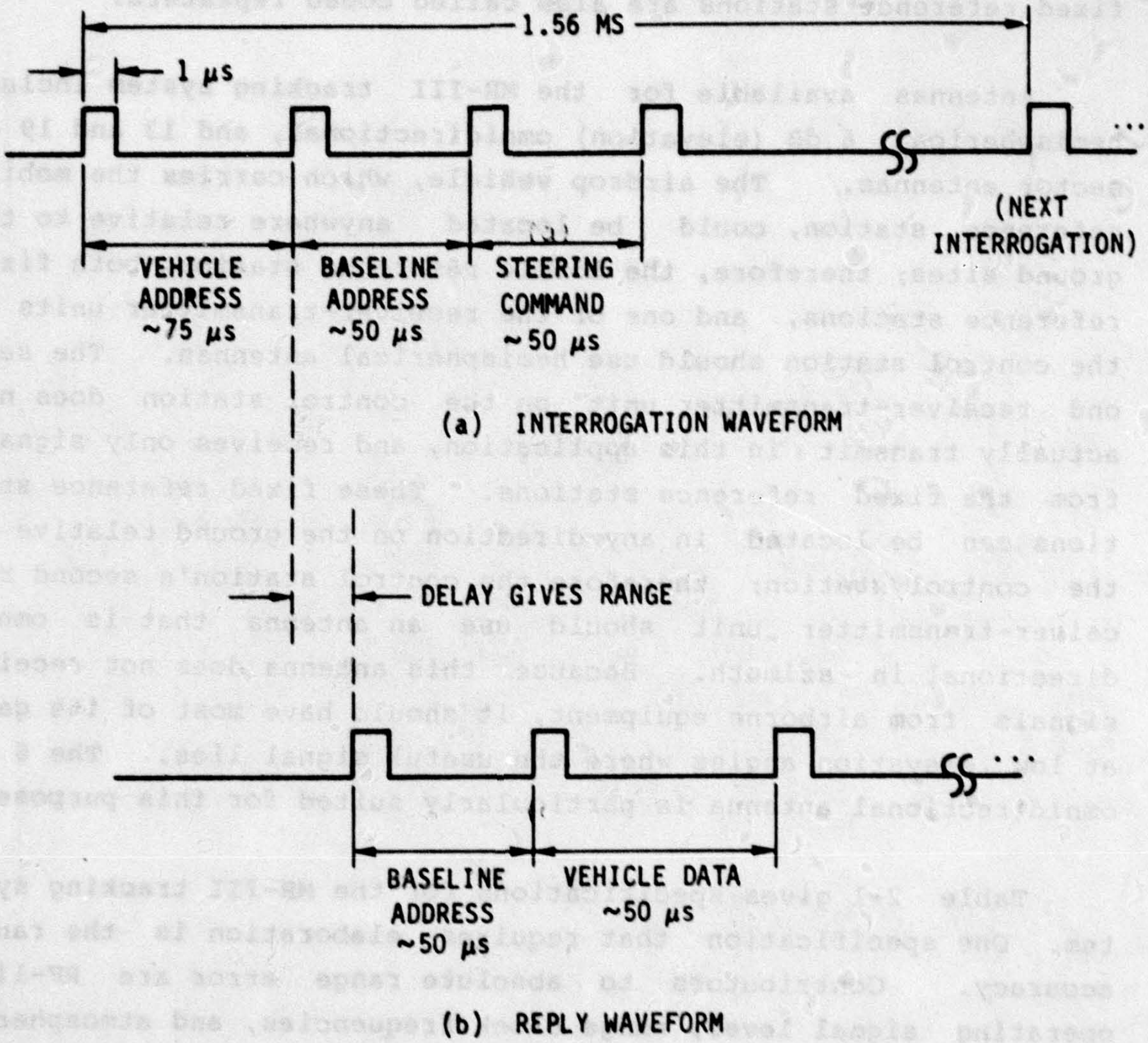

1.56 MS
1 μs
VEHICLE ADDRESS ~75 μs
BASELINE ADDRESS ~50 μs
STEERING COMMAND ~50 μs
(NEXT INTERROGATION)
(a) INTERROGATION WAVEFORM
DELAY GIVES RANGE
BASELINE ADDRESS ~50 μs
VEHICLE DATA ~50 μs
(b) REPLY WAVEFORM

Figure 2-4 - Waveforms for (a) Interrogation and (b) Reply

This reply waveform is also received by both fixed reference stations. The baseline code (the spacing between the first and second pulses of the reply waveform) will cause the appropriate fixed reference station to retransmit the reply to the control station for the loop range measurement. For this reason, the fixed reference stations are also called coded repeaters.

Antennas available for the MR-III tracking system include hemispherical, 6 dB (elevation) omnidirectional, and 13 and 19 dB sector antennas. The airdrop vehicle, which carries the mobile reference station, could be located anywhere relative to the ground sites; therefore, the mobile reference station, both fixed reference stations, and one of the receiver-transmitter units on the control station should use hemispherical antennas. The second receiver-transmitter unit on the control station does not actually transmit in this application, and receives only signals from the fixed reference stations. These fixed reference stations can be located in any direction on the ground relative to the control station; therefore the control station's second receiver-transmitter unit should use an antenna that is omnidirectional in azimuth. Because this antenna does not receive signals from airborne equipment, it should have most of its gain at low elevation angles where the useful signal lies. The 6 dB omnidirectional antenna is particularly suited for this purpose.

Table 2-1 gives specifications for the MR-III tracking system. One specification that requires elaboration is the range accuracy. Contributors to absolute range error are RF-link operating signal level, range clock frequencies, and atmospheric propagation properties. Many factors in turn contribute to each of these. Temperature and aging influence clock frequencies. The RF link signal level is influenced by RF transmit/receive power, sensitivities, and frequencies; antenna gain and aiming; and environmental multipath signal cancellation. Atmospheric properties influence the velocity of radar propagation and hence absolute accuracy.

TABLE 2-1 MR-III TRACKING SYSTEM SPECIFICATIONS

Operating Frequency	5400 to 5600 MHz
Accuracy	±3 meters probable range error
Number of Baselines (Fixed Stations)	1 standard, 3 optional
Number of Coded Mobiles	4 standard, 16 optional; can be increased by adding more control station/fixed stations combinations at different frequencies
Operating Range	Depends on antennas used at either end. Ranges for various combinations listed:

Combination	Range
6 dB omni/6 dB omni standard	19 km (10 nmi)
6 dB omni/13 dB Sector	37 km (20 nmi)
6 dB omni/19 dB Sector	75 km (40 nmi)

Area of Coverage	Depends on which antennas are used

Antenna	Angle of Coverage
6 dB Omni	360° azimuth, 25° elevation
13 dB Sector	80° azimuth, 15° elevation
19 dB Sector	80° azimuth, 15° elevation

MOBILE STATIONS AND FIXED STATION

Power	13 watts (nominal) at 24 to 30 Vdc
Weight	2.3 kg (5 pounds)
Operating Temperature	54° to +71°C
Dimensions	14 x 26 x 17 cm (5.5 x 10.3 x 6.5 in.)
Antenna	Standard - 6 dB omni-directional
Codes	4 standard, 16 optional

TABLE 2-1 MR-III TRACKING SYSTEM SPECIFICATIONS (CONT.)

CONTROL STATION RANGE CONSOLE

Range Readout	6 digit both Channel A and B in meters (std), yards or feet (optional)
Power	77 watts at 115/230 Vac, 50 to 400 Hz or 57 watts at 24 to 30 Vdc (specified at order)
Operating Temperatures	0° to 50°C
Dimensions	43 x 46 x 14 cm (17 x 18 x 5.5 inches)
Weight	14.5 kg (32 lbs)
Codes	4 standard, 16 optional

CONTROL STATION RECEIVER/TRANSMITTER

Power	Supplied by Range Console
Cable Length	7.6m (25 ft) standard, up to 305m (1000 ft) on order
Operating Temperature	-40° to +60°C
Dimensions	16 x 24 x 17 cm (6.3 x 9.3 x 6.3 inches)
Weight	2.3 kg (5 lbs)
Antenna	Standard - 6 dB omni directional
Code Control	4 standard, 16 optional

The MR-III is specified to produce a range reading within a probable three meter error after adequate calibration; that is, over the range of signal levels and environmental conditions to be experienced in actual operation, 50 percent of all readings would be within three meters of the true value.

Over an interval of a few seconds, the contributors to range accuracy and the associated range error would be fairly constant. Thus, velocity estimates computed by differencing successive range measurements would be unaffected by these errors. However, the system's range repeatability does affect the velocity estimate. Repeatability refers to the consistency with which the system will measure a fixed range from one interrogation to the next. This characteristic is unrelated to accuracy as described above. Contributors to repeatability performance include system jitter and range resolution.

The standard system averages five interrogations to generate a range measurement. The noise, or "jitter" is uncorrelated from one interrogation to the next; it gives rise to a range measurement that has a roughly gaussian density distribution with a standard deviation of 0.75 meters.

The other contributor to repeatability is range resolution. The standard system resolution is one meter; this is the least significant bit on the back panel connector, and the least significant digit on the front panel readout. Therefore, there exists a plus or minus 0.5 meter ambiguity in the range output due to the system's resolution.

Another specification that requires elaboration is the operating range. The operating range for any interrogator-transponder system is halved for every 6 dB loss of antenna gain at either end. This is reflected in the specifications of Table 2-1. The price we pay for hemispherical coverage (0dB/0dB hemi combination) is a net loss of 12 dB in antenna gain relative to the standard system, which has an operating range of 19 km. The operating range for our system with hemispherical coverage is therefore reduced to 4.75 km. This is about one-third of the maximum range at which airdrop-vehicle control is required.

The "operating range" as defined by the manufacturer, however, is not actually the maximum range at which the system will operate. Rather, it is the maximum range at which the specified accuracy of $\pm$ 3 meters is maintained. In the present application, we can tolerate degraded accuracy at longer ranges, and operate out to the receiver threshold. The corresponding "threshold" range is calculated using the range equation for a radar beacon:

$$R = \frac{P_T \, G_T \, G_R \, \lambda^2}{(4\Pi)^2 \, S} \, ,$$

where, in this system, P_T = 400 watts is the peak power of the magnetron transmitter, $G_T = G_R$ = 0dB are the gains of the transmitting and receiving antennas, λ = .055 meters is the wavelength of the radiation, and S = -100 dBW is the receiver sensitivity.

The threshold range is calculated in Table 2-2 to be 8.7 km. The estimated accuracy at this range would be $\pm$ 15 meters.

As shown in Figure 2-5, this threshold range falls short of satisfying the requirements for the gliding airdrop application for vehicle elevation angles between 18° (the minimum elevation for a vehicle with a 3:1 glide slope) and 44° (the maximum elevation for a vehicle at a 8.7 km slant range). These "corners" might be reached, however, by providing the antenna with a ground plane. This would reduce the antenna gain at low elevation angles, where it not needed, and increase it at the critical elevation angles, as shown by broken lines in the figure.

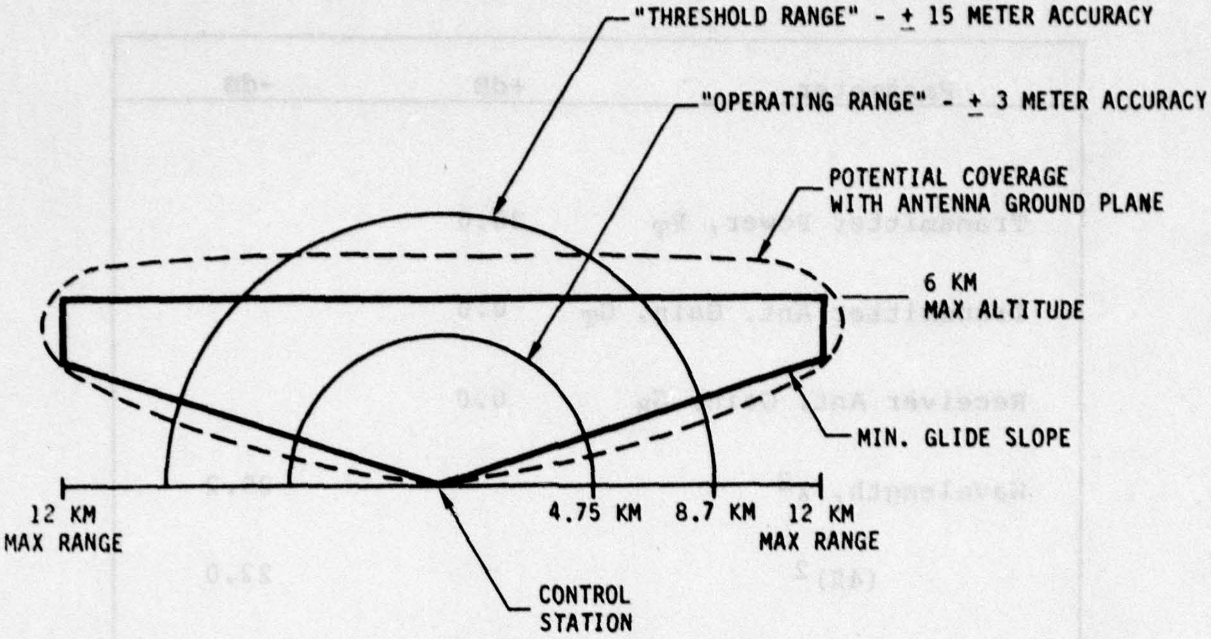
TABLE 2.2 CALCULATION OF THE THRESHOLD RANGE FOR THE MR-III TRACKING SYSTEM

Parameter	+dB	-dB
Transmitter Power, P_T	26.0	
Transmitter Ant. Gain, G_T	0.0	
Receiver Ant. Gain, G_R	0.0	
Wavelength, λ^2		25.2
$(4\Pi)^2$		22.0
Receiver Sensitivity, S	100.0	
	126.0	47.2

$R^2 = 126.0 - 47.2 = 78.8$ dB meters^2

$R = 39.4$ dB meters

$= 8.7$ km


"THRESHOLD RANGE" - ± 15 METER ACCURACY
"OPERATING RANGE" - ± 3 METER ACCURACY
POTENTIAL COVERAGE WITH ANTENNA GROUND PLANE
6 KM MAX ALTITUDE
MIN. GLIDE SLOPE
12 KM MAX RANGE
4.75 KM
8.7 KM
12 KM MAX RANGE
CONTROL STATION

REQUIRED CAPABILITY IS DEFINED BY BOLD LINES

Figure 2-5 - Range Capability of the MR-III Tracking System

2.2.2 MR-III Data Processor

The Mini-Ranger Data Processor (MRDP) is the central control and computing element of the Mini Ranger III Automated Positioning System. The MRDP is a microcomputer system based upon the Motorola 6800 family of microprocessor products. It processes range data from the Mini Ranger III using coordinate and control information entered from the operator's terminal and correlates this data with external data to compute system position in other coordinates and record system information.

The MRDP specifications are given in Table 2-3. Figure 2-6 shows the front panel and some of the circuit boards. The system description below was abstracted from the MRDP Operation and Installation Manual.[6]

The primary function of the MRDP Automatic Positioning System is to gather positioning information from the Mini Ranger III in the form of ranges to known points and, from that range data, compute the position of the system in the user's grid coordinate system.

The system can also gather other data such as time and depth and correlate this data with the position data. The data may then be output to an optional storage medium such as magnetic tape, a printer, or a plotter.

As a third function, the system can compare the present position with a previously planned line and output the result in the form of guidance information, which is used to position the system. The combination of these three functions is the basis for most automatic positioning systems' applications.

The most basic MRDP positioning system consists of a range input device (MRS-III), the Data Processor, and an operator's terminal. All operator communication with the system is accomplished through the use of a standard data terminal connected to the processor through a standard USASCII serial data line. This interface is compatible with the EIA RS-232C interface standard and also with a standard 20 MA current loop interface. Thus, a wide range of data terminal devices may be used with the system.

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[6] "Operation and Installation Manual Mini Ranger Data Processor Automatic Positioning System" Document 68-P02525F Revision A; Motorola Government Electronics Division, 8201E. McDowell Rd., Scottsdale Ariz., 85252, 15 November 1976.

TABLE 2-3 MINI-RANGER DATA PROCESSOR SPECIFICATIONS

Operating Speed	1.0 μsec basic cycle time
Memory capacity	Up to 64 kilobytes 12 or 16 kilobytes standard programmable read-only memory
Computational accuracy	40 bits binary precision plus 8 bits exponent and sign
Position fixing interval	0.5 sec
Operator interface	Serial ASCII, 10 or 30 characters per second. RS-232C and/or 20 mA current loop compatible.
Input/Output	9I/O connectors available TTL compatible, parallel BCD interface, standard
Time-of-day clock	Internal, 24-hour crystal controlled. Settable through operator's console.
Operating voltage	115/230 VAC, 50-400 Hz 24 VDC optional
Power input	100 watts, maximum
Physical dimensions	44 x 46 x 14 cm
Weight	16 KG
Operating temperature range	0 to +50°C

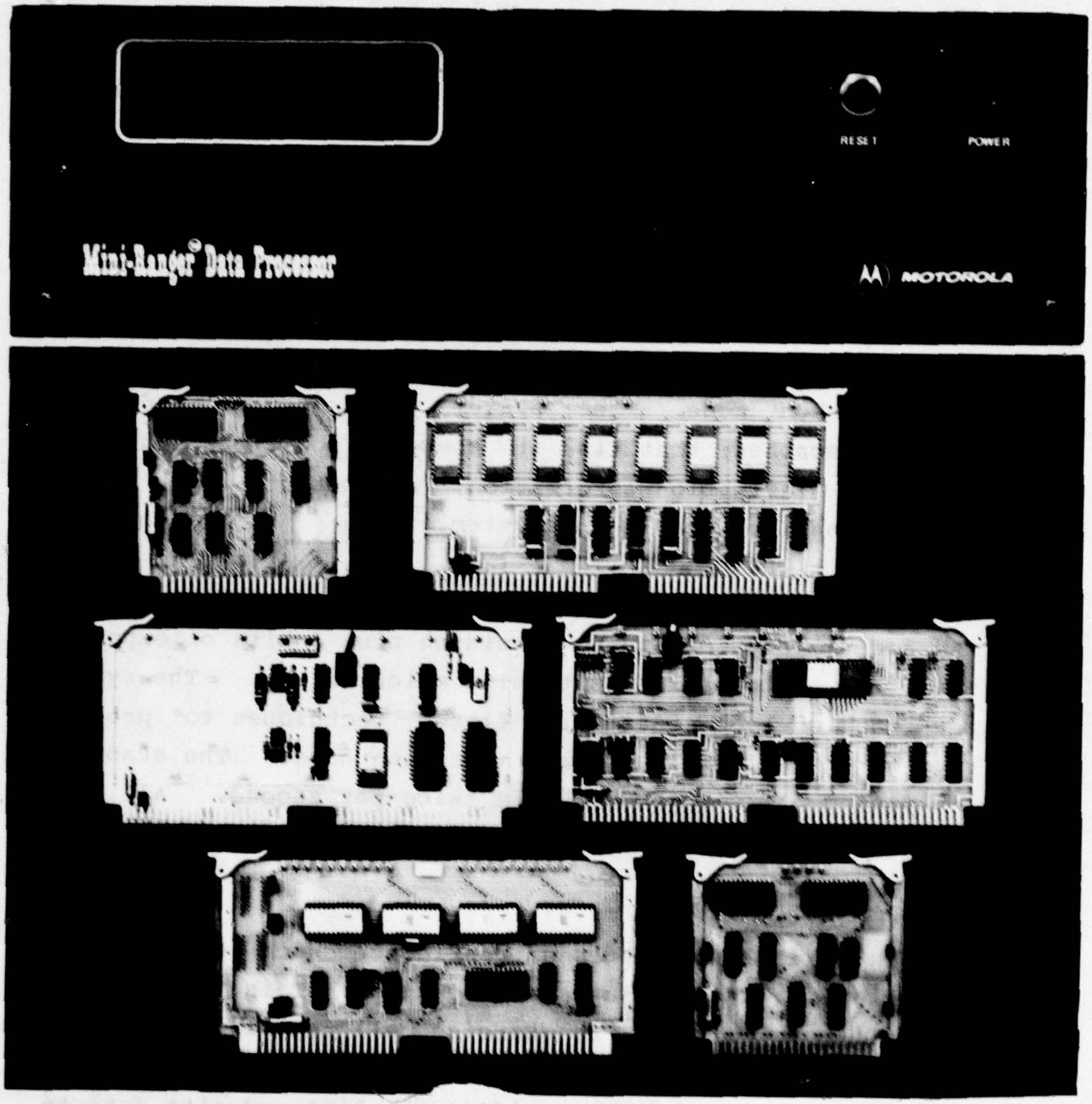

RESET
POWER
Mini-Ranger® Data Processor
MOTOROLA

Figure 2-6 - MR-III Data Processor

The system is programmed to interact with the operator through a series of messages designed to aid the operator in the correct preparation and operation of the system. Invalid responses or entries are rejected; help messages may be requested to aid in understanding.

In the Data Entry mode, the operator enters the code and coordinate information for the reference sites to be used (up to 16) and the coordinate information for the basic lines to be run (up to 10). The operator next selects the operating parameters, including the sites to be used and the line to be run and other operating details such as plotter scale or update rate. This is called the Operate Set-Up mode.

In the Run mode, the system performs the functions previously described; that is, it computes positions, gathers data, provides navigation information, and outputs data to peripheral devices included in the system.

The MRDP uses a floating-point arithmetic package with a capacity for 40 bits of binary precision plus 8 bits of exponent and sign, to perform all positioning calculations. The system utilizes tracking-loop estimation filter techniques to provide the user with reliable, accurate position data. The standard position fixing rate of the MRDP is twice per second. All program memory is in non-volatile programmable read-only-memory elements (ROM).

The MRDP system includes a confidence check feature which may be initiated by the operator at any time. This feature performs a self-test function to exercise all the elements of the MRDP system including the peripherals to find and identify faults. The system routinely verifies the line and site data to reduce errors and is designed to provide error messages to aid in elimination of operational problems.

The standard system includes an internal, 24-hour time-of-day clock, which is crystal controlled for accuracy. The system may be expanded to increase the operational capability. The addition of a track plotter provides a continuous record of the system position; additional data inputs such as depth or temperature can be included; a track indicator may be added for guidance along parallel offsets; and tape recording and printing capability may be added for permanent data records and later data reduction. Software options may also be added to increase system capabilities. These options include optional coordinate systems and post-processing of data.

The X-Y conversion ROM (Option 501) is used in the basic system to accept range-range data and compute position in an X-Y coordinate system.

The program, using the X-Y conversion ROM, can support a track plotter (Options 504, 505, or 518), a track indicator (Option 506), and an output interface, printer (Option 507). The X-Y conversion ROM can be configured for either a four-code or sixteen-code Mini-Ranger III range input.

The MRDP has a Termiflex Terminal Connector on the rear designed to interface directly with the Termiflex hand-held terminal when this is used as the operator's terminal. A standard RS-232C interface provides compatibility with standard EIA RS-232C data terminals and the data rate may be set to 10 or 30 characters per second. A 20 ma current loop interface is also provided using 3 unused pins in the RS-232C connector.

2.3 Data Acquisition

The guidance scheme implementations require differing sets of sensors and initialization and command inputs. Many of the sensors are used in a number of systems so the various Input/Output (I/O) diagrams have general similarity.

The I/O Block diagram for guidance subsystem 3a is shown in Figure 2-7. The number of lines in a data bus from each sensor is in general the maximum useable resolution from each device. This serves to identify the maximum number of digital input lines which could be required. In actual implementation, tradeoffs between cost, accuracy requirements, and resolution and quantization may permit use of lower resolution.

2.4 Mechanical Design

The mechanical design concept for the airborne guidance package of guidance subsystem 3a could be similar to that discussed insection 5.4 for subsystem 2c. The differences would be as follows:

1) the MR-III mobile reference station would replace the two ADF receivers;

2) the associated hemispherical antenna would replace the ADF antenna and ADF amplifier;

3) there would be no airborne computer;

4) there would be no separate command receiver or antenna, unless desired to establish a redundant command link.

The total airborne guidance package would weigh about 430 lbs. This represents less than 7% of the total vehicle's weight, assuming a 6000 pound payload.

2.5 Equipment List and Prices for Guidance Subsystem 3a

Table 2-4 lists equipment and prices for guidance subsystem 3a.

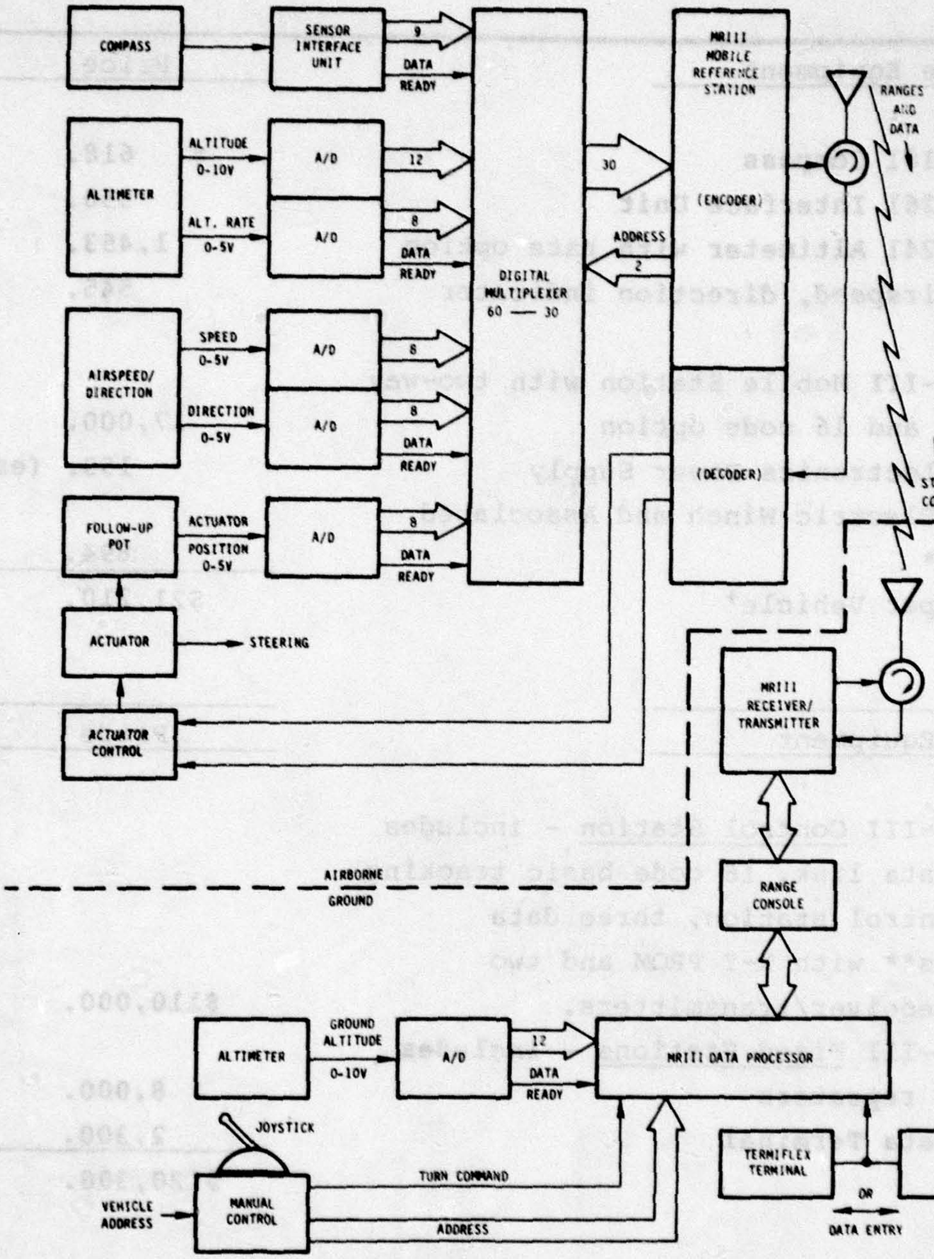

COMPASS
SENSOR INTERFACE UNIT
9
DATA READY
ALTIMETER
ALTITUDE 0-10V
A/D
12
ALT. RATE 0-5V
A/D
8
DATA READY
AIRSPEED/ DIRECTION
SPEED 0-5V
A/D
8
DIRECTION 0-5V
A/D
8
DATA READY
FOLLOW-UP POT
ACTUATOR POSITION 0-5V
A/D
8
DATA READY
ACTUATOR
STEERING
ACTUATOR CONTROL
DIGITAL MULTIPLEXER 60 — 30
30
ADDRESS
2
MRIII MOBILE REFERENCE STATION
(ENCODER)
(DECODER)
RANGES AND DATA
STEERING COMMANDS
MRIII RECEIVER/ TRANSMITTER
AIRBORNE
GROUND
RANGE CONSOLE
ALTIMETER
GROUND ALTITUDE 0-10V
A/D
12
DATA READY
MRIII DATA PROCESSOR
JOYSTICK
VEHICLE ADDRESS
MANUAL CONTROL
TURN COMMAND
ADDRESS
TERMIFLEX TERMINAL
TTY
OR
DATA ENTRY

Figure 2-7 - Guidance Subsystem 3a I/O Block Diagram

TABLE 2-4 EQUIPMENT LIST AND PRICES FOR GUIDANCE SUBSYSTEM 3a

Airborne Equipment	Price
Digicourse 101 Compass	$ 618.
Digicourse 261 Interface Unit	550.
Rosemount 1241 Altimeter with rate option	1,453.
J-Tek 320 Airspeed, direction indicator	545.
Motorola MR-III Mobile Station with two-way data link and 16 code option	17,000.
(Various) Electronics Power Supply	150. (est.)
Ramsey DC2 Electric Winch and Associated Equipment*	894.
Total per Vehicle+	$21,210.

Ground Equipment	Price
Motorola MR-III Control Station - includes two-way data link, 16 code basic tracking system control station, three data processors** with X-Y PROM and two and two receiver/transmitters.	$110,000.
Motorola MR-III Fixed Stations - includes two coded repeaters	8,000.
(Various) Data Terminal	2,300.
Total	$120,300.

* See Section 10.2 for Itemization

+ For price with Pneumatic Actuation System, add $464.

NOTE: Total does not include any required interfacing circuitry, mounting brackets, fabrication, test, or shell.

** To handle the thruput requirement

3. GUIDANCE SUBSYSTEM 3b

3.1 General Description

Guidance subsystem 3(b) is similar to 3(a), in that it uses trilateration to determine the position of the airdrop vehicles. However, whereas subsystem 3(a) measures the three ranges and computes steering commands on the ground, subsystem 3(b) does this aboard each vehicle.

The airborne equipment is the same as that required for subsystem 3(a), except that a unit known as the MR-III range processor, shown in Figure 3-1, replaces the MR-III mobile reference station; also, the airborne equipment includes a command link receiver for manual command override. The ground equipment consists only of three MR-III coded fixed reference stations, and a command link transmitter.

The airborne range processor combines the functions of the range console and the data processor as described in section 2.

The range processor interrogates a ground-based fixed reference station by using pulse-position modulation to encode that station's address. When the proper fixed reference station receives the interrogation, it transmits a reply. The range processor's receiver-transmitter unit receives the reply, and computes a range to the station based on the elapsed time between the interrogation and the reply. The processor stores this computed range in memory. The other two ground stations are interrogated in turn. The three ranges define the position of the airdrop vehicle. The processor uses this position, along with data from the airborne sensors (the compass, altimeter, and airspeed and direction indicators) to compute steering commands.

At close ranges, an observer on the ground can override the computed steering commands using the command link transmitter.

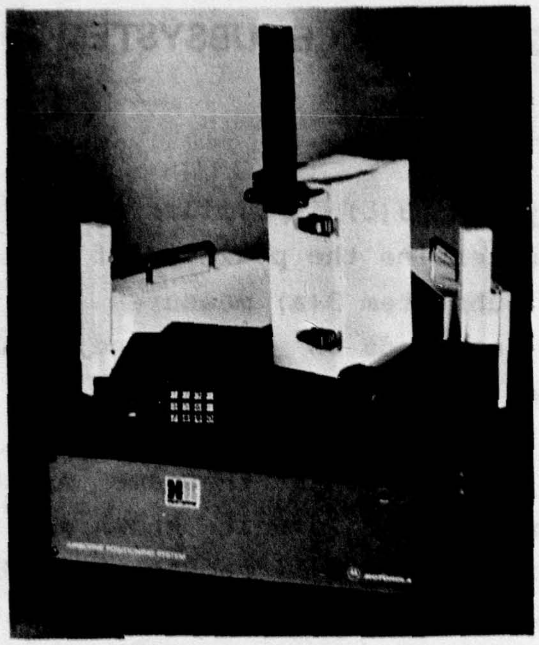


Figure 3-1 - MR-III Range Processor

The system uses only two frequencies in the operating band for position location: one for the interrogation, and one for the reply. (This is as opposed to subsystem 3(a), which uses three: one for the interrogation, one for the mobile reference station reply, and one for the fixed reference station reply.) For this reason there is only one receiver-transmitter unit associated with the range processor (rather than two, as with the range console of subsystem 3(a)). The system measures only direct ranges to the ground stations; there are no "loop-range" measurements, and therefore no requirements for line-of-sight contact between the ground stations.

In subsystem 3(a), an operator could use the interface terminal to enter required data (such as the ground sites' coordinates*, desired landing point coordinates, and the local barometric pressure) into the single ground-based processor. In subsystem 3(b), however, an operator on board the deploying aircraft would enter these data into each airdrop vehicle's computer through a common umbilical. A ground-based operator would use an existing voice link to send the required information to the airborne operator.

---

*Perhaps best expressed in a polar coordinate system, the origin of which is the control station, with angles referenced to magnetic north.

The system would accommodate several vehicles by using the "multi-user" software option. This option introduces, among other things, random timing in the interrogations from a given range processor to greatly reduce the probability of simultaneous interrogations from more than one range processor.

3.2 Data Acquisition

Figure 3-2 shows the I/O block diagram for guidance subsystem 3b. The general comments of section 2.3 apply here as well.

The command override method shown in the system I/O diagram uses the analog steering command from the command receiver converted to a digital word. The turn-rate command is input to the computer where it is compared to the actuator position measured by the follow-up pot. Commands are sent by the computer to the actuator control which then drives the actuators for steering.

A potential problem with this method of command override could be computer reliability. An alternative command override technique is shown in Figure 3-3, where the computer is bypassed in the command override mode. The analog steering command from the command receiver is compared with the follow up pot actuator position signal by two comparators (C). In this alternative system, the actuator position is continuously measured, and hysteresis and dead zones are included to prevent hunting. Braking is applied each time the desired actuator position is achieved.

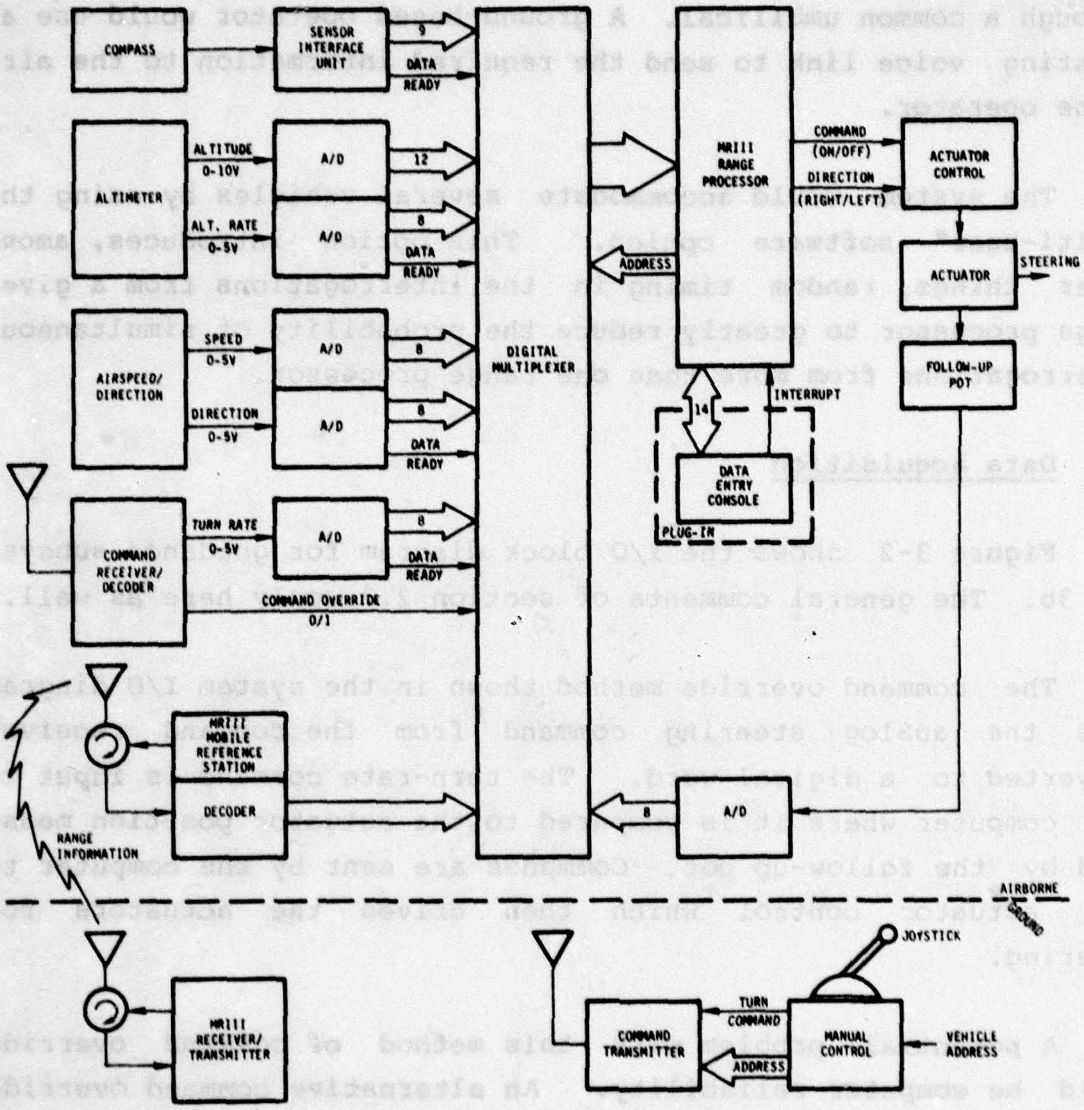

COMPASS
SENSOR INTERFACE UNIT
9
DATA READY
ALTIMETER
ALTITUDE 0-10V
ALT. RATE 0-5V
A/D
12
A/D
8
DATA READY
AIRSPEED/ DIRECTION
SPEED 0-5V
DIRECTION 0-5V
A/D
8
A/D
8
DATA READY
COMMAND RECEIVER/ DECODER
TURN RATE 0-5V
A/D
8
DATA READY
COMMAND OVERRIDE 0/1
DIGITAL MULTIPLEXER
MRIII RANGE PROCESSOR
ADDRESS
COMMAND (ON/OFF)
DIRECTION (RIGHT/LEFT)
ACTUATOR CONTROL
ACTUATOR
STEERING
FOLLOW-UP POT
INTERRUPT
14
DATA ENTRY CONSOLE
PLUG-IN
MRIII MOBILE REFERENCE STATION
DECODER
RANGE INFORMATION
A/D
8
AIRBORNE
GROUND
JOYSTICK
MRIII RECEIVER/ TRANSMITTER
COMMAND TRANSMITTER
TURN COMMAND
ADDRESS
MANUAL CONTROL
VEHICLE ADDRESS

Figure 3-2 - Guidance Subsystem 3b I/O Block Diagram

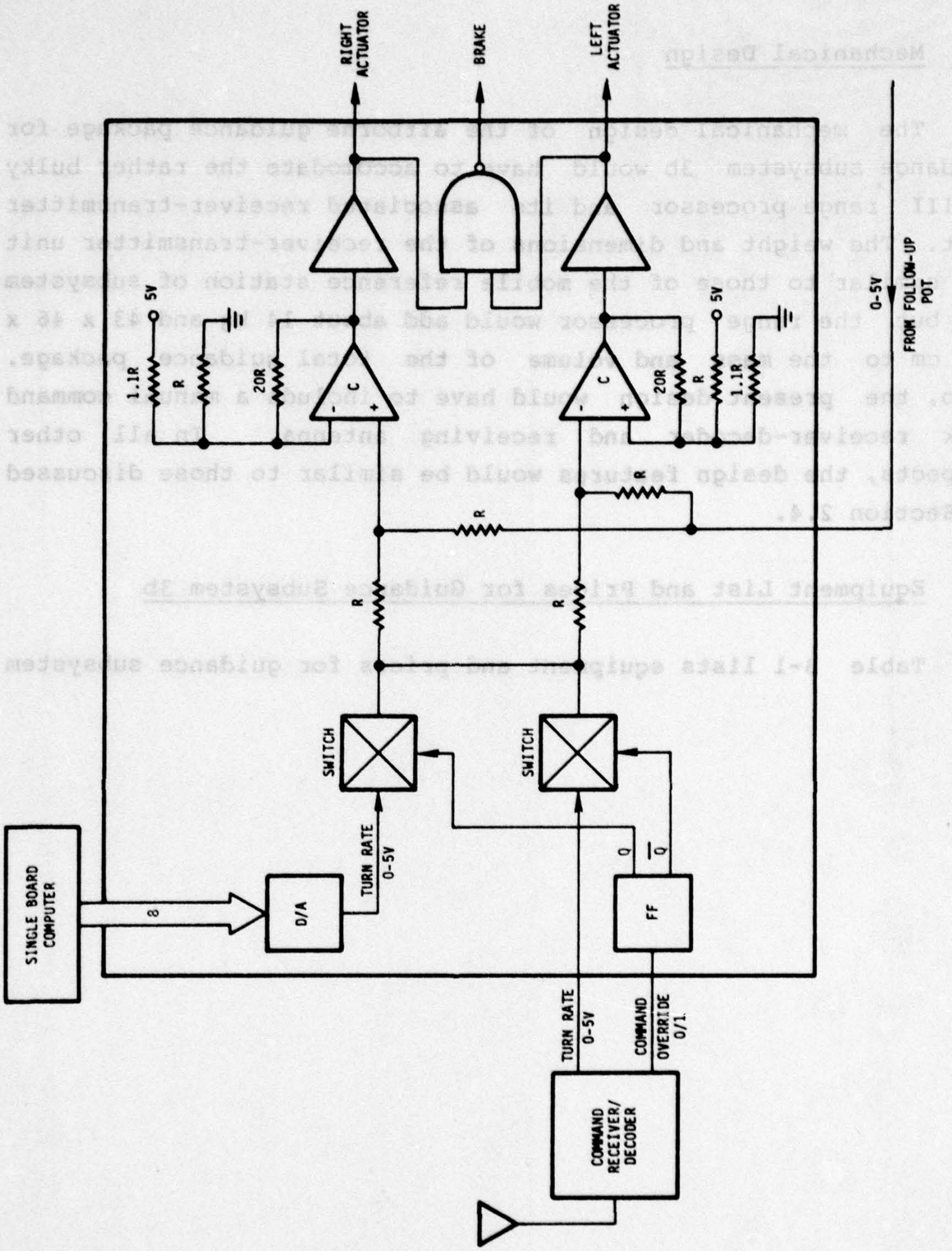

RIGHT ACTUATOR
BRAKE
LEFT ACTUATOR
0-5V
FROM FOLLOW-UP POT
5V
5V
1.1R
R
20R
C
-
+
C
-
+
20R
R
1.1R
R
R
R
R
SWITCH
SWITCH
TURN RATE 0-5V
Q
Q̄
SINGLE BOARD COMPUTER
8
D/A
FF
TURN RATE 0-5V
COMMAND OVERRIDE 0/1
COMMAND RECEIVER/ DECODER

Figure 3-3 - Alternative Manual Override Command

3.3 Mechanical Design

The mechanical design of the airborne guidance package for guidance subsystem 3b would have to accomodate the rather bulky MR-III range processor and its associated receiver-transmitter unit. The weight and dimensions of the receiver-transmitter unit are similar to those of the mobile reference station of subsystem 3a, but the range processor would add about 14 kg and 43 x 46 x 14 cm to the mass and volume of the total guidance package. Also, the present design would have to include a manual command link receiver-decoder and receiving antenna. In all other respects, the design features would be similar to those discussed in Section 2.4.

3.4 Equipment List and Prices for Guidance Subsystem 3b

Table 3-1 lists equipment and prices for guidance subsystem 3b.

TABLE 3-1 EQUIPMENT LIST AND PRICES FOR GUIDANCE SUBSYSTEM 3b

Airborne Equipment	Price
Digicourse 101 Compass	$ 618.
Digicourse 261 Interface Unit	550.
Rosemount 1241 Altimeter with rate option	1,453.
J-Tek 320 Airspeed, direction indicator	545.
Motorola MR-III Range Processor with 16 code multi-user options and one receiver/transmitter	30,000.
Kraft KTR 1-16 Manual Command Link Receiver/decoder	700.
(Various) Electronics Power Supply	150. (est.)
Ramsey DC2 Electric Winch and Associated Equip.	894.
Total per vehicle⁺	34,910.

Ground Equipment	Price
Motorola MR-III Reference Stations - includes three 16-code reference stations	$7,500.
Kraft KTT 1-16 Manual Command Link Encoder/Transmitter	700.
Total	$8,200.

* See Section 10.2 for Itemization

⁺ For price with Pneumatic Actuation System, add $464.

Note: Total does not include any required interfacing circuitry, mounting brackets, fabrication, test, shell, or deploying aircraft's data entry console.

4. GUIDANCE SUBSYSTEM 1b

4.1 General Description

An airdrop vehicle's position can be determined by measuring the slant range, azimuth, and altitude of that vehicle relative to a known ground site. The slant range measurement defines a hemisphere around the ground site. The azimuth defines a semi-infinite plane normal to the earth's surface. The altitude defines a plane parallel to the earth's surface. The intersection of the hemisphere and the two planes provides a fix. This position-fixing scheme is an extension of the rho-theta concept to three dimensions; it is the basis for guidance subsystem 1(b), a deployed version of which is depicted in Figure 4-1.

Guidance subsystem 1(b) uses a C-band MR-III tracking system to

1) measure the azimuth and slant range;
2) provide a data link from the vehicle to the ground;
3) compute steering commands, based on this information, at the ground site, and
4) transmit these commands back to the vehicle.

A barometric altimeter measures the vehicle's altitude relative to the landing zone, and this is among the data that are linked from the vehicle to the ground.

Vehicles are interrogated individually, with each assigned a unique address, allowing the system to control several vehicles simultaneously. The command link allows a manual command override, permitting remote control by an observer on the landing zone.

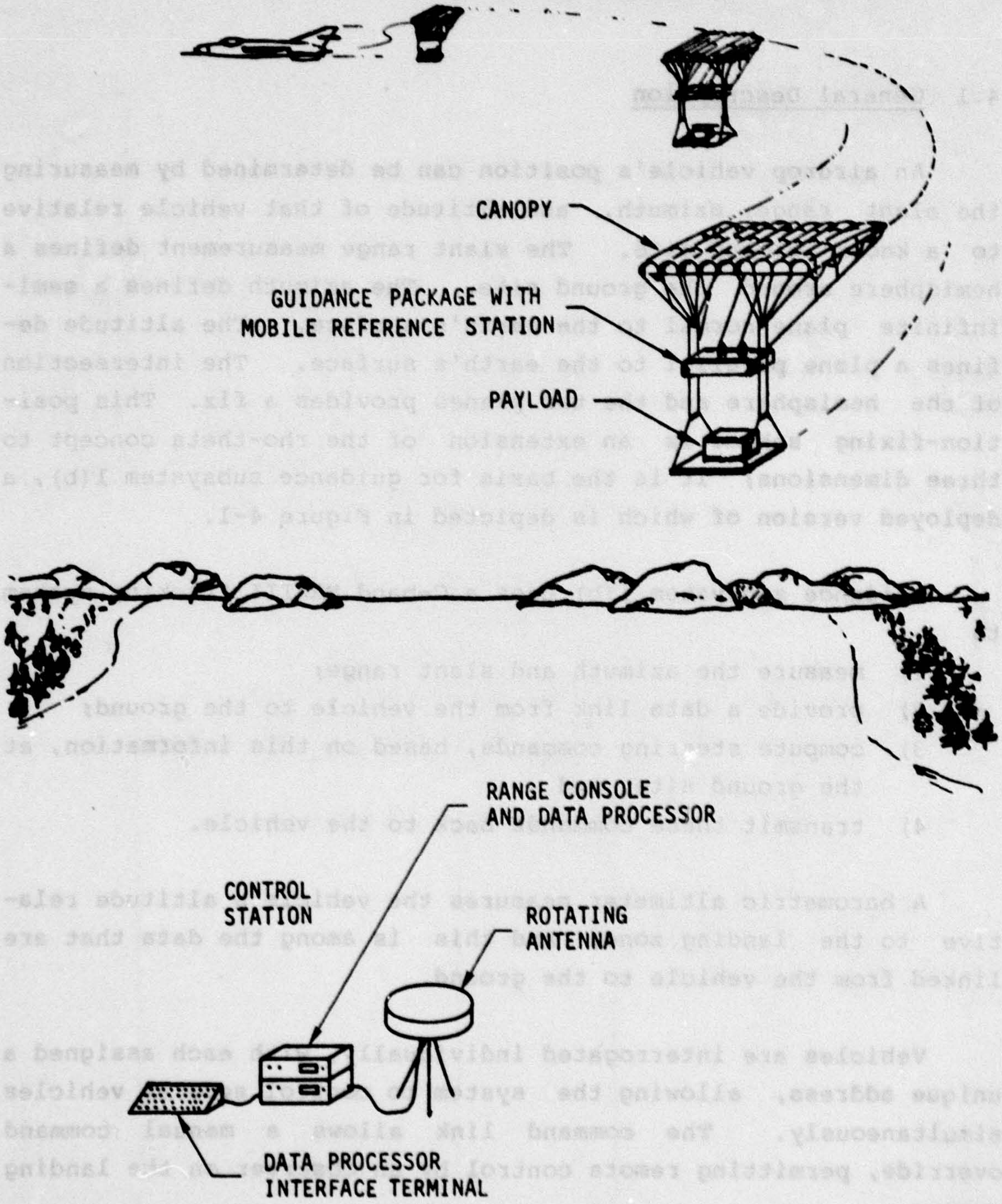

CANOPY
GUIDANCE PACKAGE WITH
MOBILE REFERENCE STATION
PAYLOAD
RANGE CONSOLE
AND DATA PROCESSOR
CONTROL
STATION
ROTATING
ANTENNA
DATA PROCESSOR
INTERFACE TERMINAL

Figure 4-1 - Deployed System Using Guidance Subsystem 1(b)

The airborne equipment is identical to that of subsystem 3(a):

1) a compass (section 7.1)
2) an altimeter (section 7.2)
3) an airspeed and direction indicator (section 7.4)
4) an MR-III mobile reference station with two-way data link capability (section 2.2.1)
5) an actuator with a follow-up potentiometer (section 10), and
6) a power supply.

The ground equipment consists of

7) an MR-III range console (section 2.2.1)
8) a rotating antenna and mainbeam detector
9) an MR-III data processor (section 2.2.2)
10) a data processor interface terminal, and
11) a power supply.

The rotating antenna is special equipment and will be discussed in the following section.

4.2 Rotating Antenna and Main Beam Detector

Guidance subsystem 1(b) uses a C-band rotating antenna in conjunction with an MR-III range console to determine the range and azimuth of an airdrop vehicle carrying an MR-III mobile reference station. Figure 4-2 shows the unit that contains the antenna, its drive motor, and the transponder. Table 4-1 lists the electrical and environmental specifications.

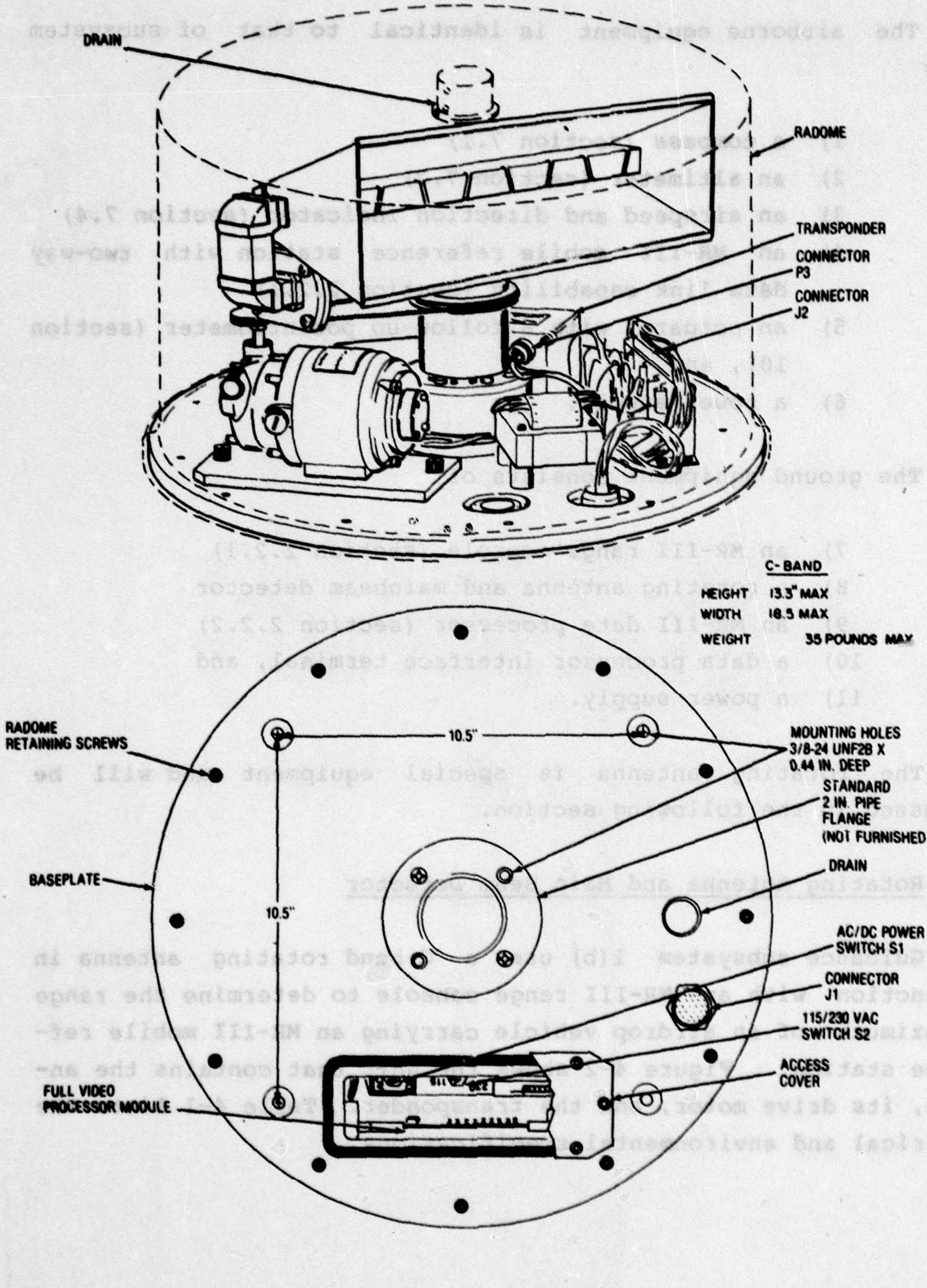

DRAIN
RADOME
TRANSPONDER
CONNECTOR P3
CONNECTOR J2
C-BAND
HEIGHT 13.3" MAX
WIDTH 18.5 MAX
WEIGHT 35 POUNDS MAX
RADOME RETAINING SCREWS
10.5"
MOUNTING HOLES 3/8-24 UNF2B X 0.44 IN. DEEP
STANDARD 2 IN. PIPE FLANGE (NOT FURNISHED)
BASEPLATE
10.5"
DRAIN
AC/DC POWER SWITCH S1
CONNECTOR J1
115/230 VAC SWITCH S2
ACCESS COVER
FULL VIDEO PROCESSOR MODULE

Figure 4-2 - Rotating Antenna for Guidance Subsystem 1(b)

TABLE 4-1 SPECIFICATIONS FOR THE ROTATING ANTENNA

ELECTRICAL	
Frequency	5400-5600 MHz
Gain	18 dB minimum
Beamwidth (3 dB)	
Azimuth	8 degrees nominal
Elevation	30 degrees nominal
Rotation Speed	30 RPM
(20 or 26 RPM optional)	
Drive Motor Power	115/230 VAC or 24 VDC
Power Consumption	20 watts nominal
Side Lobe Attenuation	10 dB minimum
ENVIRONMENTAL	
Temperature	-40°C to +60°C
Humidity	To 99% non-condensing
Wind Loading	100 kts maximum
Altitude	20,000 ft maximum
Vibration	MIL-STD-810C Process IIC; Method 514.2 (.10" D.A.: 5 to 500 Hz)

Slant range to the vehicle is measured as in the systems using trilateration. A receiver-transmitter unit at the ground station (the transponder in Figure 4.2) interrogates the airborne mobile unit. When the mobile unit receives the interrogation, it transmits a reply. The ground station receives the reply, and computes a range to the vehicle based on the elapsed time between the interrogation and the reply.

Because of the ground-station antenna's narrow beamwidth in azimuth, the strength of the returned signal at the antenna output port depends on the vehicle's angle off the mainbeam. As the antenna scans in azimuth, the returned signal strength peaks whenever the mainbeam passes by the vehicle. With an 8 degree beamwidth, a scan rate of 30 revolutions per minute, and an interrogation rate of 640 per second, there is time for 28 interrogations while the vehicle is in the mainbeam (neglecting vehicle motion in azimuth). The mainbeam detector circuit looks for the peak in the returned signal during this time. The azimuth of the antenna (as read from a shaft encoder) at the time corresponding to this peak is the azimuth of the vehicle, to within plus or minus 1 degree.

This azimuth is stored in the data processor, so that the system will know when to start interrogating the vehicle on successive scans.

While the vehicle is in the mainbeam, the interrogations carry steering commands to the vehicle (as well as the address for the vehicle), and the replies carry data from the vehicle (compass heading, airspeed, sideslip, altitude, altitude rate, and actuator follow-up). The bit lengths assigned for data and commands, and the method of encoding the information, is as described in section 2.2.1. However, the waveforms are simpler in the present method because there are no baselines to address.

The mainbeam passes by the vehicle only once every two seconds, which implies an update rate of 0.5 Hz. Furthermore, the commands for a given scan are based upon data taken from the previous scan, and are therefore stale by two seconds. One can use predictive filtering to alleviate this condition.

The actual update rate can be slower than 0.5 Hz when vehicles lie in overlapping sectors. (A sector is the angle through which the antenna sweeps while the system dedicates itself to interrogating a specific vehicle.) In the present application, a sector is about 10 deg. Overlapping sectors must be interrogated on successive scans; this means, for example, that if four vehicles shared the same sector, the update rate for these vehicles would be 0.5 Hz/4 = 0.125 Hz. Furthermore, the steering commands would be stale by eight seconds. It is unlikely, however, that this condition would last for long; in fact, since the data processor would recognize this condition, it could steer the vehicles so as to eliminate it.

An alternative to the present method, in which steering commands are computed on the ground and transmitted to each vehicle, is a method whereby the commands would be computed aboard each vehicle, based on range and azimuth data transmitted from the ground. This would eliminate the need for a downlink, since the airborne sensors would be physically close to the computer. However, it would require that the ground barometric pressure and the desired landing point coordinates be entered into each vehicle's computer before deployment, perhaps through a common umbilical. Also, if the uplink were to serve alternatively as a command link, the message would have to identify itself as containing either position data or a steering command, so that the airborne computer would properly interpret it.

One possible disadvantage of any method using the rotating antenna arises because of its limited elevation coverage of 30 deg. Airdrop vehicles at higher elevations might not be tracked.

Specifying the desired landing zone to be a fairly long distance from the antenna would reduce the probability of vehicles being within the cone of no coverage; or, the data processor could steer the vehicles so as to keep them clear of this cone.

The operating range of the rho-theta system is greater than that of the trilateration systems, due to the directivity of the rotating antenna. Assuming hemispherical antennas on the vehicles, the operating range would be 38 km for vehicles within the elevation coverage; this easily satisfies the system requirements.

4.3 Data Acquisition

The I/O diagram for guidance subsystem 1b is identical to that for subsystem 3a, described in section 2.3. Figure 4-3 shows the I/O diagram for the alternative method, whereby the commands are computed aboard each vehicle, based on range and azimuth data transmitted from the ground. The general comments of sections 2.3 and 3.2 apply here as well.

4.4 Mechanical Design

The mechanical design of the airborne guidance package for guidance subsystem 1b would be identical to that for subsystem 3a (see Section 2.4).

To implement the alternative method, whereby steering commands would be computed aboard the vehicle based on position data transmitted from the ground, the design would include a single-board computer and provisions for a data entry umbilical. And, if the data uplink would not serve alternatively as a manual command link, a command link receiver-decoder and receiving antenna would be added. In either case, the total increase in weight and volume would be small.

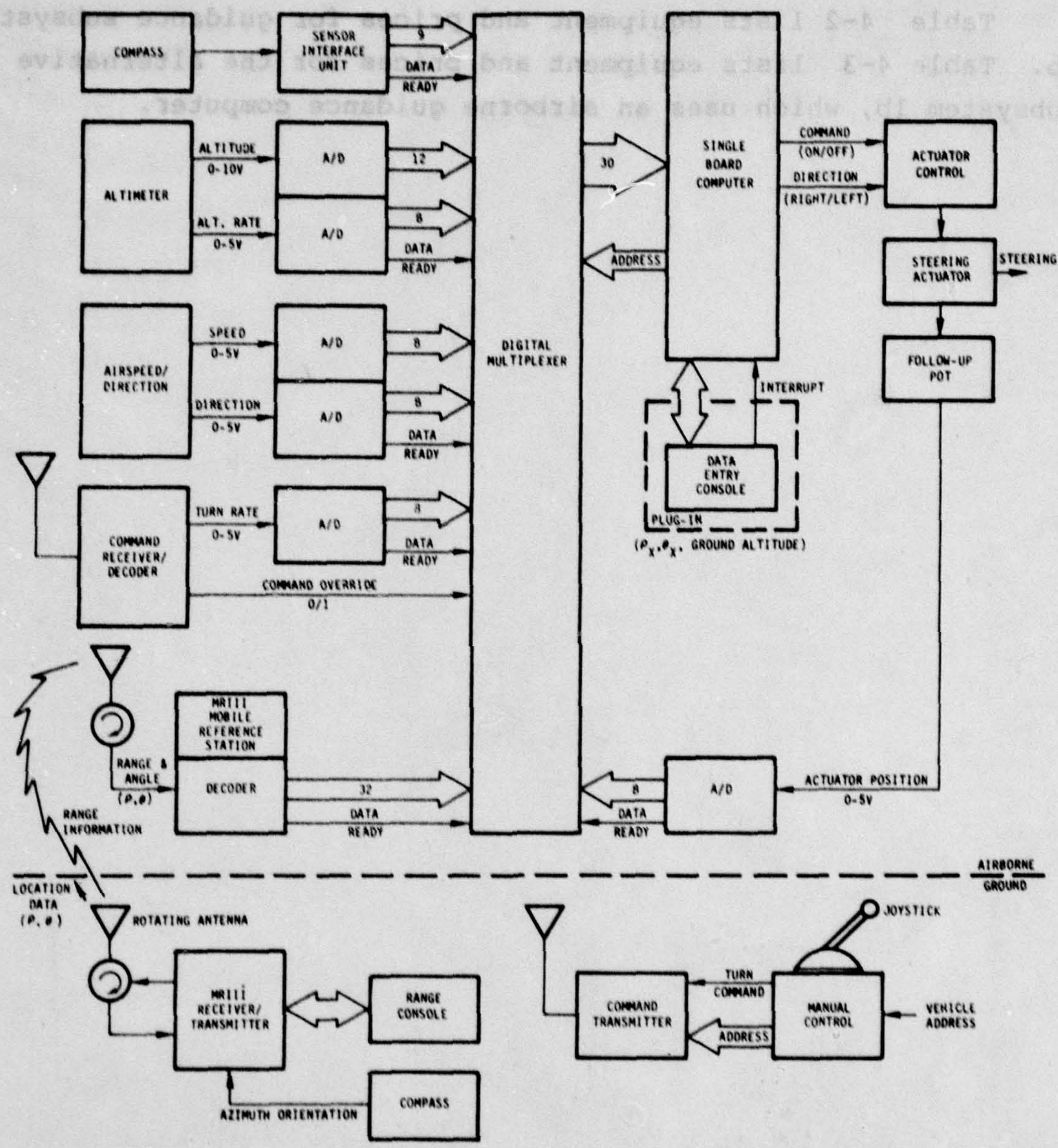

COMPASS
SENSOR INTERFACE UNIT
9
DATA READY
ALTIMETER
ALTITUDE 0-10V
A/D
12
ALT. RATE 0-5V
A/D
8
DATA READY
AIRSPEED/ DIRECTION
SPEED 0-5V
A/D
8
DIRECTION 0-5V
A/D
8
DATA READY
COMMAND RECEIVER/ DECODER
TURN RATE 0-5V
A/D
8
DATA READY
COMMAND OVERRIDE 0/1
DIGITAL MULTIPLEXER
30
ADDRESS
SINGLE BOARD COMPUTER
COMMAND (ON/OFF)
DIRECTION (RIGHT/LEFT)
ACTUATOR CONTROL
STEERING ACTUATOR
STEERING
FOLLOW-UP POT
INTERRUPT
DATA ENTRY CONSOLE
PLUG-IN
(ρ_x, θ_x, GROUND ALTITUDE)
MRIII MOBILE REFERENCE STATION
RANGE & ANGLE (ρ,θ)
DECODER
32
DATA READY
RANGE INFORMATION
A/D
8
DATA READY
ACTUATOR POSITION 0-5V
AIRBORNE
GROUND
LOCATION DATA (ρ, θ)
ROTATING ANTENNA
MRIII RECEIVER/ TRANSMITTER
RANGE CONSOLE
COMPASS
AZIMUTH ORIENTATION
COMMAND TRANSMITTER
TURN COMMAND
ADDRESS
MANUAL CONTROL
JOYSTICK
VEHICLE ADDRESS

Figure 4-3 - Alternative Method 1b I/O Block Diagram

4.5 Equipment List and Prices for Guidance Subsystem 1b

Table 4-2 lists equipment and prices for guidance subsystem 1b. Table 4-3 lists equipment and prices for the alternative to subsystem 1b, which uses an airborne guidance computer.

TABLE 4-2 EQUIPMENT LIST AND PRICES FOR GUIDANCE SUBSYSTEM 1b

Airborne Equipment	Price
Digicourse 101 Compass	$ 618.
Digicourse 261 Interface Unit	550.
Rosemount 1241 Altimeter with Rate Option	1,453.
J-Tek 320 Airspeed, Direction indicator TCC-PT	545.
Motorola MR-III Mobile Station with two-way data link and 16 code option	17,000.
(Various) Electronics Power Supply	150. (est.)
Ramsey Electric Winch and Associated Equipment*	894.
Total per vehicle$^+$	$21,210.

Ground Equipment	Price
Motorola MR-III Rho-Theta Ground Station - Includes three range processors with X-Y PROM, one Rho-Theta option with rotating antenna, and data link transmitter/receiver	$110,000.
(Various) Data Terminal.	2,300.
Total	$112,300.

* See Section 10.2 for Itemization

$^+$ For price with Pneumatic Actuator System, add $464.

NOTE: Total does not include any required interfacing circuitry, mounting brackets, fabrication, test, or shell.

TABLE 4-3 EQUIPMENT LIST WITH PRICES FOR ALTERNATIVE TO GUIDANCE SUBSYSTEM 1b

Airborne Equipment	Price
Digicourse 101 Compass	$ 618.
Digicourse 261 Interface Unit	550.
Rosemount 1241 Altimeter with Rate Option	1,453.
J-Tek 320 Airspeed, Direction Indicator	545.
Motorola MR-III Mobile Reference Station with data link decoder and 16 code option	12,000.
Single-board computer with I/O	1,000.
Kraft KTR 1-16 Manual Command Link Link Receiver/Decoder	700.
(Various) Electronics Power Supply	150. (est.)
Ramsey Electric Winch and Associated Equipment*	894.
Total per Vehicle+	$17,910.

Ground Equipment	Price
Motorola MR-III Rho-Theta Ground Station includes one range processor with X-Y PROM, one Rho-Theta option with rotating antenna, and data-link transmitter.	$60,000.
Total	$60,000.

* See Section 10.2 for Itemization

+ For price with pneumatic actuation system, add $464.

NOTE: Total does not include any required interfacing circuitry, mounting brackets, fabrication, test, or shell.

5. GUIDANCE SUBSYSTEM 2c

5.1 General Description

An airdrop vehicle's position can be determined by measuring its azimuth relative to two known ground sites and its altitude. The azimuth measurements define semi-infinite planes normal to the earth's surface, and the altitude defines a plane parellel to the earth's surface. The intersection of the three planes provides a fix. This position fixing scheme is an extension of the theta-theta concept to three dimensions; it is the basis for guidance subsystem 2c, a deployed version of which is depicted in Figure 5-1.

Guidance subsystem 2c uses two low-frequency beacons on the ground (separated by a known baseline) and two ADF receives on each vehicle to derive the azimuth measurements. The beacons operate at separate frequencies in the low-frequency band, and the ADF receivers are tuned to these frequencies. An airborne compass establishes a heading reference, which, with the two ADF bearing indications, yields the azimuth relative to each beacon.

As in the other guidance subsystems, a barometric altimeter measures the altitude above the desired landing zone.

An airborne single-board computer uses the position information, along with airborne sensor data, to compute steering commands according to a particular guidance law. The guidance package also contains a command-link receiver, enabling an operator at the landing zone to override the computed steering commands at short ranges.

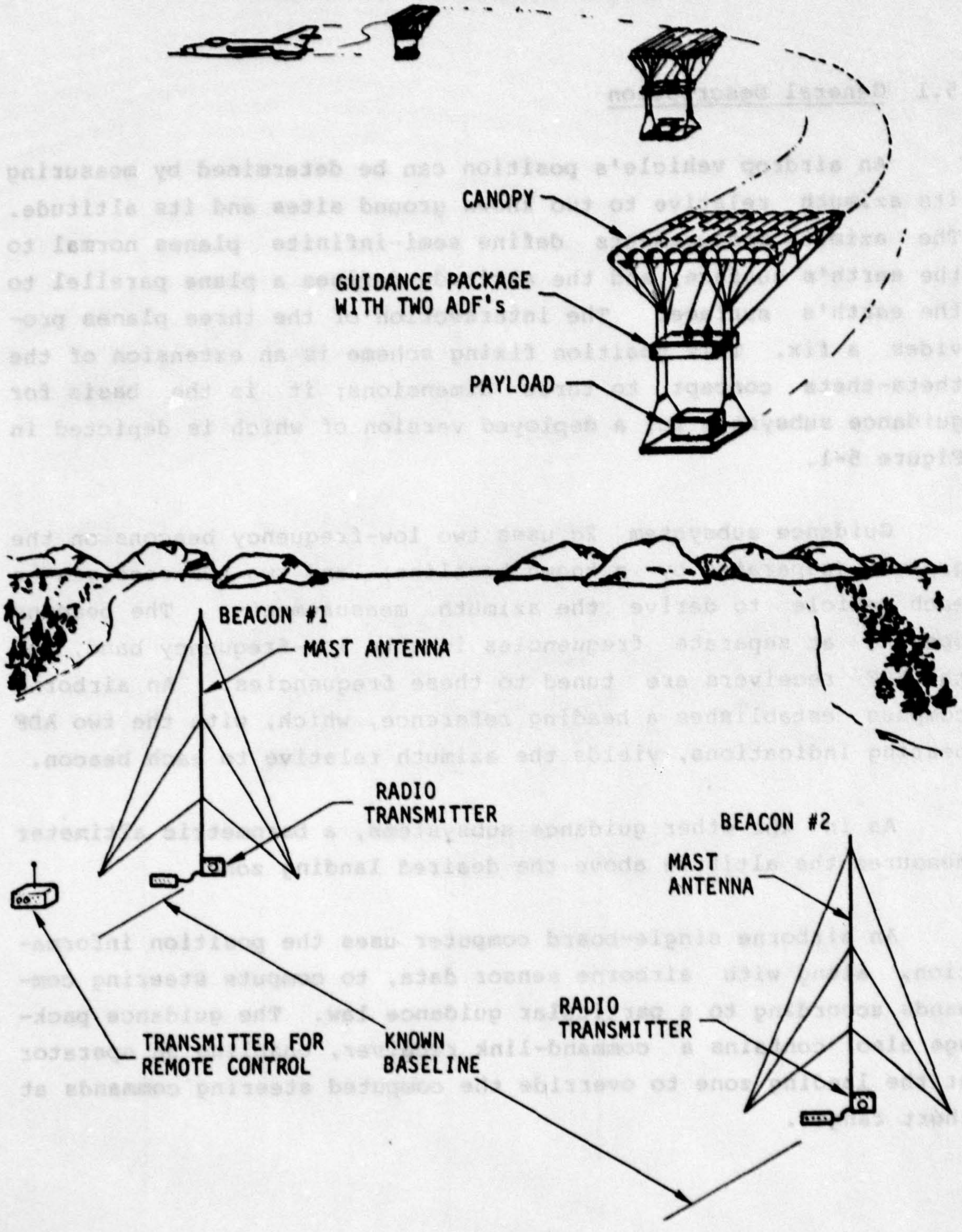

CANOPY
GUIDANCE PACKAGE
WITH TWO ADF's
PAYLOAD
BEACON #1
MAST ANTENNA
RADIO
TRANSMITTER
BEACON #2
MAST
ANTENNA
RADIO
TRANSMITTER
TRANSMITTER FOR
REMOTE CONTROL
KNOWN
BASELINE

Figure 5-1 - Deployed Version of Guidance Subsystem 2c

Because the guidance computation is airborne, an operator on board the deploying aircraft would enter the baseline length and orientation, the desired landing point coordinates, and the ground barometric pressure into the airdrop vehicle's computer before deployment. This would be done for several vehicles through a common umbilical. The information would originate from a ground-based operator using an existing voice link to the airborne operator.

One drawback of this guidance subsystem is its inherent susceptability to ECM (electronic countermeasures). Enemy forces could detect the operating frequency of either beacon, and set up their own beacon at the same frequency to confuse the ADF receivers. In fact, the Army is considering phasing out the use of these beacons for their intended purpose of aircraft navigation because of the ECM problem. One could alleviate the problem in the present application by supplying the system with frequency-agility, whereby both the beacon and the receiver would jump synchronously from one frequency to another. For the enemy to effectively jam such a system would require that he spread his power over the entire low-frequency band, thereby reducing his energy at any one frequency. This would require a great deal of power, perhaps more than he would have available.

The airborne guidance package consists of the following:

1) a compass (Section 7.1)
2) an altimeter (Section 7.2)
3) an airspeed and direction indicator (Section 7.4)
4) a command-link receiver (Section 8.2)
5) two ADF receivers with antennas
6) a single-board computer (Section 9)
7) an actuator with a follow-up potentiometer (Section 10)
8) a power supply.

The ground equipment consists of the following:

9) two low-frequency beacons
10) a command-link transmitter (Section 8.1)

The beacons and the ADF receivers are special equipment, and will be described in the following sections.

5.2 Special Equipment

5.2.1 Low-Frequency Beacons

Ground beacons are required to operate in the ADF-receiver frequency range of 200-1750 KHz. Well suited for this purpose is the AN/TRN-30 radio-navigation ground beacon, operating in the 200 to 535 KHz and 1605 to 1750 KHz frequency ranges (See Figure 5-2). It can be set up for four modes of operation: Pathfinder with 15-foot or 30-foot antennas, Tactical, and Semi-Fixed with a 60-foot antenna; of these, the Pathfinder mode is best suited for the present application.

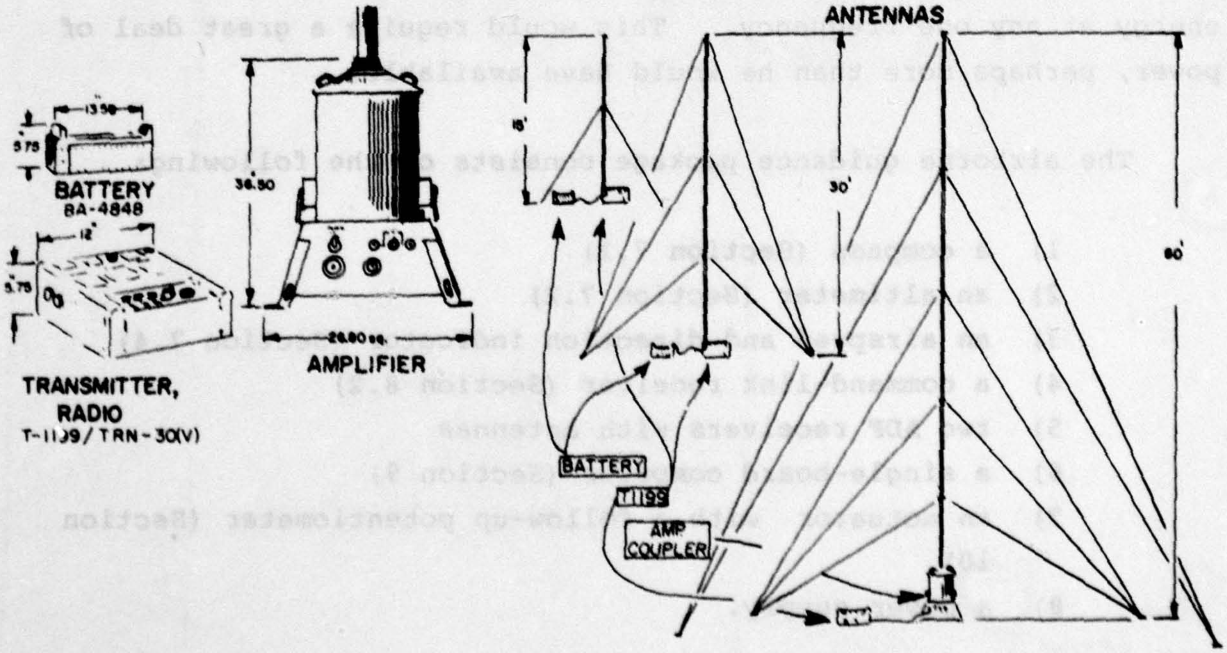

ANTENNAS
13.50
9.75
BATTERY
BA-4848
12"
5.75
TRANSMITTER,
RADIO
T-1139/TRN-30(V)
36.50
26.00 sq.
AMPLIFIER
15'
30'
60'
BATTERY
T1139
AMP
COUPLER

Figure 5-2 - AN/TRN-30 Ground Beacon

The basic Pathfinder Mode is a complete beacon transmitter, including operator controls, in a single 39.0 pound man-portable unit, which can provide a range of 25 nautical miles using a guyed 30-foot top-loaded mast in 200-535 kHz and 1605-1750 kHz or 15 nautical miles to the airborne ADF set at altitudes of 500 feet or higher, with an auxiliary 15-foot guyed antenna in the 1605-1750 kHz range. The antennas are stowed within the Pathfinder Unit Rucksack. The optional battery permits six hours of operation, or the unit can be operated from an external 26 ± 4 VDC power source.

Table 5-1 gives complete specifications for the AN/TRN-30 beacon in the Pathfinder Mode.

5.2.2 Automatic Direction Finders

Automatic direction finding (ADF) receivers are mounted on airborne vehicles and use a pair of orthogonal "loop" antennas whose outputs are combined to measure the bearing to a ground beacon. ADF receivers typically cover the frequency range from 190 kHz to 1750 in 0.5 kHz steps and provide $\pm 3^{\circ}$ to 5° bearing accuracy over the range of signal strengths from 50 microvolts per meter to 0.5 volts per meter. An ADF receiver such as the Bendix ADF 2070, shown in Figure 5-3, produces bearing output signals with two 31.25 Hz square waves whose phase difference is proportional to bearing angle. Coherent detection allows long range reception through improved interference rejection.

The principles of operation of the Bendix ADF 2070 receiver are outlined below as abstracted from the Bendix ADF 2070 Maintenance Manual and provide a summary of its operation.

TABLE 5-1 - AN/TRN-30 SPECIFICATIONS

FEATURE	PATHFINDER (a)Primary Ant. (b)Auxilliary Ant.
Operating Range at ADF alt. for 50μV/meter	(a) 25 NM at 500 ft. AGL (b) 15 NM at 500 ft. AGL
Frequency Bands	(a) 200 KHz to 535 KHz (b) 1605 KHz to 1750 KHz
Power Output	25 watts
Frequency Steps	0.5 KHz
Number of Channels	964
Frequency Stability Emission	+ .0001%
Emission - Tone automatically or manually keyed	CW or MCW
Radiated Carrier % Modulation, min.	50 - 85%
Modulation Frequency	1020 Hz + 10 Hz
No. of Morse Code Letters	26 + blank
Combination of Letters	1, 2, 3 or 4
Words/Min. Adjustment	7 to 20
Input Power:	
Ext. Source Voltage	Normal 26 to 30 V Abnormal 20 to 30 V
Ext. Source Current	3 amp
Int. Batt. Voltage	24 + 4, -2V
Int. Batt. Hours of Operation	6
Max. Antenna Height	(a) 30 ft. (b) 15 ft.
Ant. Polarization	Vertical
Harmon./Spurious Out.:	
Outside Emission Bandwidth of $f_o \pm 5\%$ per MIL-STD-461	-58 DBW
Beacon Weight:	39 lbs.

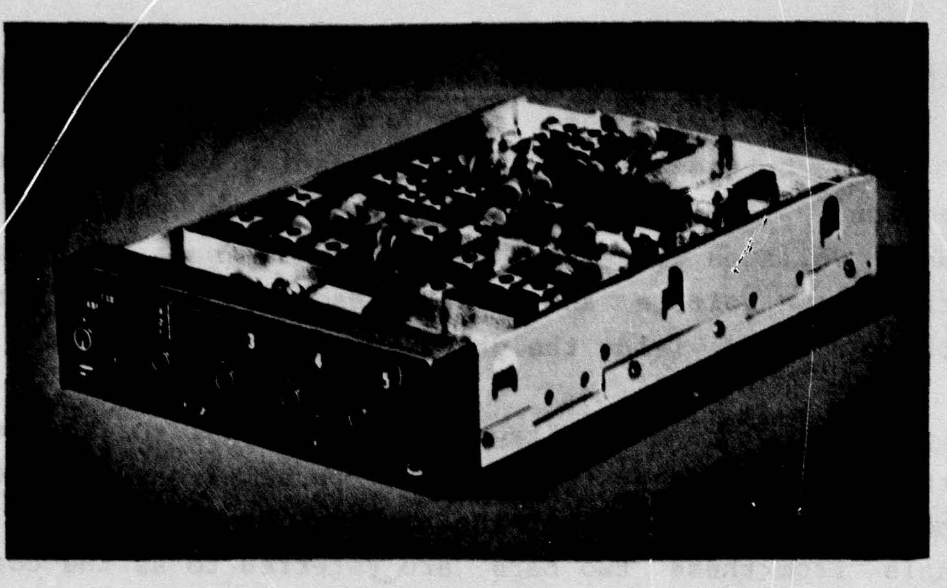


Figure 5-3 - Bendix ADF 2070 Receiver

PRINCIPLES OF OPERATION

General

The magnetic component of a received radio signal induces voltages across windings on a ferrite bar core. Maximum voltage is induced when the bar is perpendicular to the station radial. Minimum voltage is induced when the bar is parallel to the station radial.

Two mutually-perpendicular ferrite-bar loops are used in the ADF-2070 system. One bar is perpendicular to the aircraft fore-to-aft centerline and has peak voltage induced when the received station is straight ahead or straight behind. Minimum voltage occurs when the station is 90° to the right or left. The second ferrite-bar loop is parallel to the aircraft fore-to-aft centerline. Peak voltage across the second loop is induced when the station is 90° to the right or left; minimum voltage occurs with the station ahead or behind.

If the aircraft is rotated through 360°, the voltages across the two loop windings rise and fall according to the angle between the aircraft heading and the station direction. As the bars are rotated, the phase of the induced voltages reverses each time a null is passed. Plotting the voltage and phase of each winding as the aircraft is rotated yields the graph in Figure 5-4.

The perpendicular-bar voltage is proportional to the cosine of the angle to the station, and the parallel-bar voltage is proportional to the sine of the angle to the station. The signals from these two bars are referred to as the cosine signal and sine signal, respectively.

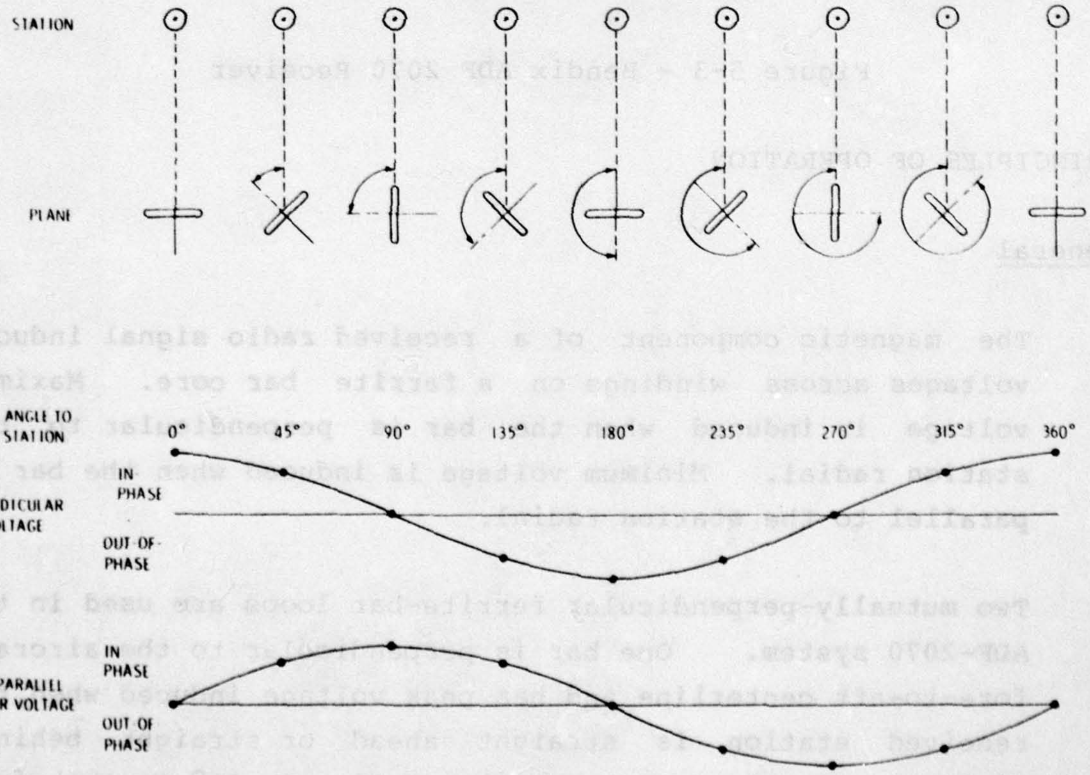


Figure 5-4 - ADF Loop Voltages

In a normal aircraft installation, a dc resolver is used to provide a visual indication of the bearing to the station. In the present application, only electrical outputs are required.

Signal Processing

In Figure 5-5 the amplitude of an rf signal is indicated by the height of the rectangle representing the signal at a point; an arrow in the box represents phase of the rf signal. An arrow pointing up indicates an rf signal with phase +90^{o} ahead of the sense antenna signal. This phase lead is due to the inherent phase difference between the magnetic component of the rf signal received by the loop and the electrical component of the rf signal received by the sense antenna. An arrow in the signal-representative rectangles of Figure 5-5 that points down represents an rf signal 180^{o} out of phase with the +90^{o} signal; this signal lags the sense antenna signal by 90 degrees (-90^{o}).

RF signals are received by loops A and B and amplified. The loop signals are proportional to the sine and cosine of the angle to the received station. Each loop signal is applied to a balanced modulator along with a 31-Hz modulation square wave. A balanced modulator passes an input signal to its output without phase reversal when the modulation input is positive, but reverses the phase of the input signal when the modulation input is negative. The modulation input to each balanced modulator is a 31-Hz square wave, so the input rf signals appear at the modulator outputs reversing phase at a 31-Hz rate. The 31-Hz modulation inputs are, however, out of phase by 90^{o} and when the balanced modulator outputs are added together the 90^{o} phase separation breaks the added signal into four equal segments per 31-Hz cycle. In Figure 5-6 a station at 45^{o} is used as an example.

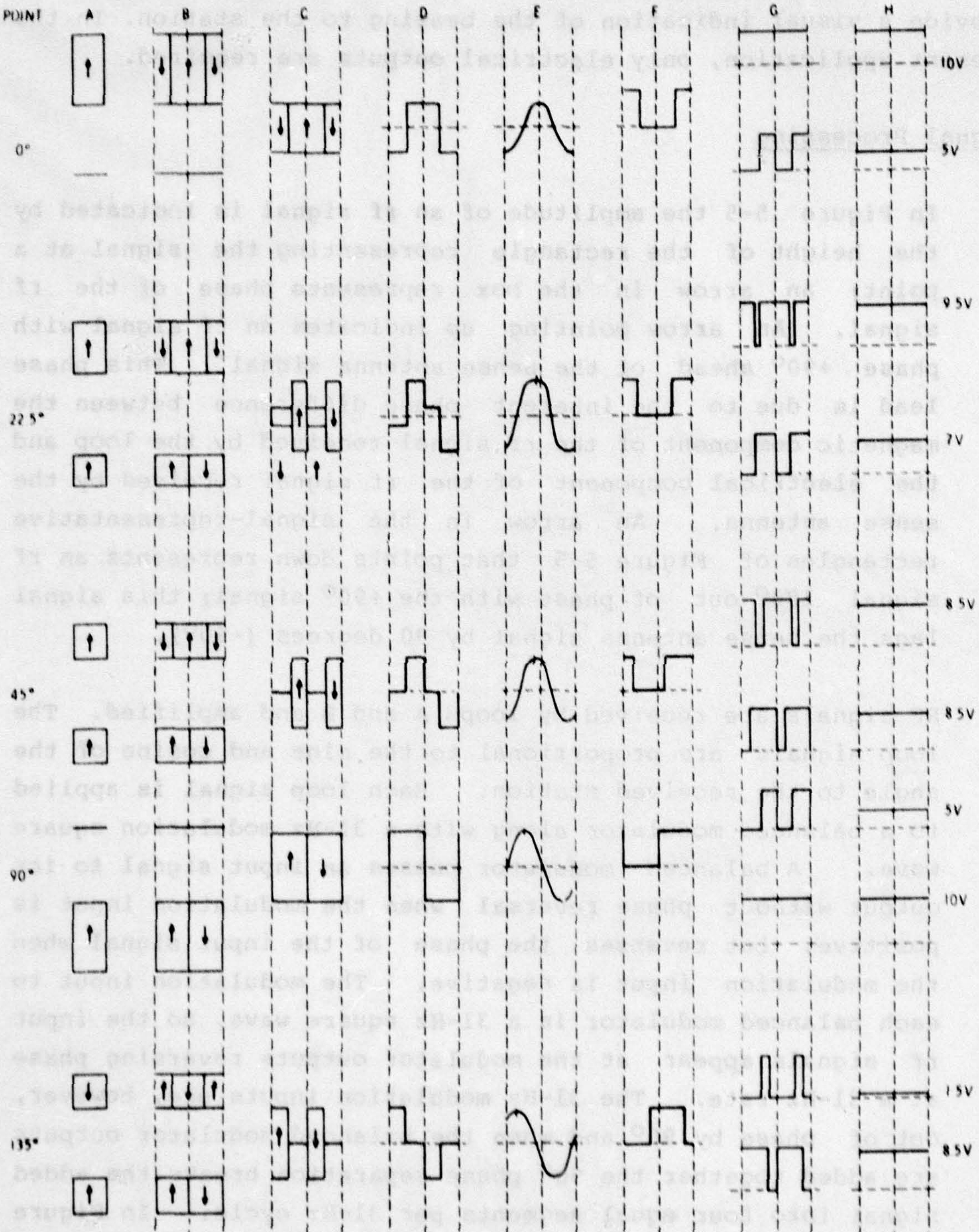

POINT
A
B
C
D
E
F
G
H
0°
22.5°
45°
90°
135°
10V
5V
9.5V
7V
8.5V
8.5V
5V
10V
7.5V
8.5V

Figure 5-5 - ADF System Waveforms (Reference Points in Figure 5.6)

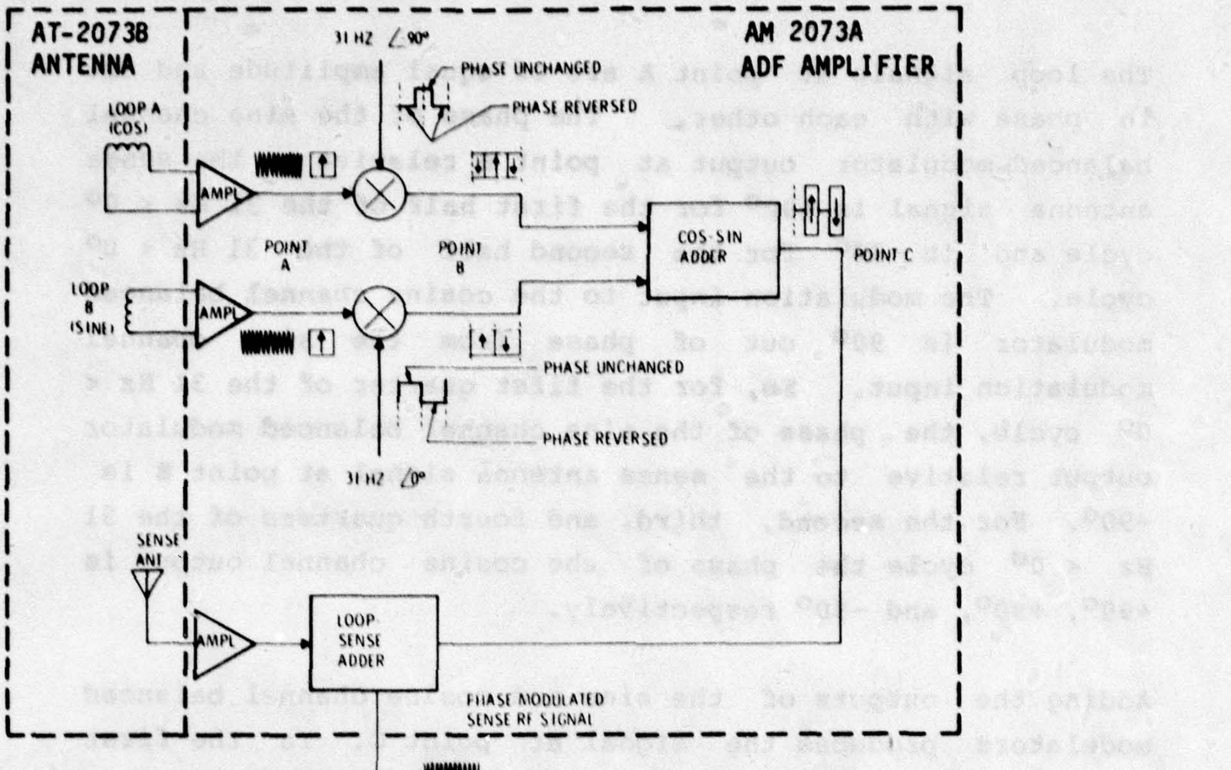

AT-2073B
ANTENNA
AM 2073A
ADF AMPLIFIER
31 HZ ∠90°
PHASE UNCHANGED
PHASE REVERSED
LOOP A (COS)
AMPL
POINT A
POINT B
COS-SIN ADDER
POINT C
LOOP B (SINE)
AMPL
PHASE UNCHANGED
PHASE REVERSED
31 HZ ∠0°
SENSE ANT
AMPL
LOOP SENSE ADDER
PHASE MODULATED SENSE RF SIGNAL
DF-2071A
ADF RECEIVER
RECEIVER CIRCUITS
POINT D
31 HZ ∠-90°
BANDPASS FILTER
EXCLUSIVE OR GATE
FILTER AMPLIFIER
COS TO INDICATOR
POINT E
POINT G
POINT H
INVERTER SQUARER
POINT F
EXCLUSIVE OR GATE
FILTER AMPLIFIER
SIN TO INDICATOR
POINT I
31 HZ ∠0°

Figure 5-6 - ADF 2070 Block Diagram

The loop signals at point A are of equal amplitude and are in phase with each other. The phase of the sine channel balanced modulator output at point B relative to the sense antenna signal is +90° for the first half of the 31 Hz < 0° cycle and is -90° for the second half of the 31 Hz < 0° cycle. The modulation input to the cosine channel balanced modulator is 90° out of phase from the sine channel modulation input. So, for the first quarter of the 31 Hz < 0° cycle, the phase of the sine channel balanced modulator output relative to the sense antenna signal at point B is -90°. For the second, third, and fourth quarters of the 31 Hz < 0° cycle the phase of the cosine channel output is +90°, +90°, and -90° respectively.

Adding the outputs of the sine and cosine channel balanced modulators produces the signal at point C. In the first quarter of the 31 Hz < 0° cycle, the cosine channel and sine channel signals are of equal amplitude but opposite phase (-90° and +90°) so they cancel and the output is zero. In the second quarter cycle, amplitudes are equal and the outputs are in phase so a double amplitude +90° signal results. In the third quarter cycle, amplitudes are equal but the phases are again opposite (+90° and -90°) so the adder output is zero. In the fourth quarter cycle, amplitudes are still equal and both outputs are in phase so a double amplitude signal results, this time of -90° phase.

The sum of the cosine and sine channel signals is added to the amplified sense antenna signal which produces an rf signal with phase modulation. This phase modulation must not be confused with the 0° or 180° modulation produced by the 31-Hz modulators. This phase modulation of the rf signal is continuously variable in phase with degrees of phase shift dependent upon the amplitude of the combined loop signals. The phase of the modulated signal leads or lags the unmodulated rf sense signal depending on whether the combined loop signal phase is +90° or -90°.

From the loop-sense adder the phase modulated rf signal goes to the receiver circuits. Conventional receiver circuits provide station selectivity, amplification, and signal detection. The detected, phase-modulated, rf signal is a stepped waveform (see Figure 5-5 point D) whose instantaneous polarity and amplitude correspond to the phase and amplitude of the signal from the cos-sin adder.

A 31 Hz bandpass filter passes only the 31 Hz fundamental of the detected, phase modulated signal. The phase of this sine wave (point E) relative to the 31 Hz @ 0° modulation signal is equal to the bearing angle to the received station. The sine wave is converted to a square wave in the inverter and squarer. Then this square wave and the 31 Hz @ 0° signal are used to measure the phase difference.

The exclusive-or gates and filter-amplifiers in the block diagram are used to derive signals proporitional to the sine and cosine of the bearing angle to drive a dc resolver for visual bearing indication. This visual indication system is not needed in our application.

Table 5-2 gives specifications for the Bendix Model 2070 ADF system. One specification, the sensitivity, relates directly to the operating range of the guidance subsystem. The AN/TRN beacon specifications of Table 5-1 indicate that the beacons will produce the 50μV/meter field required by the ADF receiver at a range of 25 nmi (46.3 km). This is well in excess of that required for the gliding airdrop application.

5.2.3 Bearing Interface

The two 31.25 Hz square waves with variable phase equal to the bearing angle must be processed to yield a digital output for use in the guidance computer. The conversion process must introduce no significant error.

TABLE 5-2 AUTOMATIC DIRECTION FINDER SYSTEM SPECIFICATIONS

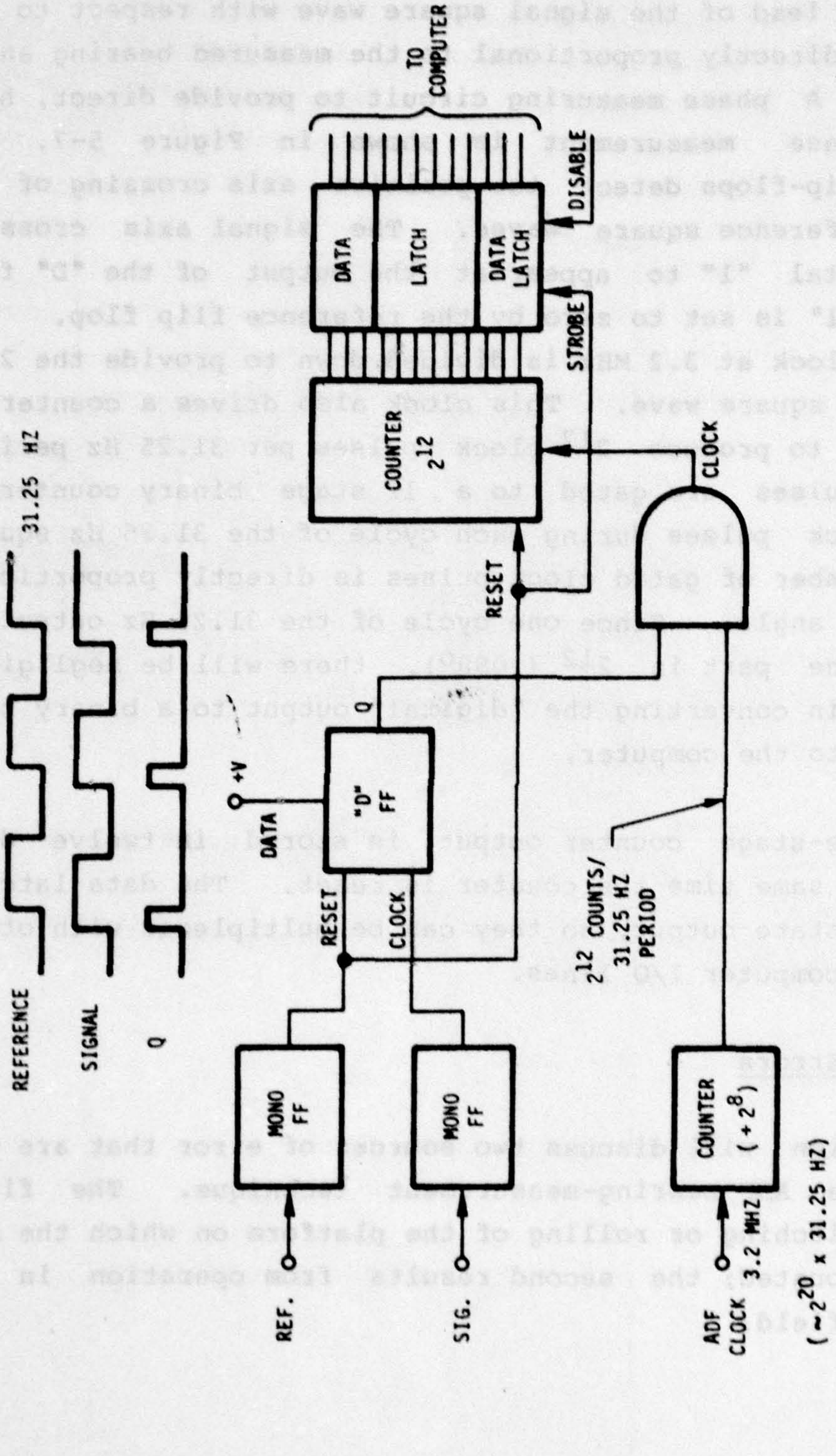
Type	Bendix System ADF 2070	
Cost	$1700 including	DF 2071A ADF Receiver AM-2073A ADF Amplifier AT-2073B Antenna
Volume	DF-2071A	4.45 cm x 15.9 cm x 23.4 cm
	AT-2073B	27.1 cm x 7.5 cm x 8.75 cm
	AM-2073A	3.23 cm x 9.96 cm x 11.48 cm
Weight	DF-2071A	1.27 kg
	AT-2073B	-
	AM-2073A	1.0 kg
Power	14 Watts	14/28 Volts
Frequency Range	200-1750 kHz	
Sensitivity	50µV/meter	
Accuracy	± 3° (200 to 850 kHz) from 60µV/m to 0.5 V/m	
	± 5° (851 to 1799 kHz) from 60 µV/m to 0.5 V/m	

The phase lead of the signal square wave with respect to the reference is directly proportional to the measured bearing angle in degrees. A phase measuring circuit to provide direct, high resolution phase measurement is shown in Figure 5-7. Two monostable flip-flops detect the positive axis crossing of the signal and reference square waves. The signal axis crossing causes a digital "1" to appear at the output of the "D" flip flop. This "1" is set to zero by the reference flip flop. The ADF receiver clock at 3.2 MHz is divided down to provide the 2070 ADF's 31.25 Hz square wave. This clock also drives a counter in the converter to produce 2^{12} clock pulses per 31.25 Hz period. These clock pulses are gated to a 12 stage binary counter to accumulate clock pulses during each cycle of the 31.25 Hz square wave. The number of gated clock pulses is directly proportional to the bearing angle. Since one cycle of the 31.25 Hz output is resolved to one part in 2^{12} $(.088^{\circ})$, there will be negligible accuracy loss in converting the "digital" output to a binary number for input to the computer.

The twelve-stage counter output is stored in twelve data latches at the same time the counter is reset. The data latches have a three state output, so they can be multiplexed with other inputs on the computer I/O lines.

5.2.4 System Errors

This section will discuss two sources of error that are peculiar to the ADF bearing-measurement technique. The first arises from pitching or rolling of the platform on which the ADF antenna is mounted; the second results from operation in the beacon's near field.


REF.
SIG.
ADF CLOCK
($\sim 2^{20}$ x 31.25 HZ) 3.2 MHZ
MONO FF
MONO FF
COUNTER ($\div 2^8$)
RESET
CLOCK
DATA
+V
"D" FF
Q
2^{12} COUNTS/ 31.25 HZ PERIOD
CLOCK
RESET
COUNTER 2^{12}
STROBE
DATA
LATCH
DATA LATCH
DISABLE
TO COMPUTER
REFERENCE
SIGNAL
Q
31.25 HZ

DATA LATCH MC14508B (DUAL 4 BIT LATCH)
2^{12} COUNTER MC14040B (12 BIT BINARY COUNTER)
"D" FF MC14013B (DUAL "D" WITH SET/RESET)
MONO FF MC14528B (DUAL RETRIGGERABLE/RESETABLE MONO-STABLE MULTIVIBRATOR)
2^8 COUNTER MC14040B (12 BIT BINARY COUNTER)
RESOLUTION - $360°/2^{12} = .088°$

Figure 5-7 - Digital Bearing Interface for the Bendix 2070 ADF Receiver

5.2.4.1 Effects of Receiving Antenna Orientation on ADF Bearing Accuracy

Pitch and roll of the gliding airdrop vehicle can produce errors in the measured bearing to the ground beacon. The geometry for pitch and roll is illustrated in Figure 5-8. Ferrite coil "A" is along the vehicle fore-aft axis while ferrite coil "B" is along the vehicle horizontal axis, perpendicular to coil A. The X axis points toward the beacon. The ferrite coils have maximum response when parallel to the magnetic field component which is horizontal and along the Y axis.

When the vehicle maneuvers, the response of the A and B coils is given by

$$Ha = H \cos \alpha_p \sin \beta \cos \phi$$
$$Hb = H \cos \alpha_r \cos \beta \cos \phi$$

where α_p = pitch angle
α_r = roll angle
β = bearing angle
ϕ = elevation angle

The bearing from the ADF receiver is obtained as:

$$\text{BEARING} = \tan^{-1} (Ha/Hb)$$
$$= \tan^{-1} \frac{\cos \alpha_p \tan \beta}{\cos \alpha_r}$$

Starting at 0° and at every 90° interval, there is negligible bearing error due to pitch and roll. Maximum error occurs at 90° intervals starting at 45°. At 45° bearing with 10° pitch or roll, about 0.44° bearing error occurs; with 20° pitch or roll, about 1.8° bearing error is produced.

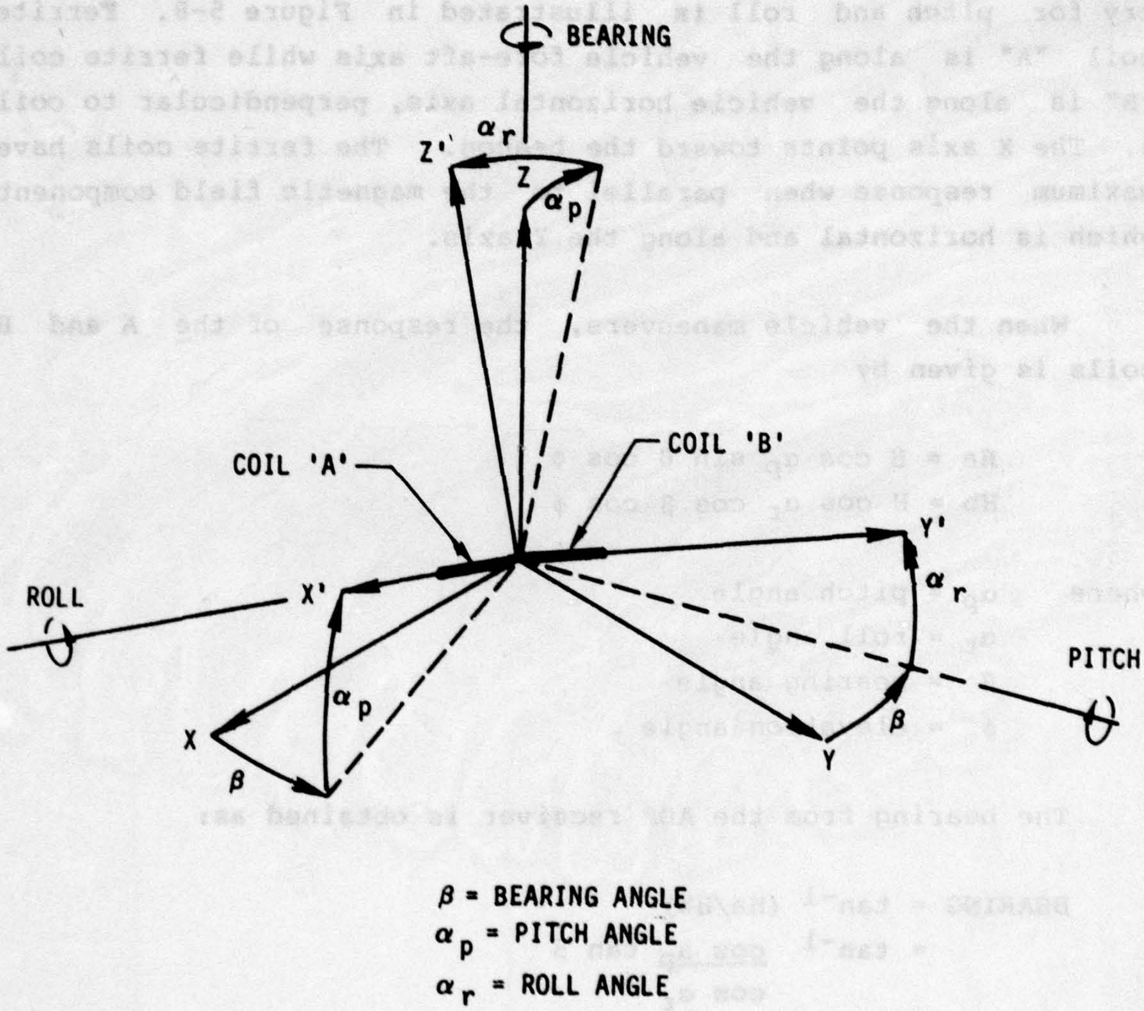

BEARING
α_r
Z'
Z
α_p
COIL 'A'
COIL 'B'
Y'
α_r
ROLL
X'
PITCH
α_p
X
β
Y
β
β = BEARING ANGLE
α_p = PITCH ANGLE
α_r = ROLL ANGLE

Figure 5-8 - Pitch and Roll Angle Geometry

5.2.4.2 Effects of Near-Field Operation on ADF Bearing Accuracy

ADF systems are normally used at distances of many wavelengths from the beacon transmitter. For the gliding airdrop vehicle, however, the point of closest approach will typically be less than a wavelength at the lowest beacon frequency ($\lambda = 1500$ m, 200 kHz) to perhaps several wavelengths at the highest frequency ($\lambda = 171$ m, 1750 kHz). At these distances, far-field approximations are no longer accurate and near-field effects must be considered.

In the far-field, the electric and magnetic components of the radiated electro-magnetic energy are in phase, and their amplitude ratio equals the impedance of free-space. In the near-field, the radial electric component becomes significant, the phase shift between the electric and magnetic fields has large deviations from the in-phase condition, and the ratio of electric to magnetic fields varies widely.

ADF Receiver Bearing Measurement Techniques

The methods used for bearing measurement in the ADF receiver must be examined to assess the effects of near-field operation.

The Bendix ADF 2070 Receiver uses three antennas to measure direction. Two horizontal ferrite bar antennas at right angles to each other are used to measure the direction of the magnetic component of the received radio signal. The sense antenna receives the electric component of the beacon signal which is used to resolve the 180° ambiguity inherent in the measurements of the magnetic component's direction.

The magnetic component of the signal radiated by the ground beacon is horizontal and tangent to the radial to the beacon at all ranges. Thus, maximum voltage is induced in a ferrite bar antenna when it is horizontal and perpendicular to the beacon radial.

At large distances from the antenna (greater than five wavelengths), the radial electric field is effectively zero and the tangential electric field is vertical (at low elevation angles). The ratio of the tangential electric field and the magnetic field equals the characteristic impedance of free space and the electric and magnetic fields are in-phase.

In the ADF receiver antenna, the magnetic component induces voltages in the bar antennae which are 90° out of phase with the electric field received by the sense antenna.

Phase Modulation

The electric and magnetic field voltages are summed in the antenna amplifier to produce phase modulation of the magnetic field voltages (see detailed description of receiver operation, section 5.2.2). Phase modulation in the antenna amplifier allows a single signal containing complete bearing information to be translated, filtered and amplified in the ADF receiver without introducing significant error.

The phase modulation is demodulated in the receiver. The phase shift of the 31.25 fundamental component is proportional to bearing angle. The phase modulation produced by summing the sense and bar antenna signals is sensitive to both signals' relative amplitudes and phases. Figure 5-9 shows the phasor diagram for the phase modulation produced by summing. The magnetic component signals are phase modulated 0° or 180° and in amplitude depending upon the bearing angle to the beacon.

If the magnetic and electric component signals are not orthogonal, or if the magnetic component signal becomes too large with respect to the electric component signal, non-linearity will

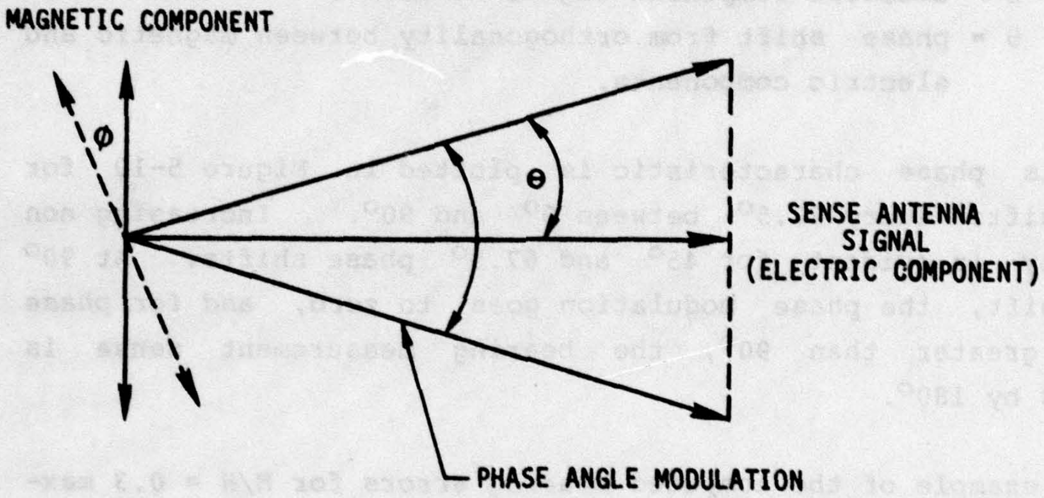

MAGNETIC COMPONENT
φ
θ
SENSE ANTENNA
SIGNAL
(ELECTRIC COMPONENT)
PHASE ANGLE MODULATION

Figure 5-9 - Phasor Diagram for Phase Modulation of the Magnetic Component Signal

be introduced in the phase modulation with resulting bearing errors. If a 90° phase shift occurs between the electric and magnetic fields, the phase modulation disappears and no bearing measurement is possible with the ADF receiver.

The phase modulation produced by summing the electrical and magnetic signals is given by:

$$\phi = \tan^{-1} (\cos \theta/(H/E + \sin \theta))$$

where H = magnetic component signal at summer
E = electric component signal at summer
θ = phase shift from orthogonality between magnetic and electric components.

This phase characteristic is plotted in Figure 5-10 for phase shifts every 22.5° between 0° and 90°. Increasing non linearity is evident for 45° and 67.5° phase shifts. At 90° phase shift, the phase modulation goes to zero, and for phase shifts greater than 90°, the bearing measurement sense is reversed by 180°.

An example of the computed bearing errors for E/H = 0.3 maximum for each of the sine or cosine antenna signals is given in Table 5-3.

TABLE 5-3 BEARING ERROR VERSUS PHASE SHIFT

Phase Shift (φ)	0°	45°	67.5°
Bearing (β)	Bearing Error (Degrees)		
0°	0	0	0
22.5°	0.81	-0.73	-2.06
45°	0	0	0
67	-0.81	0.73	2.06
90	0	0	0

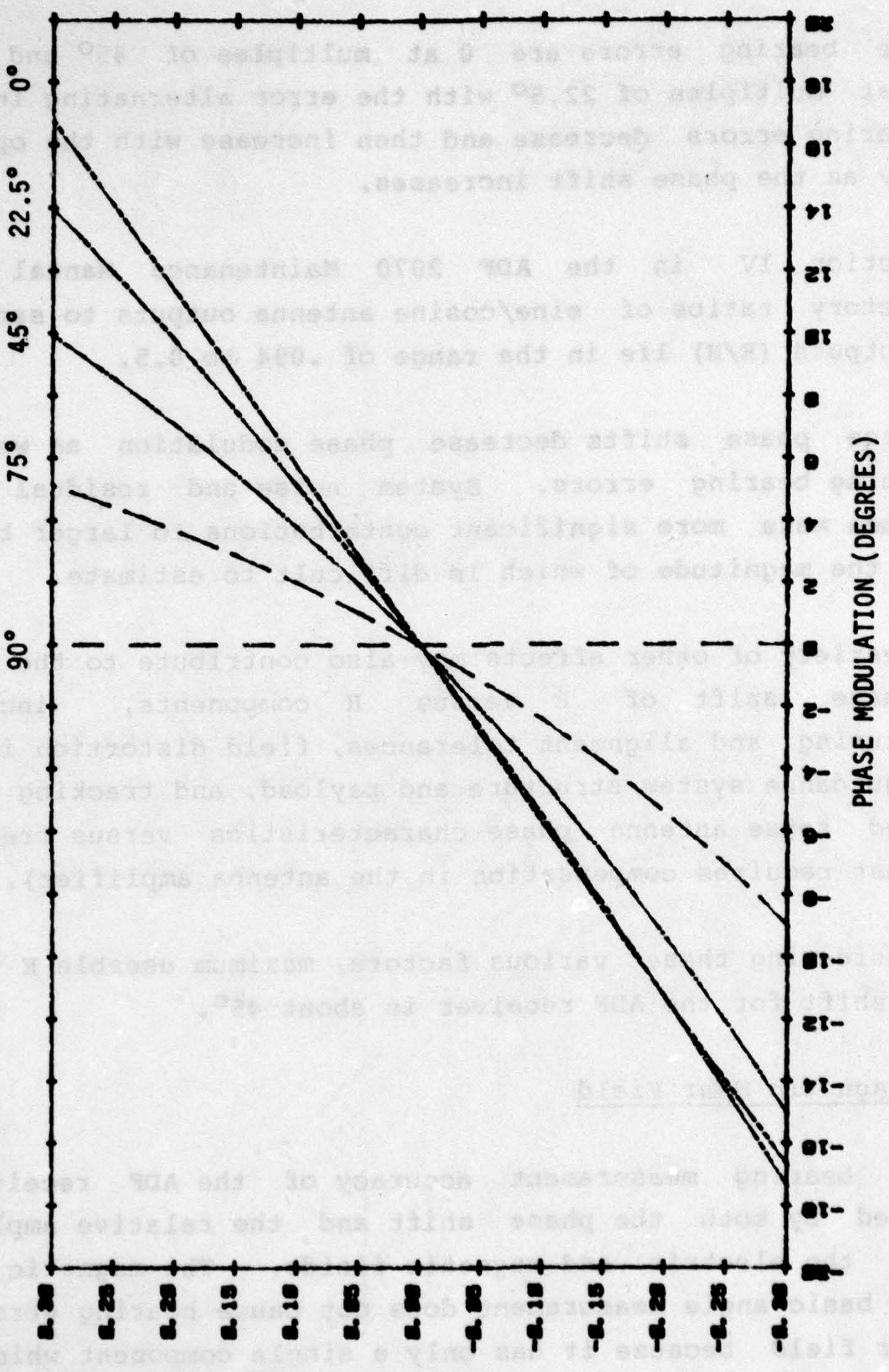


Figure 5-10 - Relative Amplitude of E/H Versus Phase Modulation for Several Phase Shifts of E Relative to H

The bearing errors are 0 at multiples of 45° and reach maxima at multiples of 22.5° with the error alternating in sign. The bearing errors decrease and then increase with the opposite polarity as the phase shift increases.

Section IV in the ADF 2070 Maintenance Manual shows satisfactory ratios of sine/cosine antenna outputs to sense antenna outputs (E/H) lie in the range of .094 to 0.5.

Large phase shifts decrease phase modulation as well as introducing bearing errors. System noise and residual errors will then make more significant contributions to larger bearing errors, the magnitude of which is difficult to estimate.

A variety of other effects may also contribute to the effective phase shift of E versus H components, including manufacturing and alignment tolerances, field distortion induced by the guidance system structure and payload, and tracking of the loop and sense antenna phase characteristics versus frequency (this last requires compensation in the antenna amplifier).

Considering these various factors, maximum useable E versus H phase shift for the ADF receiver is about 45°.

Electromagnetic Near Field

The bearing measurement accuracy of the ADF receiver is influenced by both the phase shift and the relative amplitude ratio of the electric and magnetic fields. The magnetic field used for basic angle measurement does not cause bearing errors in the near field because it has only a single component which always lies perpendicular to the beacon radial. The amplitude ratio of the electric and magnetic fields does vary in the near field, but system adjustments can allow operation over reasonably wide variations. Phase shift between the E and H components beyond about 45 degrees cannot be compensated in the system.

For an electric dipole less than 0.1λ high, such as the beacon antenna, the electromagnetic field is given by:

$$E_r = -\ (30\ \ell\ \lambda\ I/\pi)\ (\cos\theta/r^3)\ (\cos V - \alpha r \sin V)$$

$$Et = (30\ \ell\ \lambda\ I/2\pi)\ (\sin\theta/r^3)\ (\cos V - \alpha r \sin V - (\alpha r)^2 \cos V)$$

$$H = (1/4\pi)\ \ell\ I\ (\sin\theta/r^2)\ (\sin V - \alpha r \cos V)$$

Above a perfectly reflecting plane, the above values would double. Here,

Er = radial electric field component
Et = tangential electric field component
H = magnetic field component

The geometry is shown in Figure 5-11 with:

r = radius to point M, meters
θ = angle from dipole axis to point M
I = current in dipole
λ = wavelength, meters
f = frequency, Hz
ℓ = length of dipole
$\omega = 2\pi f$
$\alpha = 2\pi/\lambda$
c = velocity of light, meters/sec
$V = (\omega t - \alpha r)$, radians

Using complex notation, removing the phase shift due to wave propagation and changing the angle to elevation angle ϕ, the fields become:

$$E_r = -\ (30\ \ell\ \lambda\ I/\pi)\ (\sin\phi/r^3)\ (e^{jwt} - \alpha r\ e^{j(wt-\pi/2)})$$

$$Et = (15\ \ell\ \lambda\ I/\pi)\ (\cos\phi/r^3)\ (e^{jwt} - \alpha r\ e^{j(wt-\pi/2)} - (\alpha r)^2\ e^{jwt})$$

$$H = (1/4\pi)\ \ell\ I\ (\cos\phi/r^2)\ (e^{j(wt-\Pi/2)} - \alpha r\ e^{jwt})$$

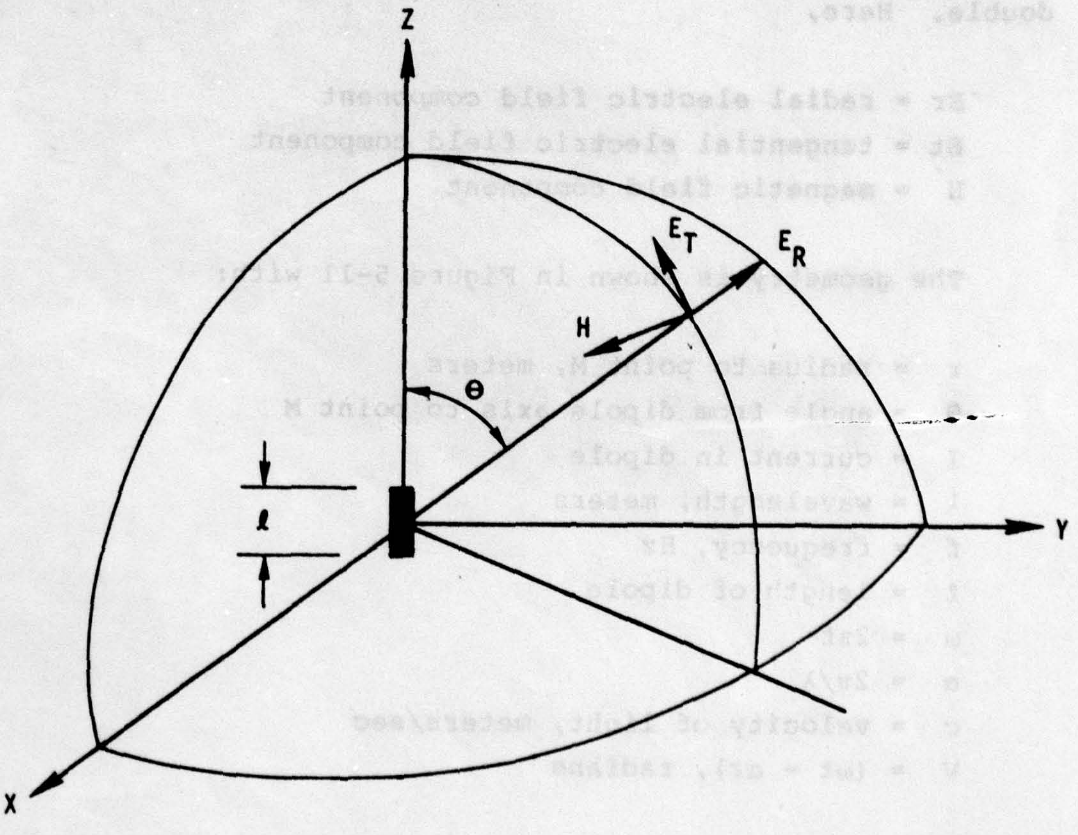

Z
E_T
E_R
H
Θ
ℓ
Y
X

Figure 5-11 - Electric and Magnetic Components in Spherical Coordinates for an Electric Dipole

The relative phase difference between the electric and magnetic components is plotted in Figure 5-12 for ranges to 1000 meters at a frequency of 200 kHz. The phase difference decreases towards zero as the range increases, but is a function of both range and elevation angle.

The amplitudes of the tangential electric and magnetic fields are proportional to the cosine of the elevation angle, thus angles up to about 75° - 80° provide useable electric and magnetic fields (ie, down 12 - 15 dB) for the ADF receiver within the 6 km altitude constraints of the gliding air drop vehicle. Just before the gliding air drop vehicle lands, the elevation angle from the beacon will approach zero. Elevation angles from 0 to 80° are plotted in Figure 5-12. To scale to other wavelengths, Figure 5-13 gives the phase difference between the E and H components versus range up to two wavelengths.

As discussed above, the ADF receiver can tolerate phase shifts between the electric and magnetic fields up to perhaps 45° before significant bearing errors will be introduced. At the lowest frequency, 200 kHz, a 45° phase shift occurs at ranges of about 500 meters at low and high elevation angles. This should be considered the minimum useable range. Range scales inversely with frequency so at higher frequencies, the minimum range would be correspondingly lower.

The preceeding discussion has addressed the idealized case of a dipole over a perfectly conducting plane. In land applications, the ground will have lower conductivity of 2 to 15 millimhos per meter which will alter the field strengths and phase relationships somewhat.

5.2.5 Selection of ADF/Beacon Operating Frequency

The operating frequency of the ADF receiver and beacon should be selected to provide the desired range (13 km) and mini-

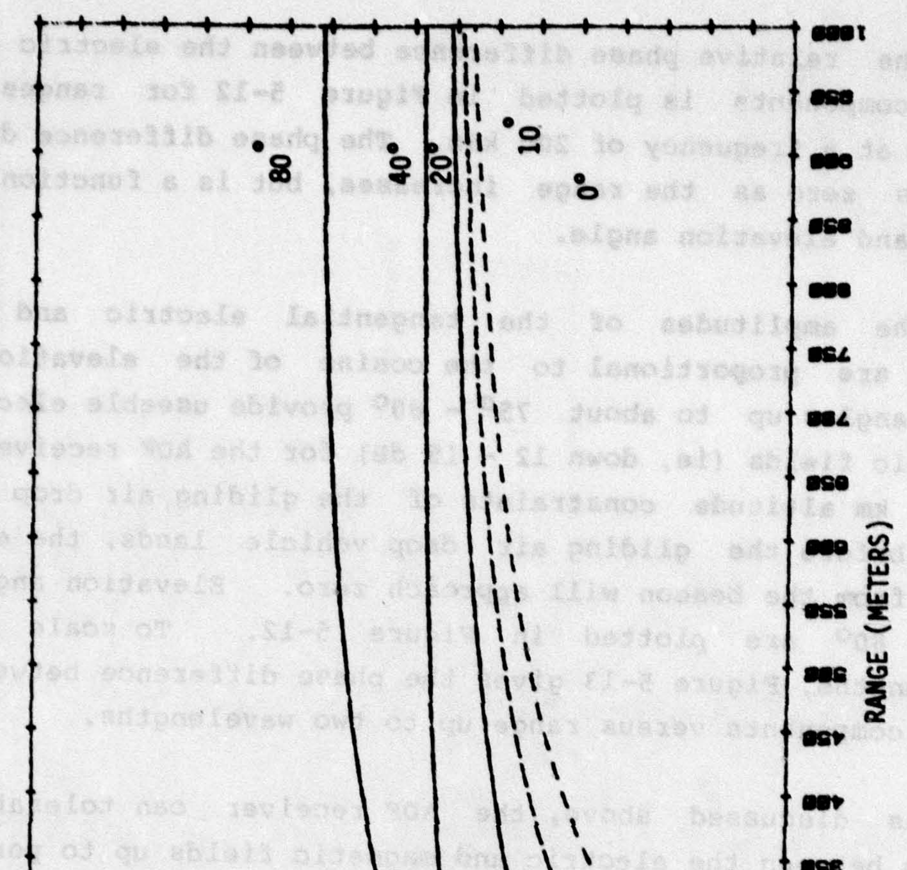


Figure 5-12 - Phase Difference Between E and H Components versus Range at Several Elevation Angles (Operation at 200 KHz)

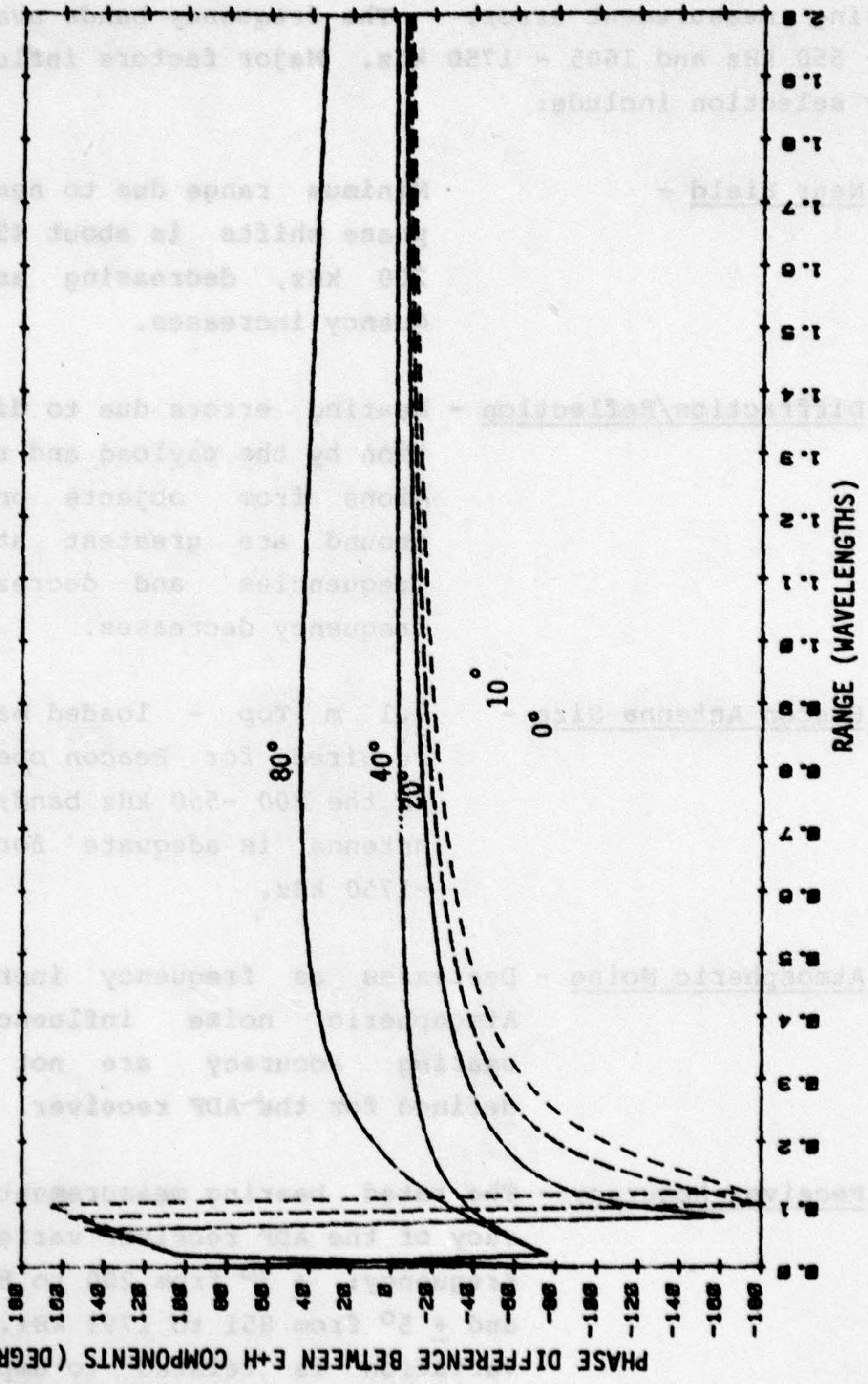


Figure 5-13 - Phase Difference Between E and H Components Versus Range (in wavelengths) at Several Elevation Angles

mize bearing measurement error. The frequency bands available are 200 - 550 kHz and 1605 - 1750 kHz. Major factors influencing frequency selection include:

1. Near Field - Minimum range due to nearfield phase shifts is about 450 m at 200 kHz, decreasing as frequency increases.

2. Diffraction/Reflection - Bearing errors due to diffraction by the payload and reflections from objects on the ground are greatest at high frequencies and decrease as frequency decreases.

3. Beacon Antenna Size - 9.1 m Top - loaded mast is required for Beacon operation in the 200 -550 kHz band; 4.57m antenna is adequate for 1605 -1750 kHz.

4. Atmospheric Noise - Decreases as frequency increases. Atmospheric noise influences on bearing accuracy are not well defined for the ADF receiver.

5. Receiver Accuracy - The rated bearing measurement accuracy of the ADF receiver varies with frequency: ± 3° from 200 to 850 kHz and ± 5° from 851 to 1799 kHz. This variation is related to amplitude and phase balance characteristics in the ADF amplifier and ADF antenna.

5.3 Data Acquisition

The I/O diagram for guidance subsysem 2c is shown in Figure 5-14. The comments of sections 2.3 and 3.2 apply here as well.

5.4 Mechanical Design

A mechanical design concept for the airborne guidance package of guidance subsystem 2c is depicted in the engineering drawing of Figure 5-15. The narrow and elongated form is driven by the somewhat arbitrary choice of a pneumatic cable-cylinder actuator (section 10.1) for this subsystem; any other subsystem using the same actuator would have a similar appearance. Conversly, the appearance of a design based arund an electric winch actuator (section 10.2) would be quite different.

The guidance package shown in the figure is composed of three major assemblies.

The first major assembly is the actuator system. It is a purchased part, structurally supported by a 2 in. by 6 in. by .25 thick aluminum extruded channel (6063-T5 alloy). The channel requires little fabrication except cutting to a specified length, and drilling holes to accomodate bolting to the actuator and shock absorber system. A protective surface finish of chromate per MIL-C-5541 should be adequate for the intended environment. This part is readily available and is purchased locally in the contractors locality.

The second major assembly is the guidance cannister which is mainly a 10 inch diameter extruded tube (6063-75 alloy). The basic tube can be purchased, cut to a specified length. A 10-inch diameter ring one inch thick will be fusion-welded on each end (welded per MIL-W-8604) to provide a mounting flange for the cannister covers and seals. All fasterners will be corrosion resistant steel of the AN-4 type. The shock mount brackets will

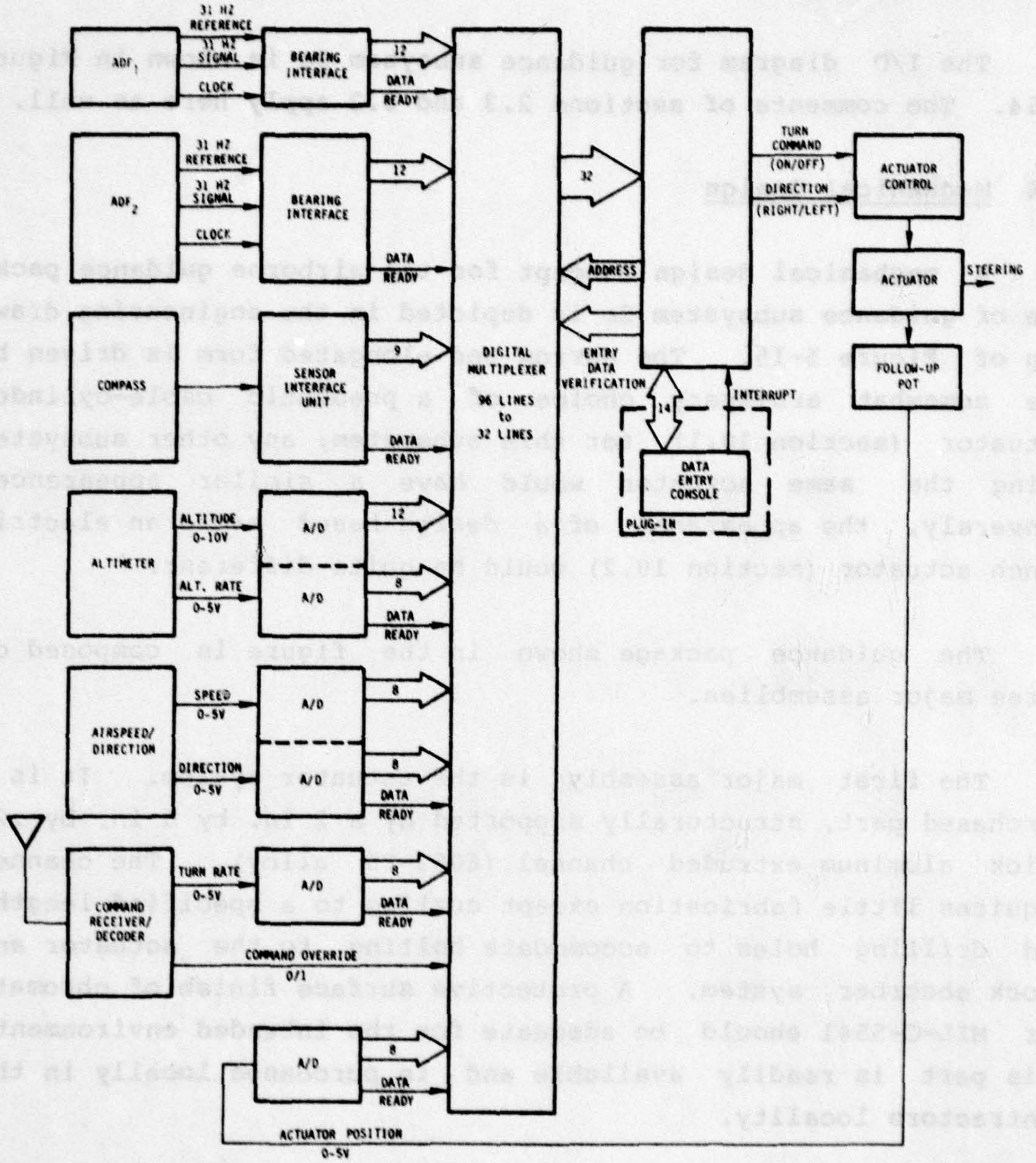

ADF1
31 HZ REFERENCE
31 HZ SIGNAL
CLOCK
BEARING INTERFACE
12
DATA READY
ADF2
31 HZ REFERENCE
31 HZ SIGNAL
CLOCK
BEARING INTERFACE
12
DATA READY
COMPASS
SENSOR INTERFACE UNIT
9
DATA READY
ALTIMETER
ALTITUDE 0-10V
ALT. RATE 0-5V
A/D
A/D
12
8
DATA READY
AIRSPEED/ DIRECTION
SPEED 0-5V
DIRECTION 0-5V
A/D
A/D
8
8
DATA READY
COMMAND RECEIVER/ DECODER
TURN RATE 0-5V
A/D
8
DATA READY
COMMAND OVERRIDE 0/1
A/D
8
DATA READY
ACTUATOR POSITION 0-5V
DIGITAL MULTIPLEXER 96 LINES to 32 LINES
32
ADDRESS
ENTRY DATA VERIFICATION
14
INTERRUPT
DATA ENTRY CONSOLE
PLUG-IN
TURN COMMAND (ON/OFF)
DIRECTION (RIGHT/LEFT)
ACTUATOR CONTROL
ACTUATOR
STEERING
FOLLOW-UP POT

Figure 5-14 - Guidance Subsystem 2c I/O Block Diagram

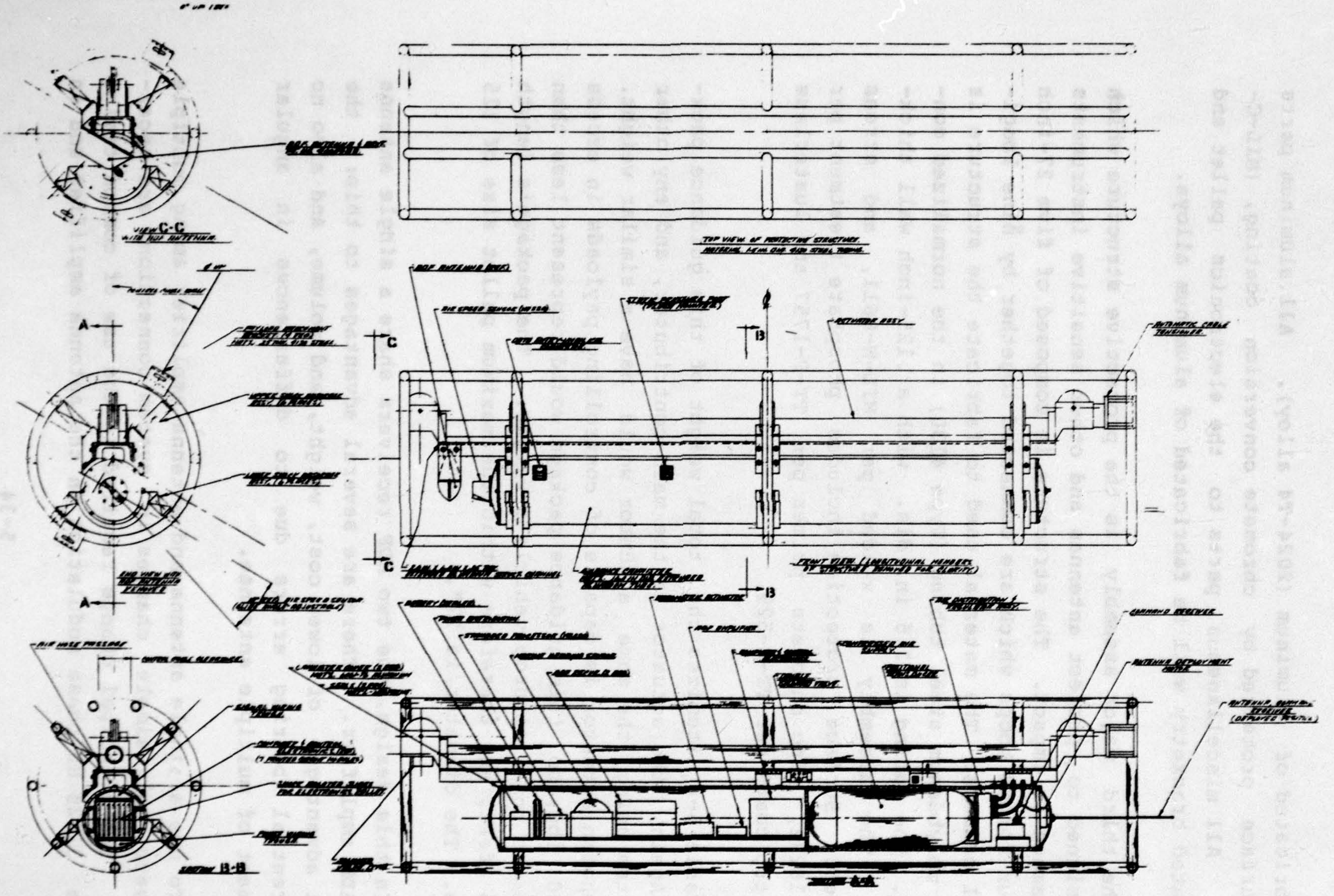

VIEW C-C
WITH ADF ANTENNA
END VIEW WITH ADF ANTENNA REMOVED
SECTION B-B
A
B
C
TOP VIEW OF PROTECTIVE STRUCTURE
ADF ANTENNA (REF.)
AIR SPEED SENSOR
ACTUATOR ASSY
AUTOMATIC CABLE TENSIONER
FRONT VIEW (LONGITUDINAL MEMBERS OF STRUCTURE REMOVED FOR CLARITY)
POWER DISTRIBUTION
ADF AMPLIFIER
COMMAND RECEIVER
ANTENNA DEPLOYMENT MOTOR
SECTION A-A

Figure 5-15 - Engineering Drawing of an Airborne Guidance Package for Subsystem 2c

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be fabricated of aluminum (2024-T4 alloy). All aluminum parts will surface protected by chromate conversion coating, (MIL-C-5541). All miscellaneous parts to the electronics pallet and associated bracketry will be fabricated of aluminum alloys.

The third major assembly is the protective structure which is designed to protect antennas and other sensitive instruments from damage at impact. The structure is composed of five 27-inch diameter formed hoops which are connected together by nine longitudinal members. The material used to fabricate the structure is chrome molybdenum steel tubing (Type 4130) in the normalized condition. The tubing is 1.5 in. dia. with a .125-inch wall thickness. The assembly is welded per MIL-W-8611, and stress relieved. Surface protection includes phosphate treatment per MIL-C-16232, zinc chromate primer per TT-P-1757 and lusterless paint top coats per TT-E-529.

Table 5-4 itemizes the total weight of this guidance package. Again, the actuator is the main contributer, and any other subsystem using the same actuator would have a similar weight. The chosen actuator is capable of controlling payloads in excess of 6000 lbs, so this guidance package would represent less than 7% of the total airdrop vehicle's weight. The package's length is 9.5 feet, and therefore within the maximum pallet size of 115 inches. The diameter is 27".

In this design, the two ADF receivers share a single antenna and ADF amplifier. There are several advantages to this: the normal advantages of lower cost, weight, and volume, and also no differential bearing errors due to differences in angular alignment of multiple antennae.

To use a single antenna and antenna amplifier among multiple receivers only simple changes in system connections are necessary. The principal change required is the use of common timing of the 31.25 Hz phase modulation in the antenna amplifier and in the bearing interface circuitry. One receiver provides the 31.25 Hz signals to the antenna amplifier and also the reference 31.25 Hz square wave signal used in the bearing interface circuits. A block diagram of a multiple receiver arrangement is shown in Figure 5-16. Both receivers have their complete, original operating capability.

5.5 Equipment List and Prices for Guidance Subsystem 2c.

Table 5-5 lists equipment and prices for guidance subsystem 2c.

TABLE 5-4 GUIDANCE PACKAGE ITEMIZED WEIGHT

	PART	WT., lbs	
1.	Standard Processor	1.5	
2.	Marine Heading Sensor	4.5	
3.	ADF Receiver (2 required)	11.4	
4.	ADF Amplifier	.4	
5.	Barometric Altimeter	1.5	
6.	Computer	3.5	(est.)
7.	Battery	10.0	(est.)
8.	Actuator System Assy.	215.0	
9.	Interconnections; Connectors; Brackets; Misc.	8.0	(est.)
10.	Shock Absorbers Assy.	50.0	
11.	Protective Structure	64.0	
12.	Cannister & Internal Structure	65.0	
13.	Misc. Antenna & Sensors	1.0	
14.	Ant. Motor	2.0	
15.	Command Receiver & Associated Brackets	1.0	
16.	Hardware; Nuts & Bolts	3.0	
		441.0	

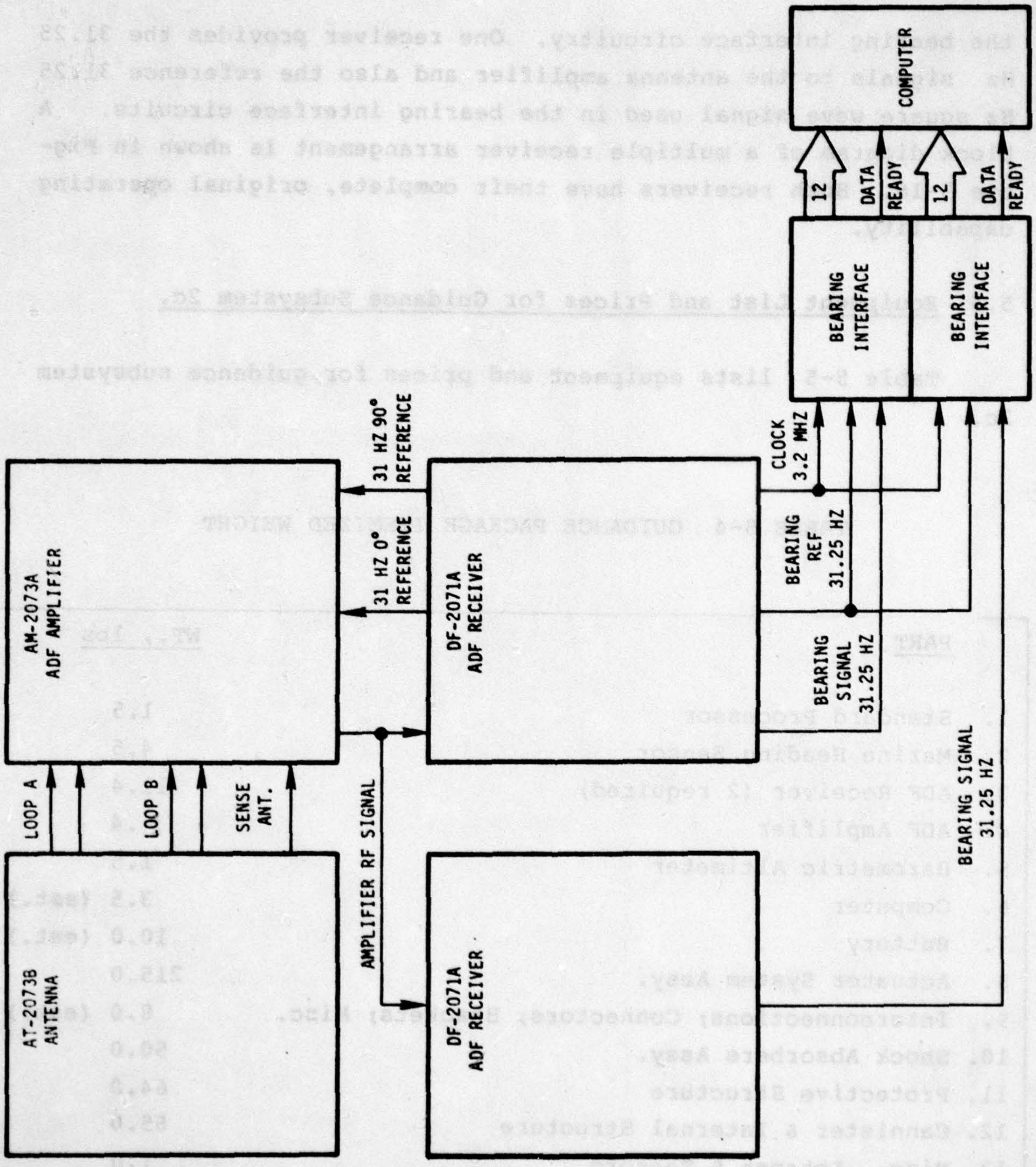

COMPUTER
12
DATA
READY
12
DATA
READY
BEARING INTERFACE
BEARING INTERFACE
CLOCK 3.2 MHZ
31 HZ 90° REFERENCE
BEARING REF 31.25 HZ
31 HZ 0° REFERENCE
AM-2073A ADF AMPLIFIER
DF-2071A ADF RECEIVER
BEARING SIGNAL 31.25 HZ
BEARING SIGNAL 31.25 HZ
LOOP A
LOOP B
SENSE ANT.
AMPLIFIER RF SIGNAL
AT-2073B ANTENNA
DF-2071A ADF RECEIVER

Figure 5-16 - Multiple ADF Receiver Connections

TABLE 5-5 EQUIPMENT LIST AND PRICES FOR GUIDANCE SUBSYSTEM 2c

Airborne Equipment	Price
Digicourse 101 Compass	$ 618.
Digicourse 261 Interface Unit	550.
Rosemount 1241 Altimeter with rate option	1,453.
J-Tek 320 Airspeed, direction indicator	545.
Bendix DF2071A ADF Receivers (2 req'd) @ 1172.	2344.
Bendix AT2073B ADF Antennas (2 req'd) @ 273.	546.
Bendix AM2073A ADF Amplifier (2 req'd) @ 261.	522.
Kraft KTR1-16 Manual Command Link Receiver/Decoder	700.
(Various) Single-board Computer with I/O	1000.
(Various) Electronics Power Supply	150. (est.)
Tol-o-matic Pneumatic Actuator and Associated Equipment*	1358.
Total per Vehicle+	$9,786.

Ground Equipment	Price
Frequency AN/TRN-30 Low-frequency Beacons (2 req'd @ $5000.)	$10,000.
Kraft KTT 1-16 Manual Command Link Encoder/Transmitter	700.
Total	$10,700.

* See Section 10.1 for Itemization

+ For price with Electric Actuation System, subtract $464.

NOTE: Total does not include any required interfacing circuitry, mounting brackets, fabrication, test, shell, or deploying aircraft's data entry terminal.

6. GUIDANCE SUBSYSTEM 4

6.1 General Description

Guidance subsystem 4 does not fix the position of the airdrop vehicle; rather, it is intended to implement guidance schemes requiring only partial-state specification (radial or cone-of-silence homing; see Introduction). It is similar to method 2(c), except that it requires only one ground beacon, and no altimeter, compass, or airspeed indicator. Furthermore, because there is only one beacon, the ADF tracks only one frequency. Both the bearing and the heading are measured relative to a vehicle-fixed axis; the difference between these angles is the homing deviation angle. An airborne signal processor derives the steering commands based on this angle. The guidance package could be provided with an aerodynamic tail to eliminate sideslip. In this case, an air-direction indicator would be unnecessary, because the heading would be along the vehicle-fixed axis, and the homing deviation angle would simply be the ADF-indicated bearing.

The airborne guidance package consists of the following:

1) one ADF receiver with antenna (Section 5.2.2)
2) an airborne signal processor
3) a command link receiver (Section 8.2)
4) an actuator with a follow-up potentiometer (Section 10)
5) a power supply

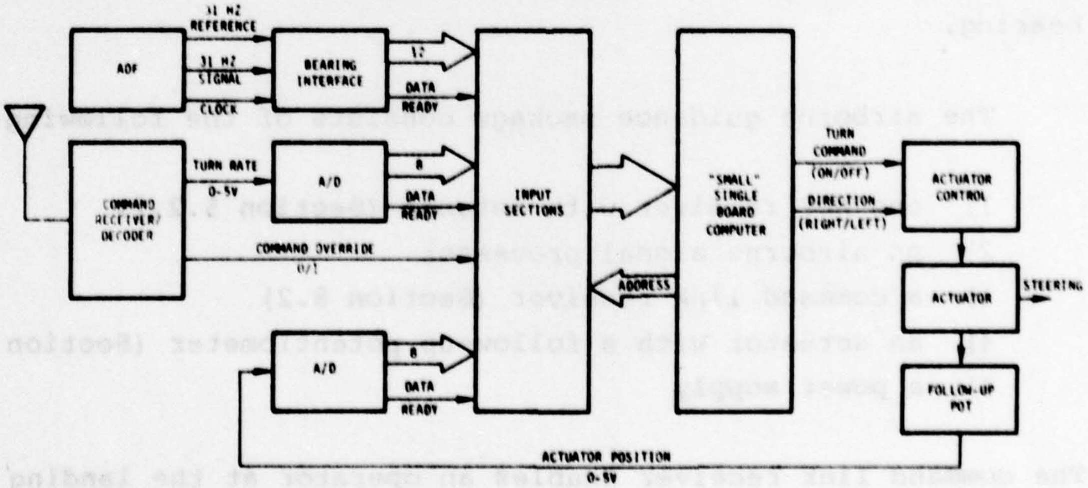
The command link receiver enables an operator at the landing zone to override the computed steering commands at short ranges. With the addition of a compass (section 7.1) or a heading gyro, this guidance subsystem could measure rotations of the horizontal (X-Y) component of the line of sight to the beacon. Driving this line-of-sight rate to zero results in direct homing (see Introduction).

The ground equipment consists of the following:

6) **one low-frequency beacon (Section 5.2.1)**
7) **a command link transmitter (Section 8.1)**

6.2 Data Acquisition

The I/O diagram for guidance subsystem 4 is shown in Figure 6-1. The comments of sections 2.3 and 3.2 apply here as well.



31 HZ REFERENCE
ADF
31 HZ SIGNAL
CLOCK
BEARING INTERFACE
12
DATA READY
COMMAND RECEIVER/ DECODER
TURN RATE 0-5V
A/D
8
DATA READY
COMMAND OVERRIDE 0/1
INPUT SECTIONS
"SMALL" SINGLE BOARD COMPUTER
ADDRESS
TURN COMMAND (ON/OFF)
DIRECTION (RIGHT/LEFT)
ACTUATOR CONTROL
ACTUATOR
STEERING
FOLLOW-UP POT
A/D
8
DATA READY
ACTUATOR POSITION 0-5V

Figure 6-1 - Guidance Subsystem 4 I/O Block Diagram

6.3 Mechanical Design

The mechanical design of the airborne guidance package for guidance subsystem 4 would be similar to that for subsystem 2c (described in Section 5.4) except for the following:

1) There would be no airspeed indicator, compass, or altimeter;
2) There would be only one ADF receiver and antenna;
3) The computer and battery would be smaller -- a hardware processing circuit might replace the single-board computer; and,
4) Because there is no baseline to define and no need for a ground barometric-pressure reference for an altimeter, there would probably be no need for a data-entry umbilical connector.

6.4 Equipment List and Prices for Guidance Subsystem 4

Table 6-1 lists equipment and prices for guidance subsystem 4.

TABLE 6-1 EQUIPMENT LIST AND PRICES FOR GUIDANCE SUBSYSTEM 4

Airborne Equipment	Price
Bendix DF2071A ADF Receiver (1 req'd)	$1172.
Bendix AT2073B ADF Antenna (1 req'd)	273.
Bendix AM2073A ADF Amplifier (1 req'd)	261.
Kraft KTR 1-16 Manual Command Link Receiver/Decoder	700.
(Custom) Processing Circuity	200. (est.)
(Various) Electronics Power Supply	150.
Tol-o-matic Pneumatic Actuator and Associated Equipment*	1358.
Total per Vehicle[+]	$4114.

Ground Equipment	Price
Frequency Egineering Laboratories AN/TRN-30 Low-frequency Beacon	$5000.
Kraft KTT 1-16 Manual Command Link Encoder/Transmitter	700.
Total	$5700.

* See Section 10.1 for Itemization

[+] For price with electric actuation system, subtract $464.

NOTE: Total does not include any required interfacing circuitry, mounting brackets, fabrication, test, or shell.

7. AIRBORNE SENSORS

This section describes sensors that are used in all full-state guidance subsystems. These comprise a compass, altimeter, and airspeed (or airspeed and direction) indicator.

7.1 Compass

All full-state guidance subsystems will use a simple compass as a heading reference. The compass recommended for these guidance subsystems is the Model 101 Marine Heading Sensor made by DigiCourse, Inc., in New Orleans, Louisiana. This sensor is an opto-electronically read magnetic compass that transmits heading information via a five-conductor cable to a Model 250 Interface Unit.

Figure 7-1 shows a photograph of the compass, and Figure 7-2 shows a cutaway view. The internal gimballing accommodates plus or minus 70 deg in pitch and roll. The binnacle contains compensation magnets mounted at each end of two plated brass rods that run at 90 deg to each other across the binnacle near the bottom. Should deviational influences in the guidance package be too great to be fully corrected by the standard magnets, all four magnets will be replaced by a set of stronger magnets supplied by the manufacturer. Table 7-1 gives detailed specifications for the compass.

The Model 250, shown in Figure 7-3 interfaces the heading sensor output to either an airborne computer or a data link encoder, depending on the guidance subsystem. This unit accepts the serial pulse train from the heading sensor, and converts it to one of several selectable outputs, as shown in the specifications given in Table 7-2.

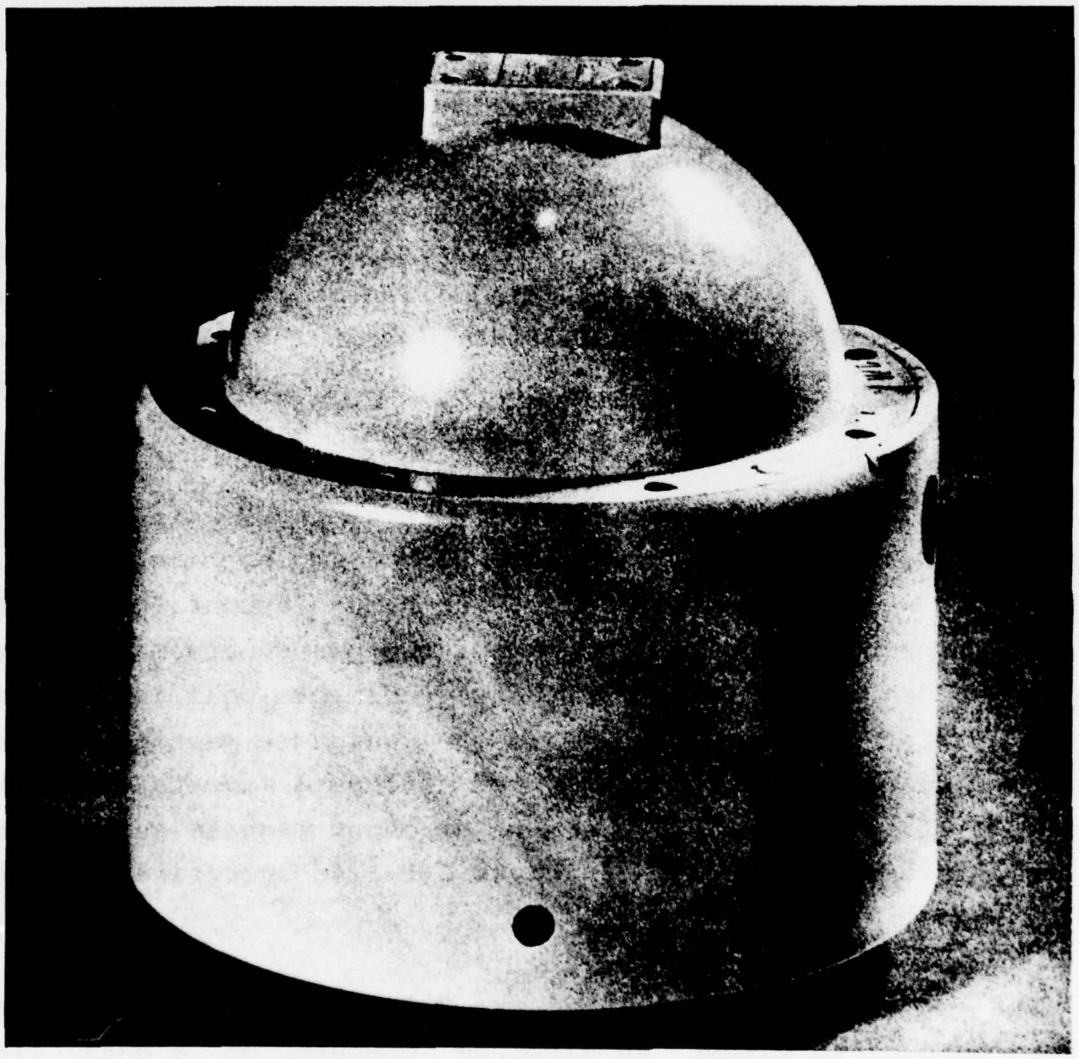


Figure 7-1 - Model 101 Marine Heading Sensor

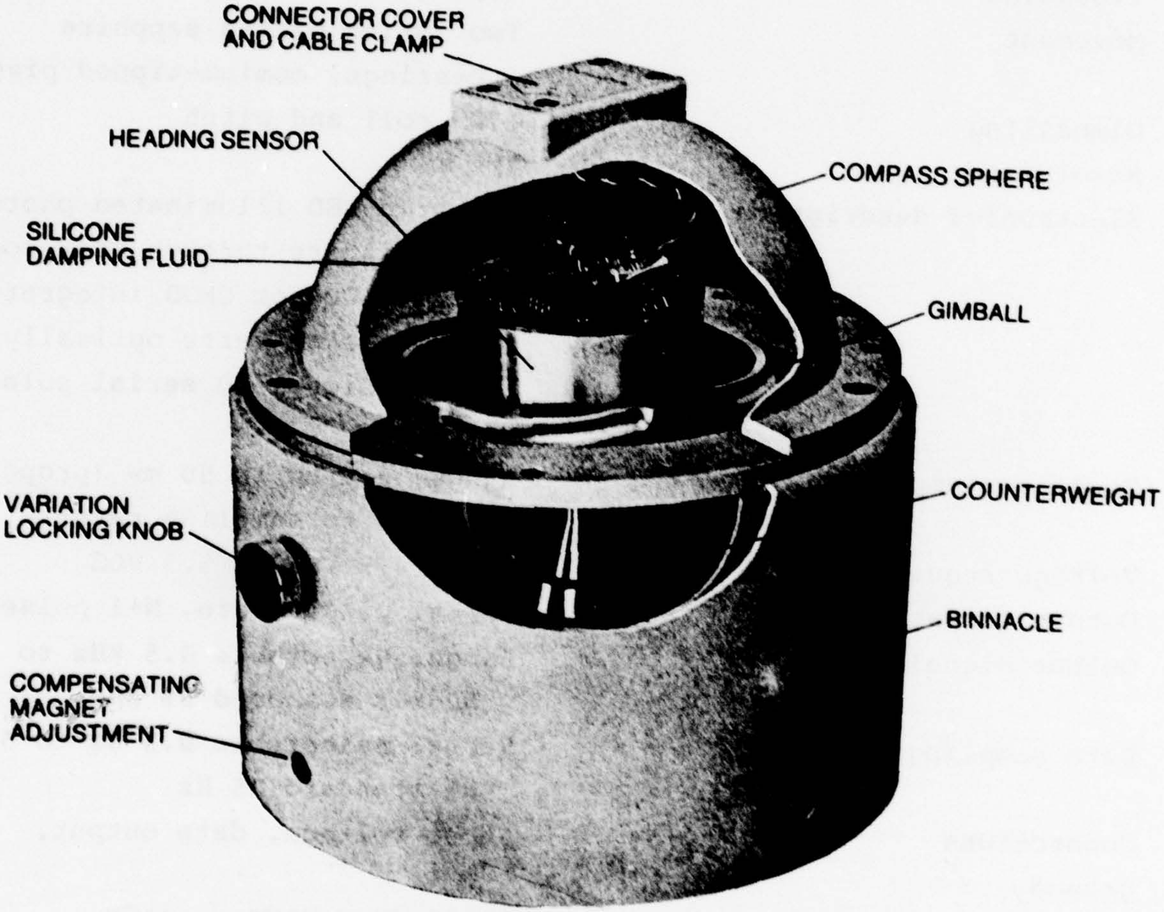

CONNECTOR COVER AND CABLE CLAMP
HEADING SENSOR
COMPASS SPHERE
SILICONE DAMPING FLUID
GIMBALL
COUNTERWEIGHT
VARIATION LOCKING KNOB
BINNACLE
COMPENSATING MAGNET ADJUSTMENT

Figure 7-2 - Cutaway View of the Model 101 Marine Heading Sensor

TABLE 7-1 SPECIFICATIONS FOR THE MODEL 101 MARINE HEADING SENSOR

Diameter of spherical housing, including flanges	6.5 inches
Height, including binnacle	7.0 inches
Weight, including binnacle	4.5 lbs
Shock	Capable of meeting MIL-S-901C
Vibration	Capable of meeting MIL-STD-167B
Movement	Two spring backed sapphire bearings, osmium-tipped pivots
Gimballing	±70° roll and pitch
Resolution	1°
Electronics description	Infrared LED illuminated phototransistors through Gray coded card. Custom CMOS integrated circuits converts optically coded signal to serial pulse train.
Power consumption	Range: 2.5 mw to 50 mw (proportional to sampling rate)
Voltage requirements	Range:4.5 VDC to 5.5 VDC
Output format	Serial pulse train, N+1 pulses
Output signal frequency	Range: Selectable 0.5 kHz to 50 kHz standard 25 kHz
Data sampling rate	Range: Selectable 0.5 Hz to 50 Hz standard 25 Hz
Connections	Input voltage, data output,
ground	
Temperature limitations	Operating -40°C to 70°C Storage -55°C to 85°C
Circuit protection	Reverse polarity, over-voltage
Housing	Waterproof, U/V stabilized Lexan

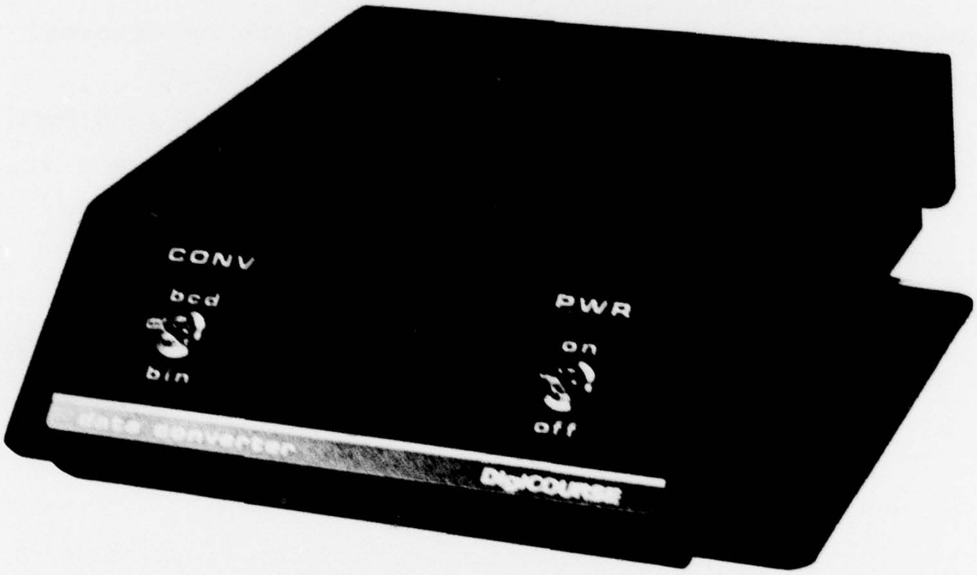

CONV
bcd
bin
PWR
on
off
data converter
DigiCOURSE

Figure 7-3 - Model 250 Heading Sensor Interface Unit

TABLE 7-2 SPECIFICATIONS FOR THE MODEL 250 HEADING SENSOR INTERFACE UNIT

Electronics description	Solid state electronics converts heading sensor data to selected output format through use of CMOS circuitry.
Selectable outputs	Static parallel binary (9 bit) Static parallel BCD (10 bit) Serial binary Serial BCD True or complement parallel binary or BCD
Output selection	Selection made by external jumper or switch
Output	Digital, buffered with CMOS type 4050 buffer, analog, zero to 3.59 VDC
Voltage requirements	7 VDC to 20 VDC
Current	6 milliamps (constant)
Housing dimensions	7.5" x 4.7" x 2.0"

An alternative to the Model 101 heading sensor is the Model 215 heading sensor, also made by DigiCourse. This sensor is shown in Figure 7-4. Although smaller and less expensive than the Model 101, this sensor has the following disadvantages:

1) The resolution and repeatability are 1.4 deg and plus or minus 0.7 deg, respectively, versus 1 deg and plus or minus 0.5 deg for the Model 101.
2) The gimbal limits are plus or minus 45 deg, versus plus or minus 70 deg for the Model 101.
3) There are no compensation magnets.

Table 7-3 gives specifications for the Model 215.

The interface unit used with the Model 215 is the Model 257 Data Converter, specifications for which are given in Table 7-4.

Prices for the heading sensors and interface units are as follows:

Model 101 Heading Sensor	$618.
Model 215 Heading Sensor	$430.
Model 250 Interface Unit	$437.

At the time of this writing, Digicourse was phasing out the Model 250 interface unit in favor of a Model 261. The new unit, priced at $550., consists of a microprocessor-based circuit on a single printed-circuit board. Complete specifications are not available, although they would be similar to those for the Model 250, given in Table 7-2.

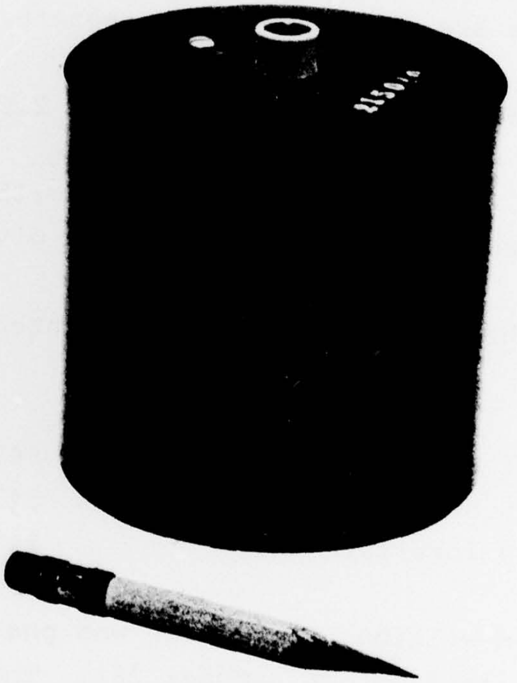


Figure 7-4 - Model 215 Heading Sensor

TABLE 7-3 SPECIFICATIONS FOR THE MODEL 215 HEADING SENSOR

Diameter of compass	3.25 inches
Height of compass	3.40 inches, not including connector 3.75 inches, including connector
Housing	Aluminum, hard anodized finish
Compass resolution	1.4 deg
Compass repeatability	±0.7 deg
Gimballing limits	±45 deg
Electronics description	All hybrid assembly. Two parallel strings of 4 LEDs in series illuminate photodiode sensors through Gray coded card. N on P photodiodes are operated in short ciruit mode.
Power requirements	LEDs require 140 ma. constant current pulse (70 ma./string). Pulse length 2 ms. min. voltage = 50 V min. Power required is proportional to sample rate (e.g., 1 MW at 1 Hz for 2 ms pulse length). Series connected LEDs (70 ma. at 10 V min) available on special order.
Output	8 bit parallel Gray, low level (30 to 50 mv). Use LM 324 op-amp or equivalent to increase output to TTL or CMOS levels. Output from LM 324 is 0 to VCC-1 volt positive going pulse. Delay + rise time 750 μsec. max.
Connector	Viking socket TKP-12, supplied with mating connector/ribbon cable to 14 pin DIP pigtail
Temperature limitations	Operation: -40°C to 70°C Storage: -55°C to +85°C

TABLE 7-4 SPECIFICATIONS FOR THE MODEL 257 DATA CONVERTER

General Description	Solid state circuit board used to interface Digi-Course Model 213 or 215 heading sensor with user's peripheral equipment.
Electronic Description	Upon user's application of power, current source circuit delivers pulsing energy to heading sensor at specified sampling rate*. Heading sensor output is amplified, and CMOS circuitry converts 8-bit parallel Gray code from heading sensor to either serial (Model 257A) or parallel binary (Model 257B) format. Model 257B also provides analog output voltage equivalent of heading. *NOTE: Sampling rate of either 257A or 257B from approximately 1 Hz to 25 Hz (user specify).
Output	1. Model 57A - Serial pulse train at 50 kHz; heading equivalent to 1.406259N-1) deg where N is number of pulses in pulse train. 2. Model 257B 8-bit parallel binary word at specified sampling rate: heading equivalent to 1.40625 N deg where N is decimal equivalent of binary word.
Power Requirements	5V ± 0.5V or 10V ± 1V DC (for use with heading sensor Model 213P and 213S, respectively). Regulation for Model 257B recommended to be ±0.5% if analog output is used.
Connections	1. 14-pin DIP header (to heading sensor) 2. 15-pin PC board edge connector (to power supply and peripheral equipment)
Physical Dimensions	PC board, 3.84 x 3.09" (9.8 x 7.8 cm). Allow 1.25 inch (3.125 cm) vertical clearance. NOTE: Vertical clearance can be reduced at factory if required.

7.2 Altimeter

Although altitude can be computed from slant ranges in a multilateration fixing scheme, a small error in measuring the slant ranges can result in an unacceptably large error in the altitude and altitude rate estimates. Therefore, an altimeter, which is required in the rho-theta and theta-theta fixing schemes, is recommended for a multilateration fixing scheme. Furthermore, the rate-of-descent signal required by the guidance law can be provided as a hardware option by at least one vendor of barometric altimeters.

A barometric altimeter is preferred over a radar altimeter for the gliding airdrop guidance subsystem for the following reasons:

1) It has lower weight and volume.
2) It is less expensive.
3) The altitude measurement range is greater (typically to 23,000 meters, versus 1500 meters for a radar altimeter).
4) It requires less power.
5) It is not subject to errors resulting from pitch or roll.
6) It measures the altitude above the landing zone (as required by the guidance law), rather than above the local terrain.
7) It is easier to package, because it does not rely on electromagnetic signals with which a payload might interfere.
8) Because it is passive, it is not subject to electromagnetic interference, and does not present a signature to hostile forces.

A barometric altimeter suitable for the gliding airdrop guidance subsystems is Rosemount's Model 1241A. (The suffix A designates an operating range of minus 1000 feet to plus 30,000 feet, or minus 305 meters to plus 9146 meters.) This altimeter, shown in Figure 7-5, senses barometric pressure with a capacitive pressure-sensing capsule. This capsule consists of a welded stainless steel case containing two capacitor plates and a "free edge" diaphragm. The chamber on one side of the diaphragm is evacuated and sealed off, while the other chamber is exposed to the static pressure source through a pressure fitting.

Since one side of the pressure-sensing capsule is referenced to a vacuum, the position of the diaphragm is dependent upon the static pressure introduced on the opposite side of the diaphragm. As barometric altitude increases, the diaphragm deflects slightly (less than 0.004 inches from minus 1000 feet to plus 75,000 feet) due to the decrease in pressure. The position of the diaphragm is detected by the two capacitor plates, and the difference in capacitance between each capacitor plate and the diaphragm produces a differential current flow through the diode ring detector circuit. A portion of this current is fed back to the control amplifier which regulates the sensor excitation oscillator.

Because the sensor and detector are in the feedback loop, the oscillator signal varies inversely with pressure and can be linearized as a function of altitude. A diode detector connected to the oscillator therefore provides a current signal which is proportional to altitude. This current is then fed into an outut amplifier and scaled to provide a high level DC output voltage that is linear with barometric altitude.

The required altitude rate signal is supplied by a differentiating rate amplifier that is connected to the altitude signal output amplifier. This circuit produces a high level DC output voltage proportional to rate-of-descent.

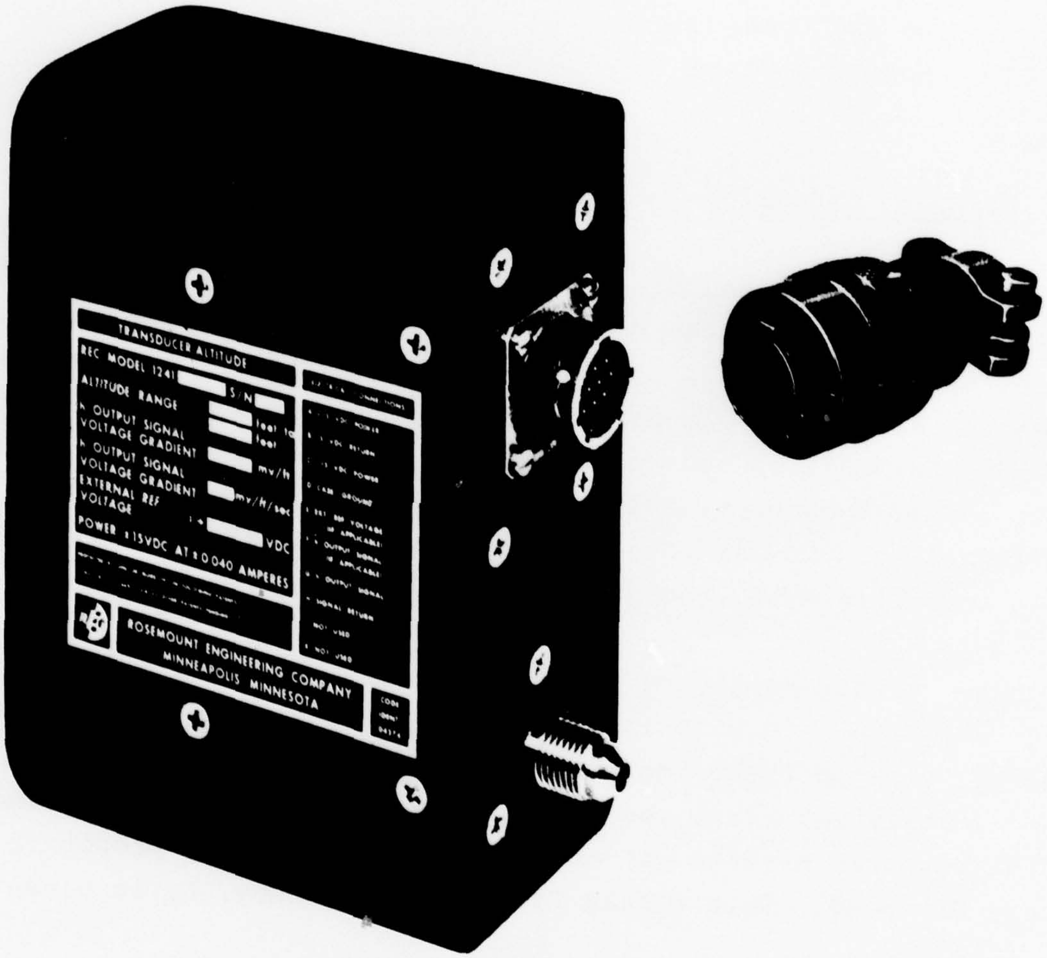

TRANSDUCER ALTITUDE
REC MODEL 1241
S/N
ALTITUDE RANGE
h OUTPUT SIGNAL
VOLTAGE GRADIENT
h OUTPUT SIGNAL
VOLTAGE GRADIENT
EXTERNAL REF
VOLTAGE
VDC
POWER ±15VDC AT ±0.040 AMPERES
ROSEMOUNT ENGINEERING COMPANY
MINNEAPOLIS MINNESOTA

Figure 7-5 - Photo of Altimeter with Mating Connector

Figure 7-6 shows a block diagram of the altimeter. Table 7-5 gives its specifications. Figure 7-7 shows a dimentional drawing.

The price of the altimeter is itemized as follows:

Basic Unit	$1155.
Descent Rate	250.
Internal Ref. Voltage	27.
Mating Connector	9.
Mounting Plate	12.
	$1453.

7.3 Airspeed Sensor

The airspeed sensor recommended for the gliding airdrop guidance subsystem is the Model VA-220 vortex-type sensor made by J-Tec Associates, Inc., of Cedar Rapids, Iowa. This sensor, shown in Figure 7-8, measures true airspeed to an accuracy of 1 percent full scale, and operates down to airspeeds as low as one knot. Unlike conventional airspeed sensors, the J-Tec device is unaffected by the air density, pressure, or temperature. The basic sensor is small enough to hold in the palm of the hand.

The sensor employs a small obstruction in the form of a cylindrical strut to generate a series of small vortices. The spacing between these vortices is a well-defined constant and is approximately 2.5 times the strut diameter. The number of individual vortices created per unit of time is directly proportional to the airspeed. This vortex formation frequency, F, is given by

$$F = Sv/d \text{ (Hz)},$$

where

v = airspeed (ft/sec)
d = strut diameter (ft)
S = Strouhal number (0.207)

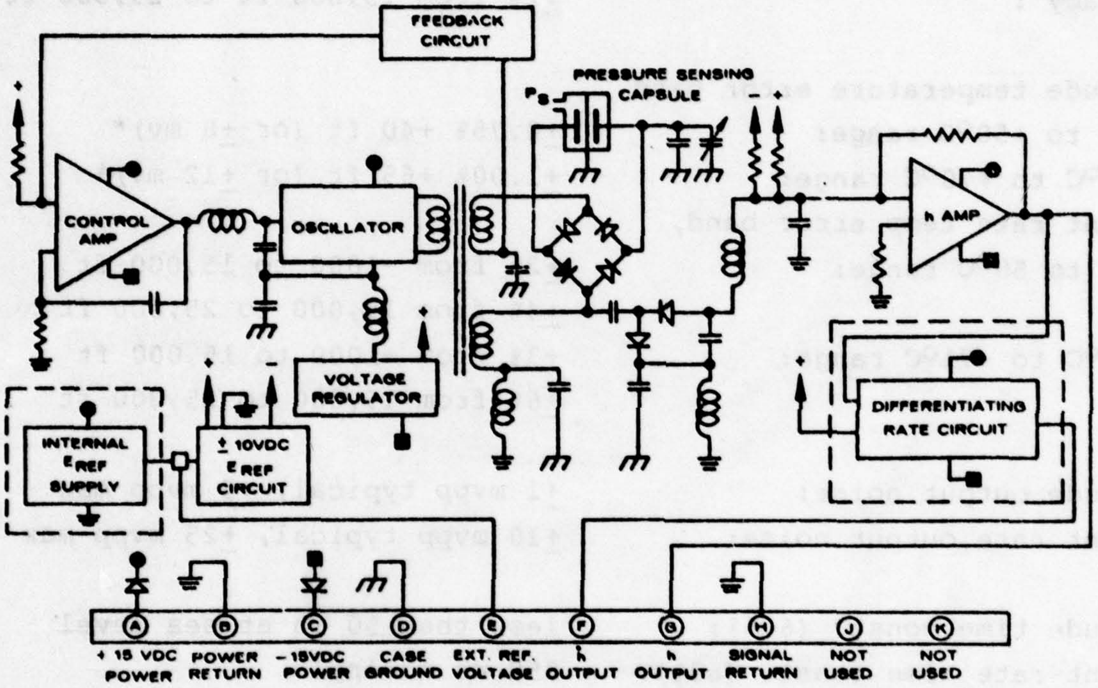

FEEDBACK CIRCUIT
PRESSURE SENSING CAPSULE
P_S
CONTROL AMP
OSCILLATOR
VOLTAGE REGULATOR
ḣ AMP
DIFFERENTIATING RATE CIRCUIT
INTERNAL E_{REF} SUPPLY
± 10VDC E_{REF} CIRCUIT
A
B
C
D
E
F
G
H
J
K
+ 15 VDC POWER
POWER RETURN
− 15VDC POWER
CASE GROUND
EXT. REF. VOLTAGE
ḣ OUTPUT
h OUTPUT
SIGNAL RETURN
NOT USED
NOT USED

Figure 7-6 - Block Diagram of Altimeter

TABLE 7-5 ALTIMETER SPECIFICATIONS

PERFORMANCE SPECIFICATIONS

Altitude sensitivity:	0.5 mv/ft (20 kft max)
Descent rate sensitivity:	100 mv/ft/sec (3000 fpm max)
Altitude accuracy[+]:	±0.25% of reading +20 ft (or ±5 mv)*
Descent rate accuracy[+]:	±1% from -1000 to 15,000 ft ±2% from 15,000 ft to 25,000 ft
Altitude temperature error band,	
0°C to +50°C range:	±0.75% +40 ft (or ±8 mv)*
-55°C to +70°C range:	±1.00% +65 ft (or ±12 mv)*
Descent rate temp error band,	
0°C to 50°C range:	±2% from -1000 to 15,000 ft ±4% from 15,000 to 25,000 ft
-55°C to +71°C range:	±3% from -1000 to 15,000 ft ±6% from 15,000 to 25,000 ft
Altitude output noise:	±1 mvpp typical, ±5 mvpp max
Descent rate output noise:	±10 mvpp typical, ±25 mvpp max
Altitude time const. (63%):	less than 50 ms at sea level
Descent rate time const. (63%):	550 ms nominal
Power supply effect:	±30 ft/volt DC (altitude)
Vibration effect:	±6 ft/G (altitude)

---

*whichever is greater

[+] includes resolution, repeatability, and hysteresis

TABLE 7-5 ALTIMETER SPECIFICATIONS (CONT.)

ELECTRICAL SPECIFICATIONS

Power Requirements

+15 VDC ±5% at 0.050 amperes.

-15 VDC ±5% at 0.050 amperes.

Insulation Resistance

The insulation resistance between all signal and power leads tied together and case ground is 100 megohms, minimum, at 100 VDC. (100 VDC is the voltage rating of the internal capacitors connected between signal return and case ground.)

Input-Output Isolation

The 15 VDC power return and the signal return are internally connected together. It is recommended that the 15 VDC return or the signal return be externally connected to case ground during testing and in actual use to keep output signal noise at a minimum.

Output Impedance

Less than 50 ohms.

Output Current Capability

The altitude output amplifier is capable of supplying current to load impedances of 5000 ohms or higher.

ENVIRONMENTAL SPECIFICATIONS

Vibration

±0.10" double amplitude or 10 G's peak from 5 to 500 Hz.

Humidity

95% relative humidity or less.

Operating Temperature

-55°C to +71°C.

Storage Temperature

-65°C to +85°C.

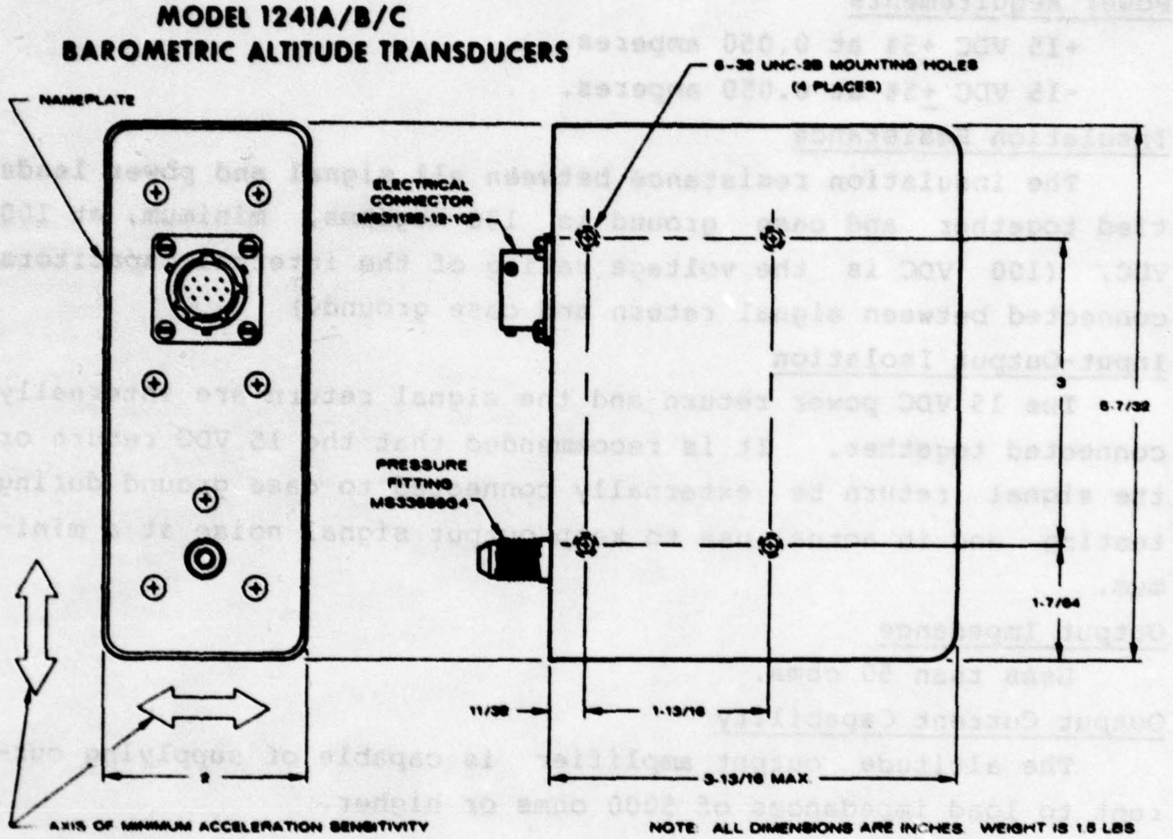

MODEL 1241A/B/C
BAROMETRIC ALTITUDE TRANSDUCERS
NAMEPLATE
6-32 UNC-2B MOUNTING HOLES
(4 PLACES)
ELECTRICAL
CONNECTOR
MS3112E-12-10P
PRESSURE
FITTING
MS33656G4
3
5-7/32
1-7/64
11/32
1-13/16
2
3-13/16 MAX
AXIS OF MINIMUM ACCELERATION SENSITIVITY
NOTE: ALL DIMENSIONS ARE INCHES. WEIGHT IS 1.5 LBS

Figure 7-7 - Dimensional Drawing of the Model 1241 Altimeter

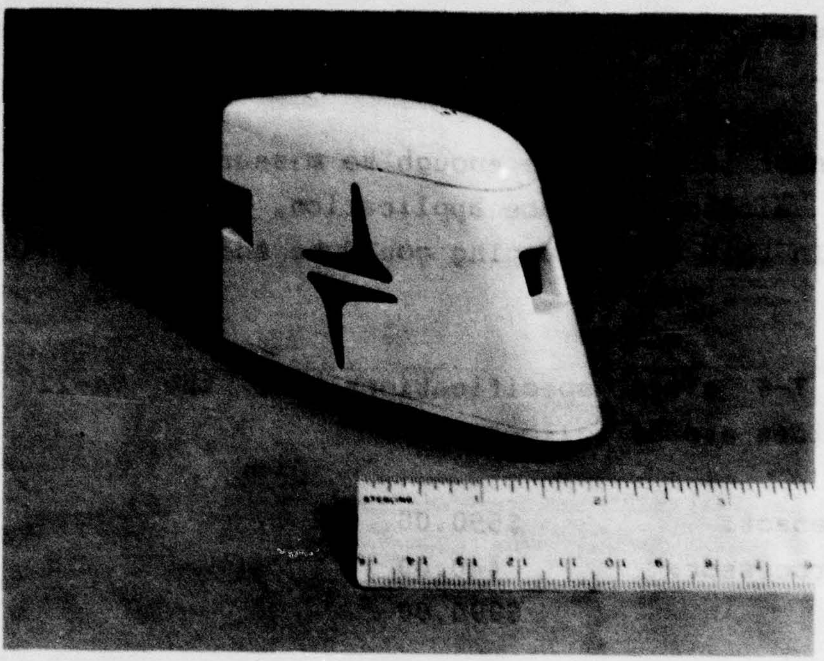


Figure 7-8 - Photo of Airspeed Sensor

To count this rate, J-Tec employs an ultrasonic beam, located downstream of the obstruction-strut. An ultrasonic generator is mounted on one wall of the device and an ultrasonic receiver is located on the opposite wall so that the vortices pass through the resulting "beam".

As each vortex passes through the ultrasonic beam, it produces both amplitude and phase modulation of the beam. Demodulation of the beam signal serves to generate a pulse for each passing vortex. A digital counter and timing circuit determines the passing rate of the vortices which is directly proportional to airspeed. The output is inherently digital, which is an advantage for the gliding airdrop guidance application.

Wind tunnel tests have shown very good linearity and have demonstrated that the accuracy is not significantly affected at yaw angles up to 15 deg and pitch angles up to 30 deg. This is another feature that makes the device ideal for the gliding airdrop system, which can encounter varying angles of sideslip and descent.

The sensor is sensitive enough to measure gusts aloft. For the gliding airdrop guidance application, this might be too sensitive. In this case, damping could be added to eliminate gust transients.

Table 7-6 gives specifications for the VA-220 airspeed sensor. Prices are as follows:

Sensor:	$550.00
Processor:	440.00
	$990.00

TABLE 7-6 VA-220 SPECIFICATIONS

Range	2 to 200 knots
Accuracy	±1% full scale
Response to speed changes (frequency)	1/8 inch air movement
Immune to	
Pitch	Up to 30°
Yaw	Up to 15°
Power	18 to 32 VDC, 100 ma
Output (typical)	70 Hz/knot (frequency) 50 mv/knot (analog)
Size (inches)	4.0L x 0.9 W x 2.6 H (VA-220) 3.5 x 3.5 x 5.5 (Processor)
Weight (lbs)	0.375 (VA-220) 1.5 (Processor)

7.4 Airspeed and Direction Sensor

If the guidance subsystem package is not provided with an aerodynamic tail and freedom to yaw into the airstream, the subsystem must include a vane for measuring sideslip. The J-Tec model VA-320 vortex anemometer, shown in Figure 7-9, provides precision airspeed and direction measurement with a single instrument. The airspeed sensing technology used in this instrument is identical to that used in the model VA-220 airspeed sensor described in the previous section. The added direction-sensing capability results in a larger instrument, but it is actually less expensive due to a reportedly higher sales volume.

Table 7-7 gives specifications for the VA-320 vortex anemometer. The price, including processor, is $545.

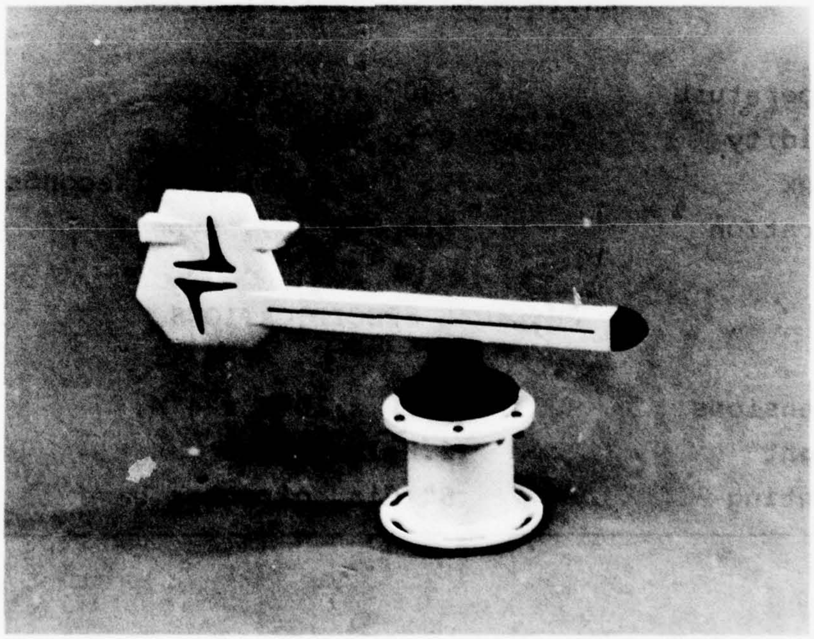


Figure 7-9 - Photo of Airspeed/Direction Sensor

TABLE 7-7 VA-320 SPECIFICATIONS

PERFORMANCE SPECIFICATIONS

Range	2-135 mph (60 m/s) (higher range available on special order)
Accuracy	Speed ±2% full scale Direction ±4° at 4.5 mph ±2° above 9 mph
Speed constant	6 mm
Direction constant	10 m
Voltage	10-24 vdc
Current	30 ma
Speed Output	0-5 vdc and 43 Hz/mph
Direction output	0-5 vdc or synchro

ENVIRONMENTAL SPECIFICATIONS

Temperature	-30° to 71°C
Humidity	0 to 100%
Shock	15 G's at 11 milliseconds
Vibration	MIL-STD-167, type 1

PHYSICAL SPECIFICATIONS

Dimensions	16"L x 10"H x 4"W
Weight	2.8 lbs
Mounting	5" dia. circular base

8. COMMAND TRANSMITTER AND RECEIVER

A command transmitter and receiver are required for manually overriding the automatic control signal in those guidance subsystems where an uplink does not otherwise exist. And, they would be required for all guidance subsystems if the manual override function is to be independent of any existing uplink.

The recommended manual command link consists of an encoder/transmitter and receiver/decoder taken from existing equipment and repackaged for the gliding airdrop application. The existing equipment is manufactured by Kraft Systems, Inc. This company has designed and manufactured equipment for industrial and military applications, including equipment for drones and remotely-piloted vehicles, since 1964.

8.1 Transmitter

The transmitter control panel would be like that shown in Figure 8-1, except that a thumbwheel switch would replace one of the two joysticks. This thumbwheel switch would be used to select one of up to 16 vehicles, and the remaining joystick would be used for controlling the selected vehicle. The encoder, taken from a Kraft radio-control set KP-6A FM, generates the baseband waveform shown in Figure 8-2; this waveform consists of a sync pulse, a vehicle address (set by the thumbwheel switch), and a control pulse (set by the joystick). Each pulse is separated by a 0.5 ms clock. The pulse widths are as follows:

sync pulse:	8 ms
address bits:	logical 1, 2.5 ms
	logical 0, 1.5 ms
control pulse:	full left, 1.4 ms
	full right, 2.4 ms
	neutral, 1.9 ms

The message encoding method results in a frame time that varies from 20.4 ms to 26.4 ms.

The transmitter RF section is the Kraft Model KTT 1-16, shown in Figure 8-3. This generates a frequency-shift keyed signal in the 72-75 MHz or 150 MHz band with a 3.5 kHz frequency deviation, as shown in Figure 8-2. The use of frequency-shift keying as opposed to on-off keying results in a signal that is virtually impervious to electrical noise and interference.

8.2 Receiver

The receiver would be adapted from the Kraft Model KTR 1-16, also shown in Figure 8-3. This receiver translates the RF signal back to the baseband waveform. A separate decoder determines if the address matches the one programmed into it (perhaps set by DIP switches), in which case it puts out a valid-address signal and an analog control signal. The airborne computer monitors the logic state of the valid-address signal; when this signal is true, the system switches from automatic (computed) control to manual control, and uses the decoder's analog control signal to drive the actuator. The valid address signal will vanish roughly 1.5 frames (or within 50 ms) after manual control of the associated vehicle is released.

The system described is capable of operating over a range in excess of one mile. Table 8-1 gives specifications for the KTT 1-16 transmitter and the KTR 1-16 receiver. Prices are as follows:

Non-recurring cost for repackaging	$7200.
Encoder-Transmitter	$700.
Receiver-Decoder	$600 - $800.

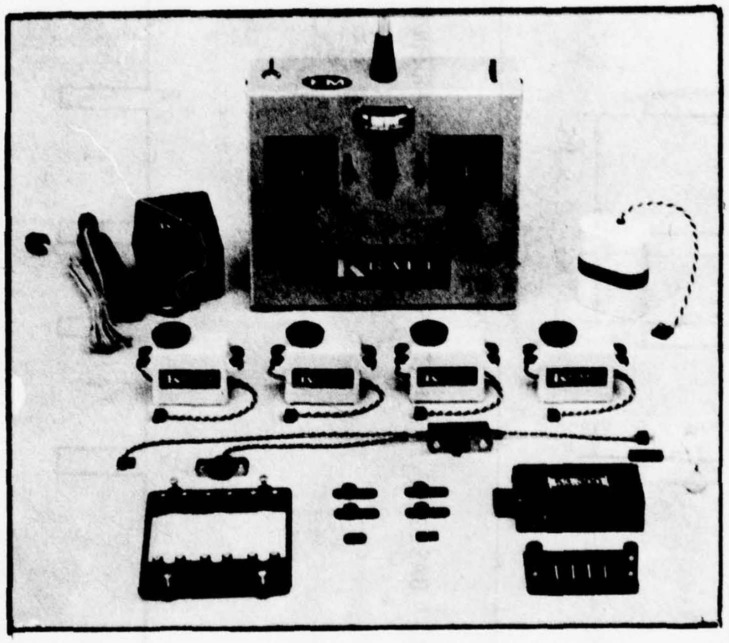
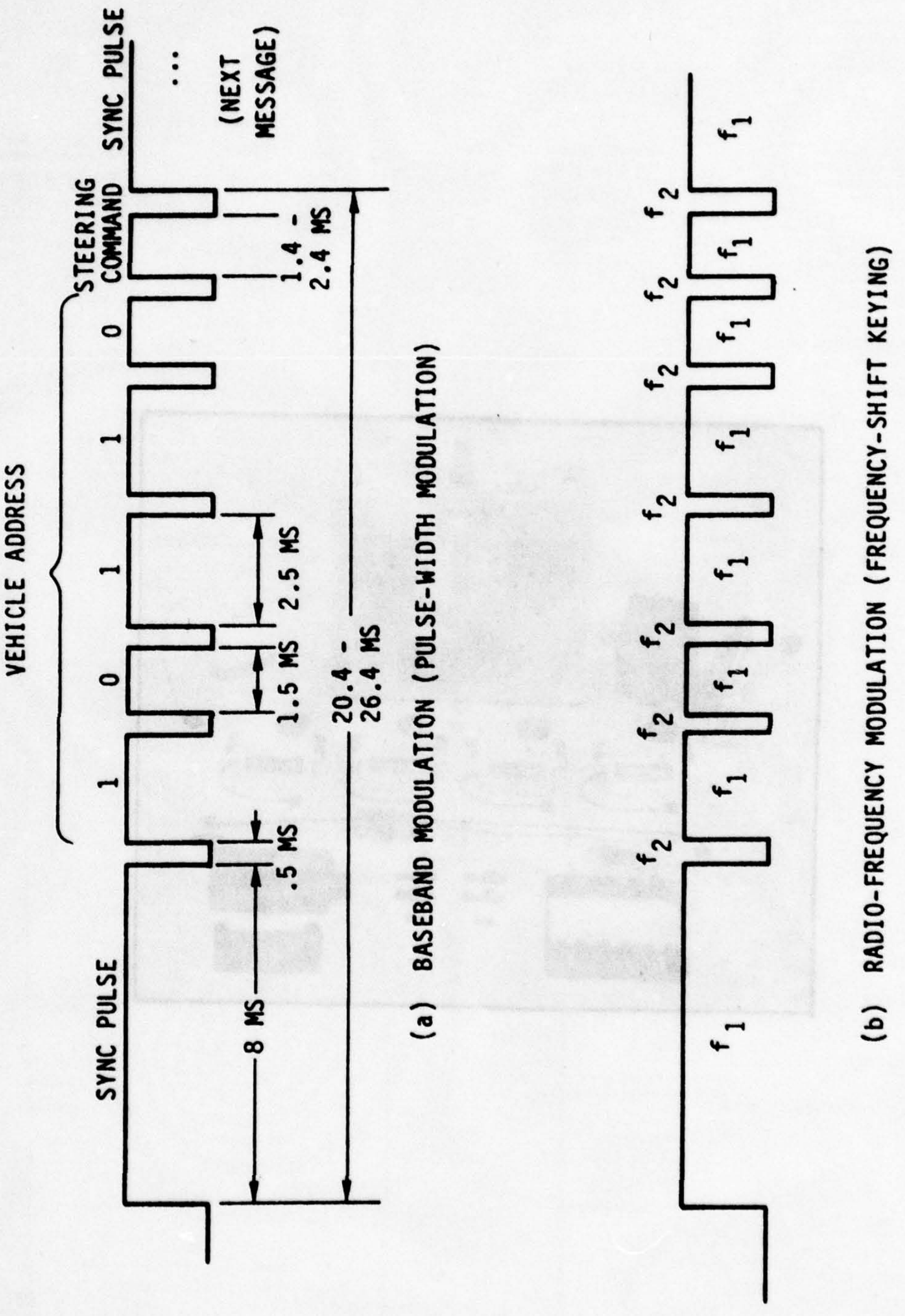


Figure 8-1 - Photo of the Kraft Model KP-6A FM


SYNC PULSE
VEHICLE ADDRESS
1
0
1
1
0
STEERING COMMAND
SYNC PULSE
(NEXT MESSAGE)
...
8 MS
.5 MS
1.5 MS
2.5 MS
1.4 - 2.4 MS
20.4 - 26.4 MS
f_1
f_2

(a) BASEBAND MODULATION (PULSE-WIDTH MODULATION)

(b) RADIO-FREQUENCY MODULATION (FREQUENCY-SHIFT KEYING)

Figure 8-2 - Command Link Baseband and Radio-Frequency Modulation

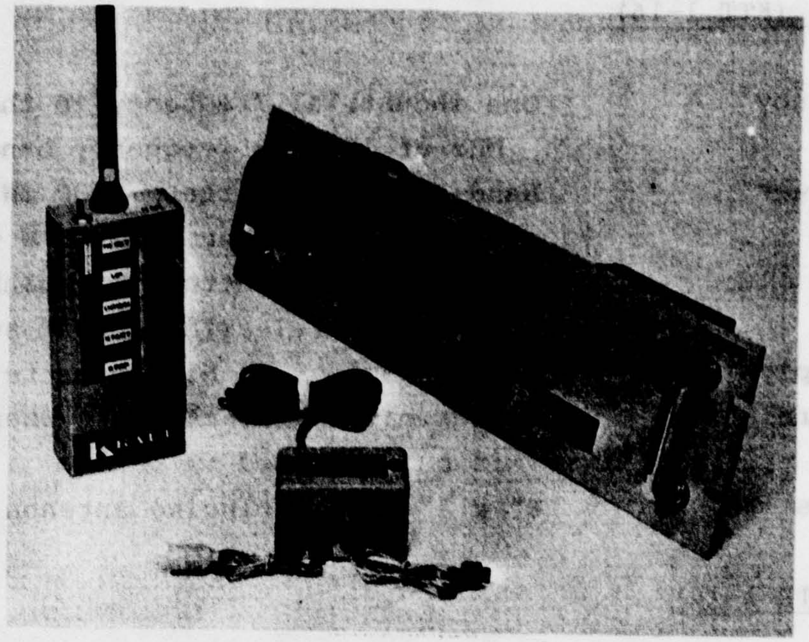


Figure 8-3 - Photo of the Kraft Model KT 1-16

TABLE 8-1 COMMAND TRANSMITTER AND RECEIVER

SPECIFICATIONS

Transmitter (KTT 1-16)	
RF frequency	One industrial frequency in the 72-75 MHz or 150 MHz frequency bands
Output power	Hand-held transmitter - 500 mW typical (high power transmitter 8 W typical)
Controls	Up to five pushbuttons or pushbutton pad, self-releasing on/off switch
Power supply	Rechargeable 9.6V Ni-Cad battery
Battery drain	Approximately 150 mA, only when command is being issued
Dimensions	6" x 2" x 3" excluding antenna
Receiver (KTR 1-16)	
RF frequency	Same as transmitter
Sensitivity	1.0 μV typical
Power supply	10.0 to 15.0 V DC
Battery drain	35 mA (standby)
Command outputs	One form "C" contact per channel or a 100 mA (maximum) solid state current sink
Command response time	0.2 seconds

9. COMPUTER

The guidance systems for the gliding airdrop vehicle include sensors, data input devices and ports, command links, actuators, power supplies and a computer. The computer must accept data from a number of sources, filter some data for smoothing, perform the required guidance computations, and output commands to the actuator.

The Intel or National Semiconductor Corp. single board computers were selected as the preferred type of computer because of second sourcing. Also, a ruggedized military environment equivalent is available: the ISBC 80/10A single board computer made by Severe Environment Systems which is electrically and functionally identical with the Intel and National SBC 80/10A and BCL 80/10 computers.

The National Semiconductor single board computer series is described in the following paragraphs.

The BLC 80/11, 80/12, 80/14 are self-contained singleboard computers including the central processor, system clock, RAM and ROM memories, I/O lines, serial communications interface, and bus logic and drivers on a 6.75 inch by 12.00 inch printed circuit board.

The INS 8080A n-channel LSI microprocessor is the central processor for the BLC 80/10. The 8080A provides six general purpose 8-bit registers, and accumulator, a 16-bit program counter and a 16-bit stack pointer register. The general-purpose registers can be utilized singly, or in pairs where double-precision operations are required. The 16-bit program counter allows direct addressing of a full 64K bytes of memory. The stack pointer controls addressing of an external stack located anywhere within the read/write memory. The stack may be used to store the contents of the various registers while servicing interrupts and subroutines.

The BLC 80/11, 80/12, 80/14 contain integral read/write and read-only memory. 1K, 2K, or 4K bytes of static read/write capability are provided by MM2114 RAMs while sockets for MM2708/MM2716 electrically programmable ROMs or MM2308/MM2316E ROMs give up to 8K bytes of read-only memory in 1K or 2K increments. All ROM and RAM operations are performed at maximum processor speed.

Input/Output

The use of 2 INS8255 Programmable Peripheral Interface circuits provides 48 I/O lines which can be configured by software into any combination of unidirectional/bidirectional and input/output. Figure 9-1 shows the various options for the 48 lines. Sockets are provided on the board to allow the user to select the proper drivers and terminators appropriate to each application. All I/O lines plus a corresponding signal ground for each are brought out to a pair of 50-position card-edge connectors which mate with cable connectors.

The INS8251 Universal Syncronous/Asynchronous Receiver Transmitter provides the capability of selecting, via jumpers, all the standard communications frequencies. System software can be programmed to select the required synchronous or asynchronous mode of operation, the format for the data and control characters, and the use of the parity bit. The 8251 contains logic for detection of framing, overrun, and parity errors as well as double buffering for full duplex transmit and receive operations. Teletypewriter and RS232 interfaces are included on the board and can be selected by means of programmable jumpers.

		MODE OF OPERATION					
		UNIDIRECTIONAL					
		INPUT		OUTPUT			
PORT	NO. OF LINES	UNLATCHED	LATCHED AND STROBED	LATCHED	LATCHED AND STROBED	BIDIRECTIONAL	CONTROL
1	8	X	X	X	X	X	
2	8	X	X	X	X		
3	8	X		X			X
4	8	X		X			
5	8	X		X			
6	4	X		X			
	4	X		X			

Figure 9-1 - Parallel I/O Operating Modes

Communications/Interrupts

TTY or RS232 signals are brought out to a 25-position card-edge connector which mates with an appropriate cable connector. On-board jumpers allow the user to select the I/O pins for the RS232 interface. This allows the interface to be configured in a receive mode and communicate with another RS232 interface configured in the transmit mode. The BLC 80/11, 80/12, 80/14 can handle up to 6 interrupt requests. Two of these can be jumper selected to be automatically generated when the 8255 input buffer is full or when its output buffer is empty. Two more can be generated by the 8251 USART when data is ready for transfer to the CPU or when data has been transmitted and a new output character is needed. All four of these interrupts can be masked individually under software control. Two additional interrupt lines are available, one through the I/O connector and one on the system bus, for use by user-specified peripherals. The six interrupts share a common CPU level which causes a RESTART 7 instruction to be executed. The user response to the interrupt is handled by an interrupt processing routine starting at location 0038_{16}.

A block diagram of the computers is shown in Figure 9-2 and specifications are given in Table 9-1. The program for each of the guidance implimentations can be developed and stored in PROM memory. Initial data such as beacon baseline coordinates, landing point coordinates, and ground altitude can be entered through the serial interface ports using an RS232C device or teletype. The digital multiplexer can expand the I/O lines by multiplexing to accomodate all of the sensor and data inputs. The output lines would not require multiplexing.

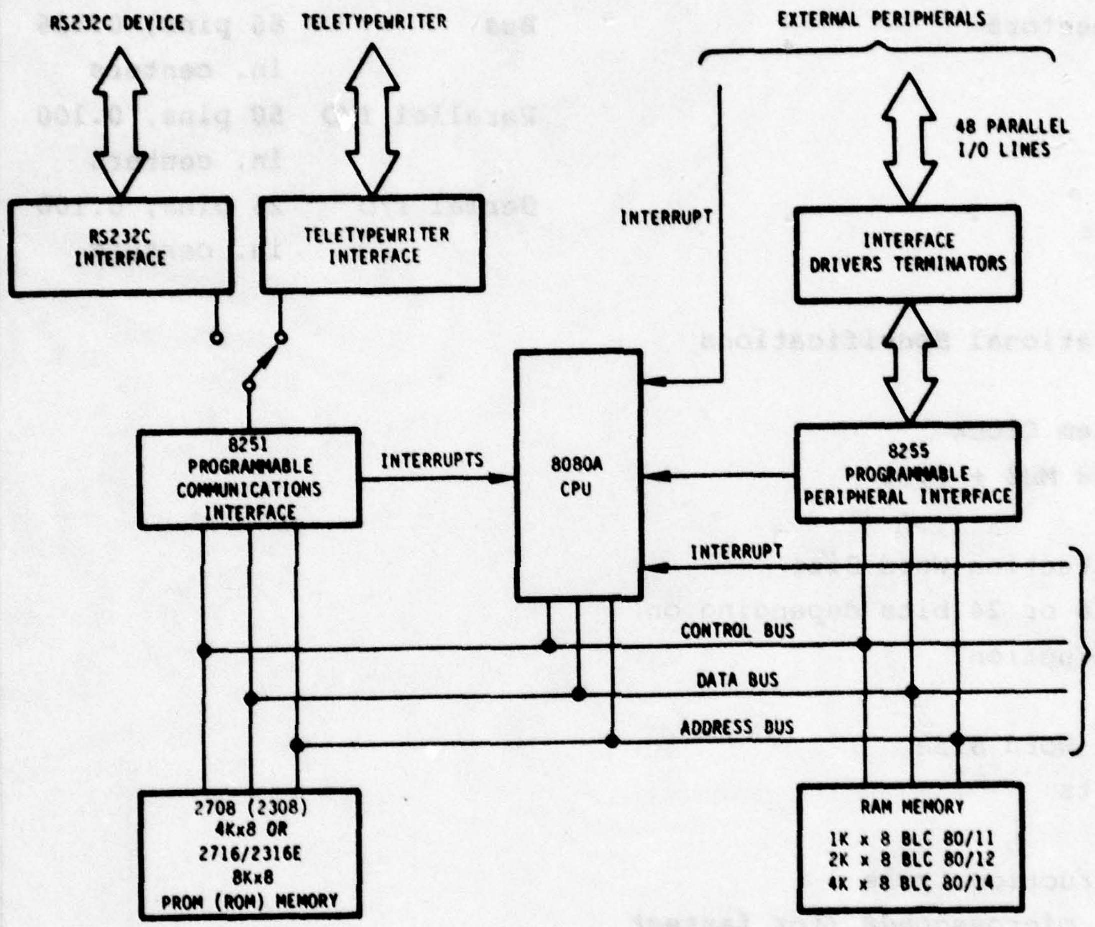

RS232C DEVICE
TELETYPEWRITER
EXTERNAL PERIPHERALS
48 PARALLEL I/O LINES
INTERRUPT
RS232C INTERFACE
TELETYPEWRITER INTERFACE
INTERFACE DRIVERS TERMINATORS
8251 PROGRAMMABLE COMMUNICATIONS INTERFACE
INTERRUPTS
8080A CPU
8255 PROGRAMMABLE PERIPHERAL INTERFACE
INTERRUPT
CONTROL BUS
DATA BUS
ADDRESS BUS
SYSTEM BUS
2708 (2308) 4Kx8 OR 2716/2316E 8Kx8 PROM (ROM) MEMORY
RAM MEMORY
1K x 8 BLC 80/11
2K x 8 BLC 80/12
4K x 8 BLC 80/14

Figure 9-2 - Single-Board Computers BLC 80/11, 80/12, 80/14 Block Diagram

TABLE 9-1 SINGLE BOARD COMPUTER SPECIFICATIONS

Physical Specifications	Height	6.75 in.
	Width	12.00 in.
	Depth	0.50 in.
	Weight	14 oz.
Operating Temperature		0°C to 55°C
Connectors	Bus	86 pins, 0.156 in. centers
	Parallel I/O	50 pins, 0.100 in. centers
	Serial I/O	26 pins, 0.100 in. centers
Operational Specifications		
System Clock		
2.048 MHZ ± 0.1%		
Instruction Word Size		
8, 16 or 24 bits depending on instruction		
Data Word Size		
8 bits		
Instruction Cycle		
1.95 microseconds (for fastest instruction)		

TABLE 9-1 SINGLE BOARD COMPUTER SPECIFICATIONS (CONT.)

Memory Capacity

On-board RAM

80/11	1K
80/12	2K
80/14	4K

On-board ROM,PROM,EPROM sockets for up to 8K bytes on all boards. Expansion boards available to increase memory to a maximum of 65,536 bytes of RAM/PROM combined.

RAM Memory Addressing

80/11	$3C00_{16}$ - $3FFF_{16}$
80/12	3800_{16} - $3FFF_{16}$
80/12	3000_{16} - $3FFF_{16}$

ROM/PROM Memory Addressing

0 - $03FF_{16}$ to $1FFF_{16}$

(Depending on amount installed)

Power Requirements

Vcc = +5V ± 5% @2.9A max

Vdd = +12V ± 5% @ 150 ma max

Vbb = -5V ± 5% @ 2 ma max

Vaa = -12V ± 5% @ 150 ma max

(not including power for I/O drivers and terminators and user supplied PROMs)

Programming the computer can be considerably expedited using one of the development systems available for 8080A microprocessor-based systems such as these single board computers.

Digital Input Multiplexer

The Intel Corp. SBC 80/10A has 48 parallel programmable I/O lines. To accommodate asynchronous data up-date from the external input devices and greater than 48 data lines, a digital input multiplexer is required.

Digital outputs will be received from devices such as the magnetic compass, altimeter, altimeter rate, air speed, air direction, follow-up pot and the command receiver. Digital numbers will also be input from the coordinate-entry switches or data-entry console.

Many of the sensors have analog outputs which must be digitized. The usual approach has been to multiplex a single A/D converter of 12 bit accuracy between 16 single ended inputs or 8 differential inputs. Boards incorporating this capability are available for the single board computer, but problems with this approach are that all channels are digitized with maximum accuracy and the outputs are sequentially available after conversion intervals of about 50 microseconds per channel. Thus, the computer must take time to sequentially interrogate the A/D converter output for each multiplexed input.

A more flexible, time- and cost-efficient approach is to have an individual, low cost A/D converter for each analog input. The A/D converter resolution and accuracy will be selected to be commensurate with the accuracy of each sensor. Single package 12 bit CMOS A/D converters are now available for as low as $22 each, with 8 and 10 bit resolution A/D's for less.

A digital multiplexer is needed in this approach to allow the limited number of computer I/O lines to handle two to three times as many inputs. For all devices completely asynchonious operation is assumed, i.e., the digitizing process is not synchronized or clocked by the computer. The basic problem with this approach is the digital data could be changing when the computer requests data, thus introducing significant data errors. Handshaking logic is required to delay transfer until data update has been completed. There are a number of ways this may be done.

Figure 9-3 shows the block diagram of one section of a typical digital input multiplexer system. When the external device has completed its conversion or measurement cycle, it places valid data on its output data bus, and sends a data-ready strobe pulse. The data-ready pulse strobes the input data into data latch 1. As required, the computer sends an input select pulse to couple the three-state output of data latch 2 to the multiplexed data bus. During the same time, the input-select signal also strobes the data from data latch 1 into data latch 2. If the data from the external device were changing, the data pulse would be high and the "anded" inverted data-ready and input-select signals would delay the strobe to data latch 2 until the end of the data input transfer cycle to latch 1. Monostable multivibrators are used to introduce a small delay in the strobe for each data latch. The delay for latch 2 allows time for data from latch 1 to propagate through to its output. The delay for latch 1 prevents entry of new data into latch 1 until latch 1's data output has been read.

Figure 9-4 shows a block diagram of a typical digital multiplexer using a number of input multiplexer sections. External devices receive digital data or perform A/D conversions at their own rates and maintain the latest digital data on their output data busses. During data up-date, a data-ready signal is sent, delaying data collection during this interval.

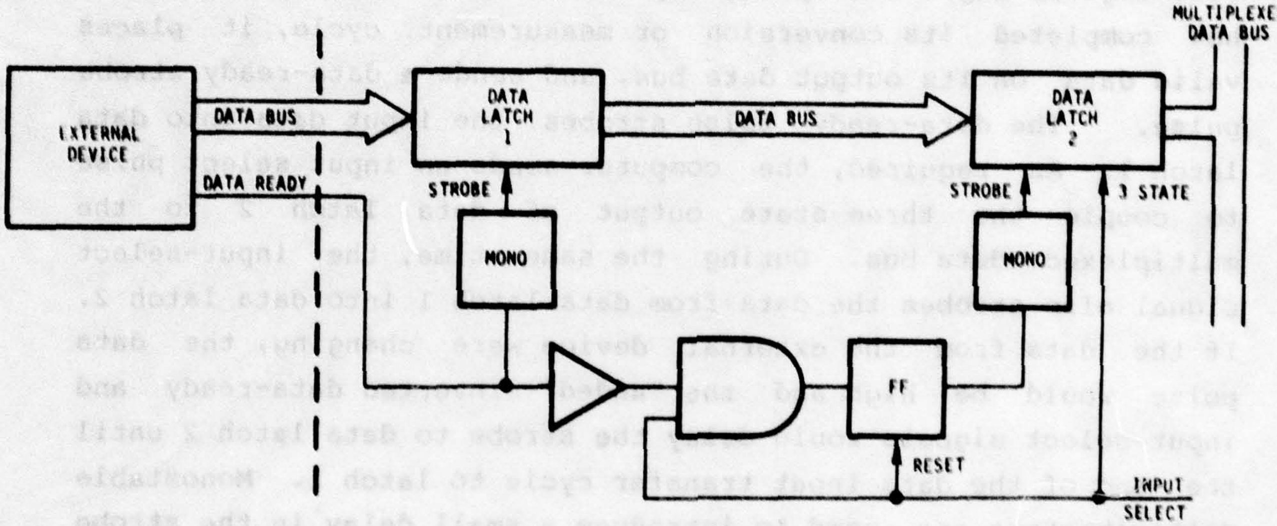

MULTIPLEXED DATA BUS
EXTERNAL DEVICE
DATA BUS
DATA READY
DATA LATCH 1
STROBE
MONO
DATA BUS
DATA LATCH 2
STROBE
3 STATE
MONO
FF
RESET
INPUT SELECT

Figure 9-3 - Block Diagram: One Section of a Digital Input Multiplexer

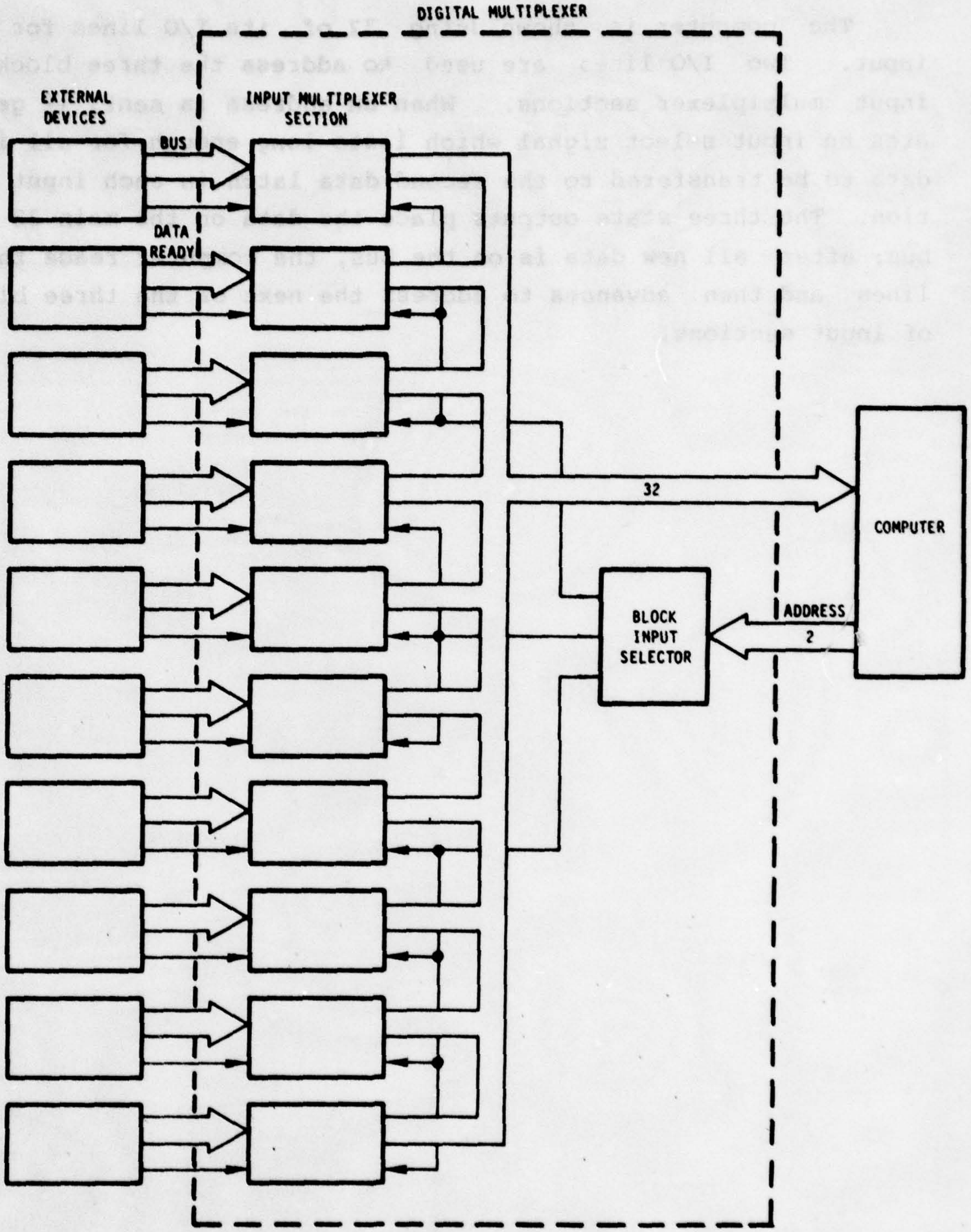

DIGITAL MULTIPLEXER
EXTERNAL DEVICES
INPUT MULTIPLEXER SECTION
BUS
DATA READY
32
COMPUTER
BLOCK INPUT SELECTOR
ADDRESS
2

Figure 9-4 - Block Diagram of a Digital Multiplexer

The computer is shown using 32 of its I/O lines for data input. Two I/O lines are used to address the three blocks of input multiplexer sections. When an address is sent, it generates an input select signal which lasts long enough for all input data to be transfered to the second data latch in each input section. The three state outputs place the data on the main 32 line bus; after all new data is on the bus, the computer reads the 32 lines and then advances to address the next of the three blocks of input sections.

10. ACTUATORS

10.1 Cable Cylinder

The cable cylinder, shown in Figure 10-1, is a pneumatic or hydraulic linear actuator. It utilizes a floating piston encased in a cylinder. The piston has a nylon-covered steel cable connected to both sides, which exits via seals at either end of the cylinder.

Figure 10-2 shows an exploded view of the cylinder. Pressure applied to one side of the piston (A) moves it within the cylinder (B), pulling the cable around the pulley (C), imparting the desired force to the load via the bracket (D).

The force that the cable cylinder can produce is directly proportional to the pressure of the applied fluid times the cylinders effective cross-sectional area (which varies as the cylinder bore varies). This pressure can vary between 25 psi to 150 psi above atmospheric pressure. The bore diameter is available from 1 inch to 8 inches. Also, the cylinder length and thus the stroke can be specified at any value up to forty feet.

Although it is not shown in Figure 10-2, two basic additions to the cable cylinder assembly must be made. The first is an automatic cable tensioner which maintains constant tension on the cable. This minimizes stress on the cable and also picks up any stretching which may occur.

The other is a pneumatic disc brake. This will be used to stop and hold the load at the desired position. It should be mentioned that the control switch for the cylinder will be a solenoid-activated one that will keep pressure on the appropriate side of the piston, aiding the brake to stop and hold the load stable. This will also eliminate any possible slippage of the

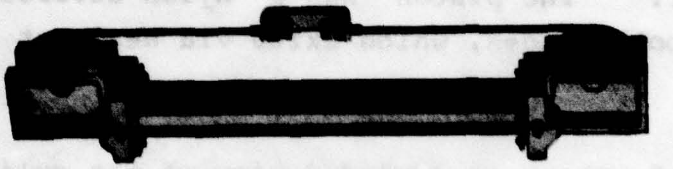


Figure 10-1 - Cable Cylinder*

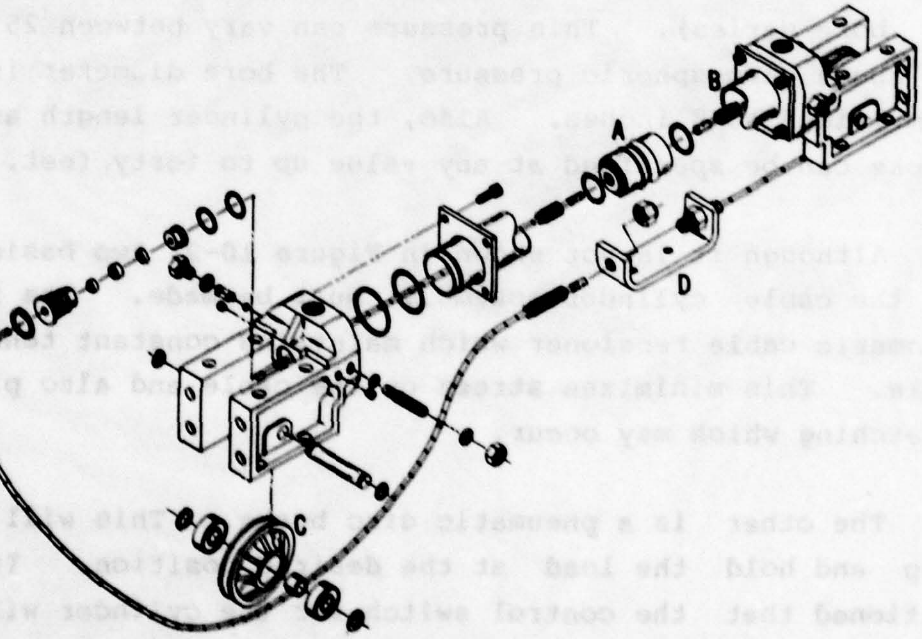


Figure 10-2 - Exploded View of the Cable Cylinder

* **Manufactured by Tol-o-matic Inc., Minneapolis, Minnesota**

cable over the pulley, since the disc brake holds the pulley. Figure 10-3 shows the cylinder with tensioner and caliper disc brake.

When the system is required to execute a maneuver, a control signal will originate from the computer. This signal will activate either the left or right solenoid of a double solenoid control value, depending upon the type of maneuver desired. The control value will allow the appropriate side of the piston within the cable cylinder to be pressurized. The resulting force will move the control lines as much as is needed up to its maximum stroke.

The position of the cable will be monitored by a position transducer, shown in Figure 10-4. This position transducer is essentially a rotary transducer with a cable wound onto a reel. As the cable is extended or retracted, a corresponding electrical level is transmitted back to the computer; thus, the loop is closed. A block diagram of the system is shown in Figure 10-5.

Two implementations of the cable cylinder concept are applicable to the gliding airdrop system. The larger payloads will use a single-stroke cable cylinder. It will be slightly longer than the desired stroke of eight feet. The large load will have a correspondingly large pallet (up to 115 inches) that will accommodate the mounting of the cylinder.

For the smaller payload range, the reduced pallet size limits the cylinder length, but the eight-foot stroke is still desired. Therefore, a double purchase design, shown in Figure 10-6, will be implemented. Here a pulley system connected to the cable cylinder's output bracket doubles the stroke. But the system's output force will be halved while the velocity doubled. Fortunately, since we will be dealing with a lighter payload, less control force is needed and thus the double purchase design lends itself quite well to this situation.

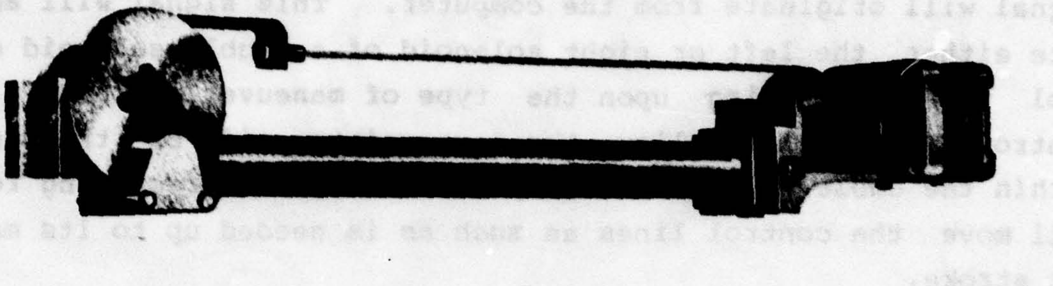


Figure 10-3 - Cable Cylinder with Tensioner and Caliper Disc Brake

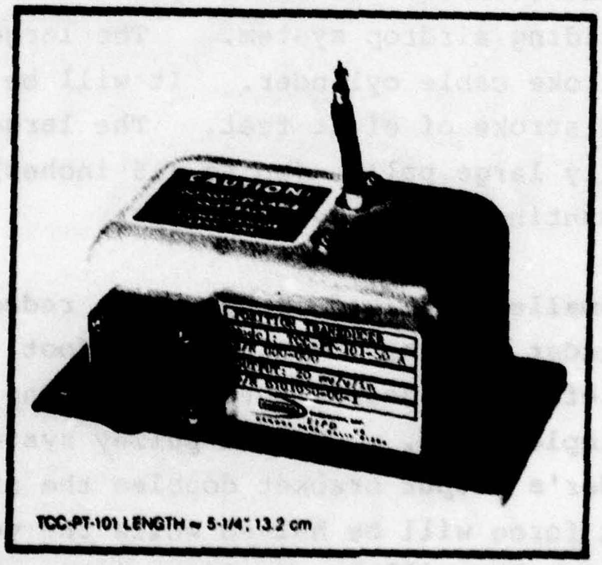

CAUTION
TCC-PT-101 LENGTH ≈ 5-1/4", 13.2 cm

Figure 10-4 - Position Transducer

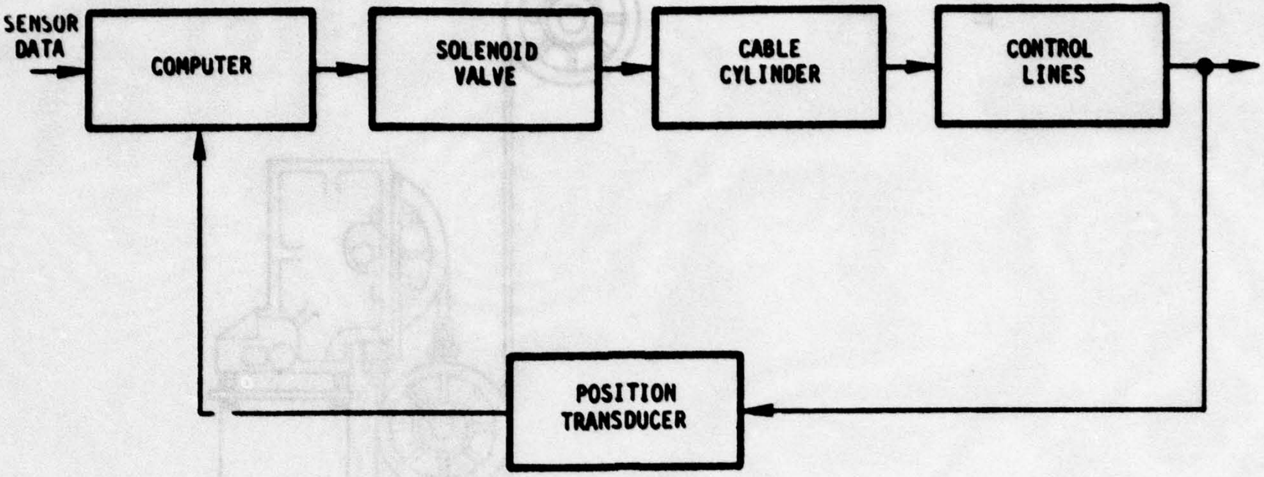

SENSOR DATA
COMPUTER
SOLENOID VALVE
CABLE CYLINDER
CONTROL LINES
POSITION TRANSDUCER

Figure 10-5 - Block Diagram of the Actuator System

Cable Cylinder Design - Single Stroke

There are a limited number of bores available which will cover the required payload ranges. Table 10-1 indicates the bores and the corresponding payloads.

TABLE 10-1 PAYLOAD RANGES FOR VARIOUS CYLINDER BORES

Bore (in)	Effective Area (in^2)	Pressure Range (psi)	Control Force (lbs)	Payload Range (lbs)
6	28.078	150-50	4212-1404	14,040-4680
4	12.4897	150-50	1874-624	6247-2080
3	6.9919	150-50	1049-350	3496-1166
2 1/2	4.8596	150-50	729-244	2430-810

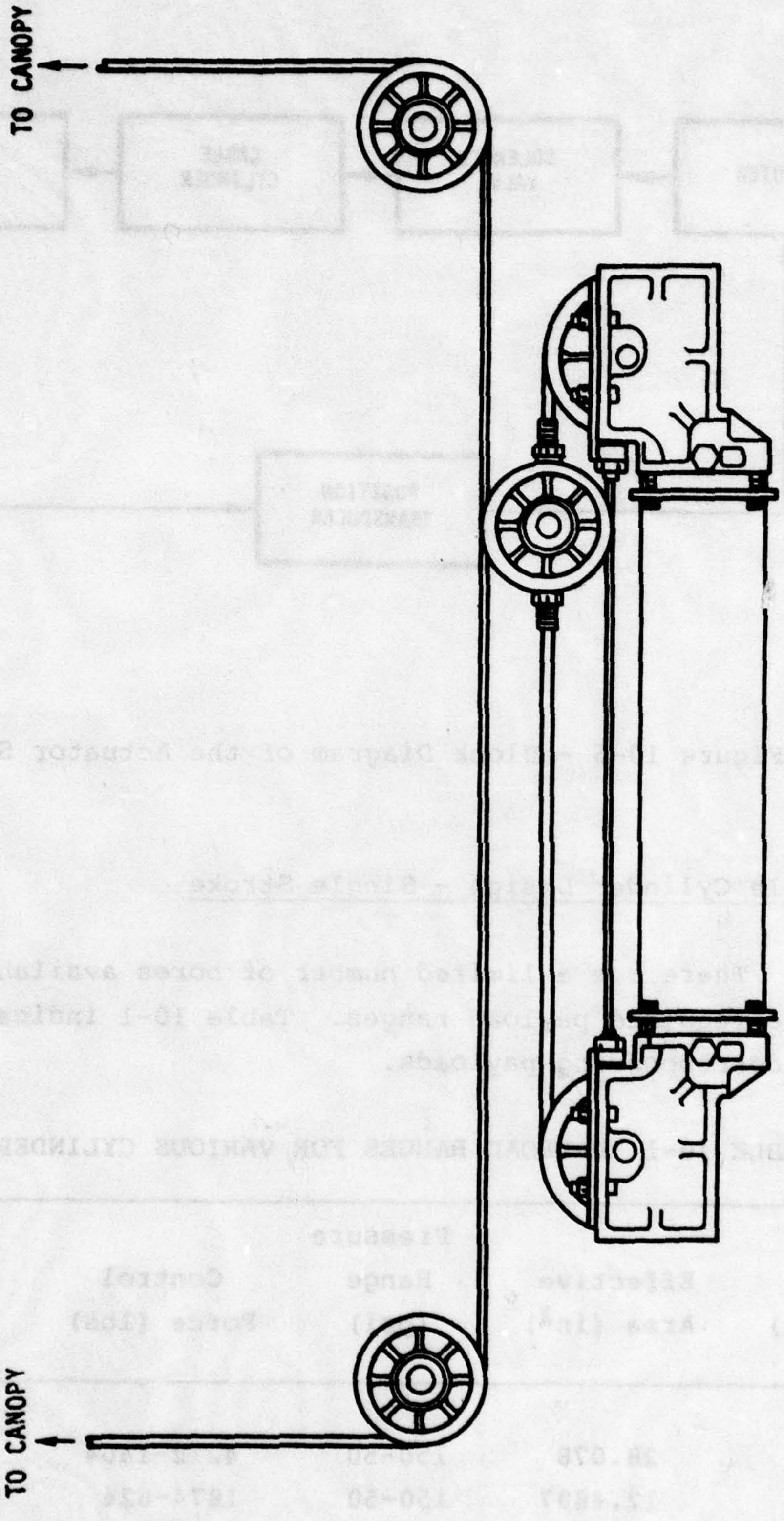
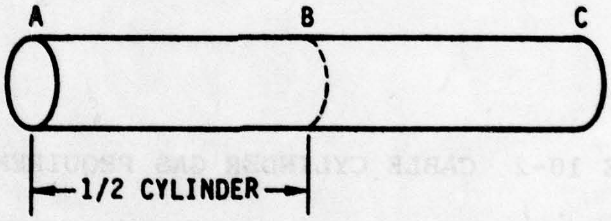

TO CANOPY
TO CANOPY

Figure 10-6 - Double Purchase Arrangement

The total volume of gas required to operate the system through 10 maneuvers can be calculated. A maneuver will be defined (referring to Figure 10-7) as moving from position B to position A and back to B.

It can be seen that for the initial maneuver, 1 1/2 cylinder volumes will be required and from then on, only 1 cylinder volume per maneuver. Therefore the system can expend 10 1/2 cylinder volumes of gas during its flight.

In calculating the volume of the storage tank, a maximum storage pressure of 2015 psi will be used. The simple expression $P_{cy}V_{cy} = P_tV_t$ will give good results. The cy subscript refers to the cable cylinder pressure and volume, while the t subscript refers to the storage tank parameters. Also, the maximum cable cylinder pressure will be used.



POSITION	CYLINDER VOLUMES
B	0
A	1
B	1/2
TOTAL	1-1/2

Figure 10-7 - Gas Volume Calculation

For example, to achieve a control force of 2250 lbs using the 6 inch bore requires a pressure of 80 psi. plus 14.7 psi to counteract the atmospheric pressure. Thus, we have

$$P_{cy}V_{cy} = P_tV_t$$

$$(94.7)(28303) = (2015)(V_t)$$

$$V_t = 1330 \text{ in}^3.$$

The recommended tank size is the sum of the minimum required volume, plus a safety volume, plus the volume needed to control the brake and auto-tensioner, plus any possible leakage. All but the first of these are approximated. These values are in Tables 10-2 and 10-3.

TABLE 10-2 CABLE CYLINDER GAS REQUIREMENTS

				Total		Cylinder
Volume	Maximum	Required				
Bore (in)	Effective Area (in^2)	Stroke (in)	Volume (in^3)	Required (in^3)	Required Pressure (psi)	Storage Volume (in^3)
6	28.078	96	2696	28303	80	1330
4	12.4897	96	1199	12590	150	1029
3	6.9917	96	671	7046	150	576
2 1/2	4.8596	96	467	4898	150	401

TABLE 10-3 RECOMMENDED STORAGE TANKS

Required Cylinder Volume (in^3)	Recommended Tank Volume (in^3)	Weight (lbs)	Length (in)	O.D. (in)	Part* Number	Price (dollars)
1330	2300	102	51.5	8.63	60010	150
1029	1510	81	35.25	8.5	67079	150
579	1044	63	25.38	8.5	240517	150
401	855	44	27.00	7.25	240516	150

*Manufactured by Walter Kidde & Company

Tables 10-4 and 10-5 give the weights and prices for cable cylinders according to bore.

TABLE 10-4 CABLE CYLINDER WEIGHTS (lbs)

		Tubing			Total	
Bore (in)	Base	Aluminum	Steel	Auto Tensioner and Disc Brake	Aluminum	Steel
6	130	N.A.	134	10 (tensioner only)	N.A.	274
4	41	15	44	11	67	96
3	47	12	33	11	70	91
2 1/2	27	10	28	11	48	66

TABLE 10-5 CABLE CYLINDER PRICES (DOLLARS)

Bore (in)	Base	Tubing		Total	
		Aluminum	Steel	Aluminum	Steel
6	1820	N.A.	840	N.A.	2660
4	433	232	182	665	615
3	419	193	144	612	563
2 1/2	413	144	134	557	547

Cable Cylinder Design - Double Purchase

The double purchase calculations are essentially the same as those used in the single stroke design, but here the cylinder will have a length of only four feet. This will have some impact on both gas storage requirements and price.

The 6-inch bore is not available in a double purchase arrangement. Payload ranges accommodated by the other bores are given in Table 10-6.

TABLE 10-6 PAYLOAD RANGES FOR VARIOUS CYLINDER BORES, DOUBLE PURCHASE ARRANGEMENT

Bore (in)	Effective Area (in^2)	Pressure Range (psi)	Control Force (lbs)	Payload Range (lbs)
4	12.4897	150-50	937-312	3124-1041
3	6.9919	150-50	525-175	1750-584
2 1/2	4.8596	150-50	365-122	1217-406

The 2 1/2 inch bore will be eliminated since it cannot meet the minimum payload requirement of 1500 lbs.

The total volume of gas required for 10 maneuvers is shown in Table 10-7.

TABLE 10-7 CABLE CYLINDER GAS REQUIREMENTS, DOUBLE PURCHASE ARRANGEMENT

Bore (in)	Effective Area (in^2)	Length (in)	Cylinder Volume (in^3)	Total Volume Required (in^3)	Maximum Required Pressure (psi)	Required Storage Volume (in^3)
4	12.4897	48	600	6295	150	515 @ 2015 psi
3	6.9919	48	336	3523	150	322 @ 1800 psi

Recommended storage tanks and cable cylinder weights and prices for the double-purchase arrangement are given in Tables 10-8, 10-9 and 10-10.

TABLE 10-8 RECOMMENDED STORAGE TANKS, DOUBLE PURCHASE ARRANGEMENT

Required Tank Volume (in^3)	Recommended Tank (in^3)	Weight (lbs)	Length (in)	O.D. (in)	Part Number*	Price (Dollars)
515 @ 2015 psi	855 @ 2015 psi	44	27	7.25	240516	150
322 @ 1800 psi	640 @ 1800 psi	24	23.25	6.75	240500	150

* Manufactured by Walter Kidde and Company

TABLE 10-9 CABLE CYLINDER WEIGHTS (LBS), DOUBLE PURCHASE ARRANGEMENT

		Tubing				Total	
Bore (in)	Base	Aluminum	Steel	Auto Tensioner and Disc Brake	Double Purchase Unit	Aluminum	Steel
4"	41	8	22	11	15	75	89
3"	47	6	17	11	15	79	90

TABLE 10-10 CABLE CYLINDER PRICES (DOLLARS), INCLUDING DOUBLE PURCHASE ARRANGEMENT

		Tubing			Total	
Bore (in)	Base	Aluminum	Steel	Double Purchase Unit	Aluminum	Steel
4"	433	116	91	171	720	695
3"	419	96	72	170	685	661

Table 10-11 lists the remaining components of the cable cylinder system. Figure 10-8 shows the single- and double-solenoid values.

TABLE 10-11 ASSOCIATED EQUIPMENT REQUIRED WITH THE CABLE CYLINDER ACTUATOR

Component	Manufacturer	Part Number	Price ($)	Weight (lbs)
Pressure Regulator	Rego	1608	72.00	8
Pressure Regulators (2)	Watts	R10-02	12.00 ea.	1.125 ea.
Flow Meter	Deltrol Easy Read	EFL30B	10.50 ea.	1.25 ea.
Pressure Line (100 ft.)	Sunflex	3600-08002	69.13	14
Double Solenoid Value	AAA	SY4 1/2"	107.23	4.75
Single Solenoid Value	Humphrey	062E1-3-11-20-36	19.50	1.25
Position Transducer	Celesco	TCC-PT-101	280.00	3
Total			$593.00	36 lbs.

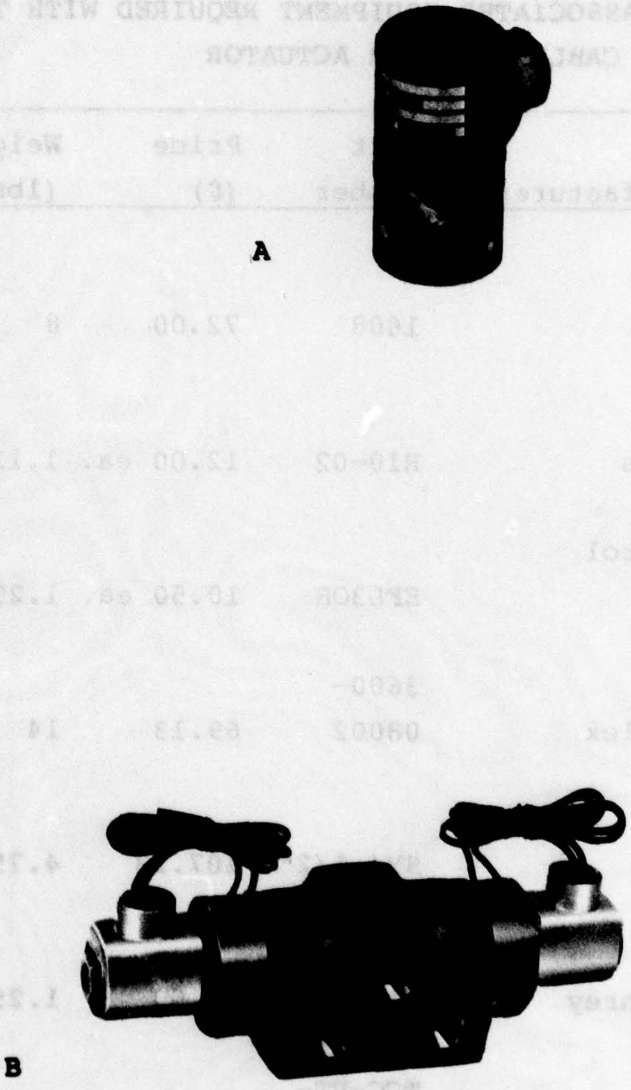


Figure 10-8 - (a) Single and (b) Double Solenoid Values

Tables 10-12 and 10-13 summarize the single-stroke and double-purchase systems. There appears to be a logical range of payloads for both systems to operate cost-effectively.

It should be mentioned that the 6" bore is not available with a disc brake. In order to stop and hold the load at the desired position, pressure will need to be maintained on the appropriate side of the piston. This will result in the system being somewhat sensitive to a change in the control force, perhaps due to a gust or lull in the wind. The piston will then react to this change in applied force by creeping to a new position. The position transducer will signal the computer of a change. The computer will then react by activating the solenoid control values and compensating for the change. Depending upon the sensitivity of the system, the operation of just holding a particular maneuver could result in the depletion of the gas supply.

Another disadvantage of the 6" bore is that it is relatively expensive for use on a narrow payload range. The upper limit on the 4" bore cable cylinder is based on a recommended operating pressure. It may be possible to increase this some what in an effort to close the gap between its present limit and 7500 lbs. With the 4" single-stoke system covering the payload range of 6,250 to 3,125, the 4" double purchase system would cover the lower range, 3,125-1,500, in half the space. Again, the upper limit of 3,125 is based on a recommended maximum operating pressure, so it may be possible to safely exceed this range somewhat.

Both systems' speeds are variable, depending upon the flow meter setting. To reuse the system, recharging the gas tank is all that is required. If nitrogen is used, this would cost less than ten dollars a flight.

The cable cylinder system is a simple, efficient, quick-responding one which is also lightweight and cost effective.

TABLE 10-12 SINGLE STROKE SYSTEM SUMMARY

	Payload (lbs)	Control Force (lbs)	Bore (in)	Tank (in^3)	Weight (lbs)	Price ($)	Stroke (in)	Speed Ft/sec
Steel	7,500- 4,680	2,250- 1,404	6	2,300	412	3,403	96	1
Aluminum	6,247- 2,082	1,874- 624	4	1,510	184	1,408	96	1
Steel	6,247- 2,082	1,874- 624	4	1,510	213	1,358	96	1
Aluminum	3,496- 1,166	1,049- 350	3	1,040	169	1,355	96	1
Steel	3,496- 1,166	1,049- 350	3	1,040	190	1,306	96	1
Aluminum	2,430 810	729- 244	2 1/2	855	128	1,300	96	1
Steel	2,430- 810	729- 244	2 1/2	855	146	1,290	96	1

TABLE 10-13 DOUBLE PURCHASE SYSTEM SUMMARY

	Payload (lbs)	Control Force (lbs)	Bore (in)	Tank (in^3)	Weight (lbs)	Price ($)	Stroke (in)	Speed Ft/sec
Aluminum	3,125 1,041	940- 312	4"	855 @ 2,015 psi	155	1,463	96	1
Steel	3,125 1,041	940- 312-	4"	855 @ 2,015 psi	169	1,438	96	1
Aluminum	1,750 585	525- 176	3"	640 @ 1,800 psi	139	1,418	96	1
Steel	1,750 585	525 176	3"	640 @ 1,800 psi	150	1,404	96	1

10.2 Electric Winch

A simple, readily-available device for taking in or reeling out a control line is the electric winch. A signal from the computer initiates the control. Depending upon the desired turning direction, relays provide the appropriate polarity to the winch motor. As the control line is reeled in or let out, a transducer monitors its position. The output of the transducer is fed back to the computer which compares it with the desired position. Once the correct amount of line has been displaced, the relays will break contact and the winch will hold the load in that position. Depending upon the particular winch, this braking will be done by an electro-mechanical brake within the winch, or by the large gear reduction between the winch motor and the output.

Assuming a desired pull-rate of one foot per second, a force ranging from 450 to 2250 pounds, and a gearing effeciency of 75%, the required horsepower would range from 1HP to 5HP. When dealing with battery-powered motors, these are large figures. The few available candidates were selected on the basis of their braking and reversing capability, and their ability to withstand deployment and landing shock.

Specifications for these candidates are given in Table 10-14. Figure 10-9 plots the output line speed as a function of the pull force for these winches. The available line speeds are somewhat lower than the desired one foot per second. The Thern 486 and the Ramsey DC246, shown in Figure 10-10, come closest to meeting the system requirements; their most applicable region of operation is indicated by bolder lines in the force line-speed curves.

TABLE 10-14 SPECIFICATIONS FOR VARIOUS ELECTRIC WINCHES

Winch Model	Weight (lbs)	Price (Dollars)	Type of Braking	Operating DC Voltage (volts)	Required Max. Current (amps)	Line Speed Range (fmp)
Ramsey DC246*	130	559.00	gearing	12	175	19-13
Ramsey DC7-B	50	472.00	gearing	12	205	22-8
Thern 486*	166	1,082.00	electro-mech.	12	150	27-7
Thern 476	111	826.00	electro-mech.	12	150	26-3
My-Te 1200(1:1)	160	679.00	gearing	12/6	160	5.5-4.5
My-Te 1200(2:1)	160	679.00	gearing	12/6	160	10-7
My-Te 20-12(1:1)	62	395.00	gearing	12/6	160	12-1
My-Te 20-12(2:1)	62	395.00	gearing	12/6	160	17-

* **Recommended**

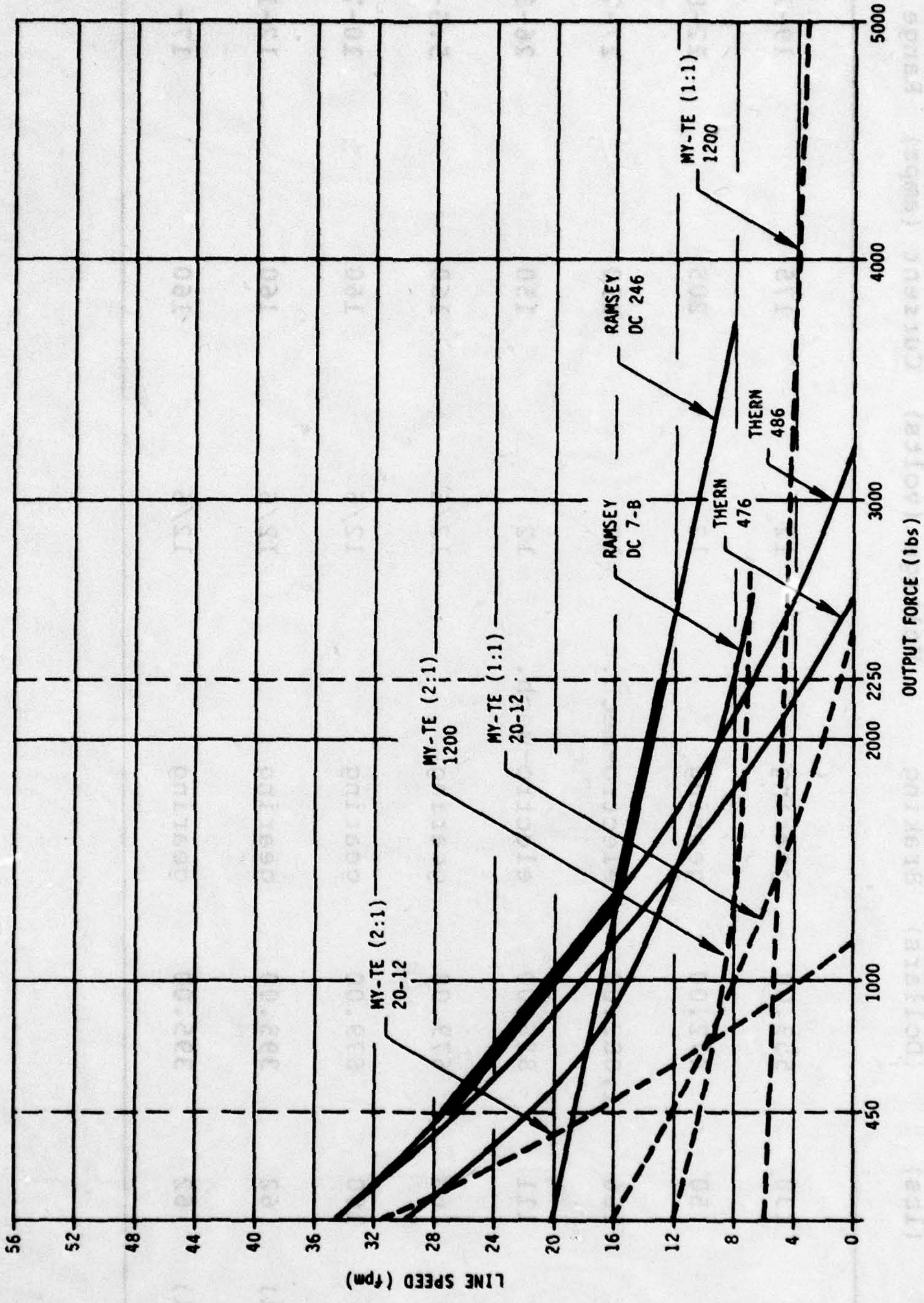


Figure 10-9 - Line Speed versus Force curves for Various Electric Winches

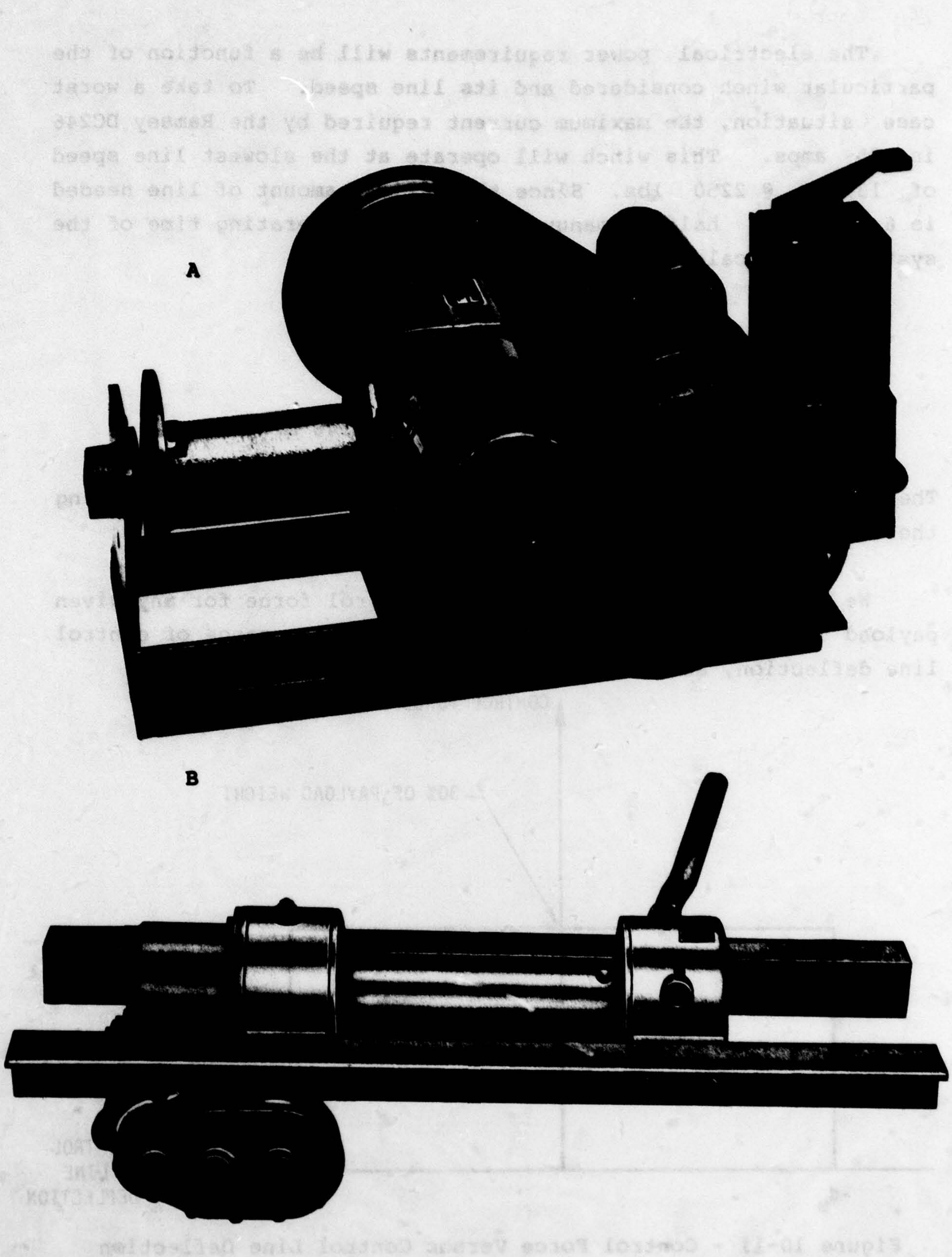


Figure 10-10 - Electric Winches manufactured by (a) Thern, and (b) Ramsey

The electrical power requirements will be a function of the particular winch considered and its line speed. To take a worst case situation, the maximum current required by the Ramsey DC246 is 175 amps. This winch will operate at the slowest line speed of 13 fpm. @ 2250 lbs. Since the maximum amount of line needed is 6 feet per half a manuver, the total operating time of the system can be calculated as follows:

pull rate $V = 13$ feet/minute
maximum deflection $d_m = 6$ feet

time for 1/2 maneuver $t = d_m/v = .46$ minutes

The system will complete one full maneuver in .92 minutes; during the entire flight, 9.2 minutes of operating time is expected.

We assume here that the required control force for any given payload is the maximum value over the entire range of control line deflection, as shown in Figure 10-11.

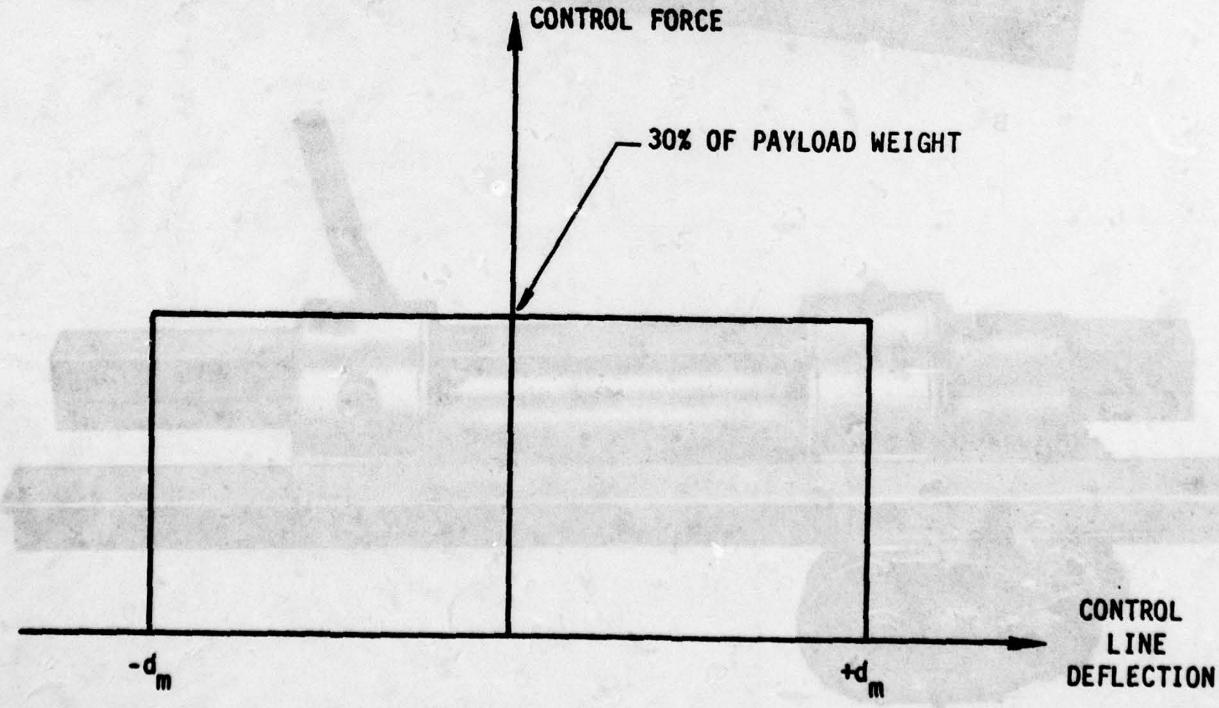


Figure 10-11 - Control Force Versus Control Line Deflection

To calculate the battery requirements, a maximum current of 175 amps will be used, as well as an operating time of 10 minutes. During this time, the system use will be intermittent, thus extending the life of the battery.

Taking the maximum current(I) of 175 amps and assuming a discharging rate(D) of 15 minutes, the required battery rating is

ID = (15 min) (175 amps) = (1/4 hr) (175 amps) = 45 amp-hours.

Since the power requirement is needed over a short time, the battery must actually be rated higher than the 45 amp-hours indicated. A 12 volt battery with a rating of about 100 ampere-hours will suffice. This is the size of a large automotive battery.

A #2 welding cable, single conductor with a neoprene installation, will carry the power to the winch.

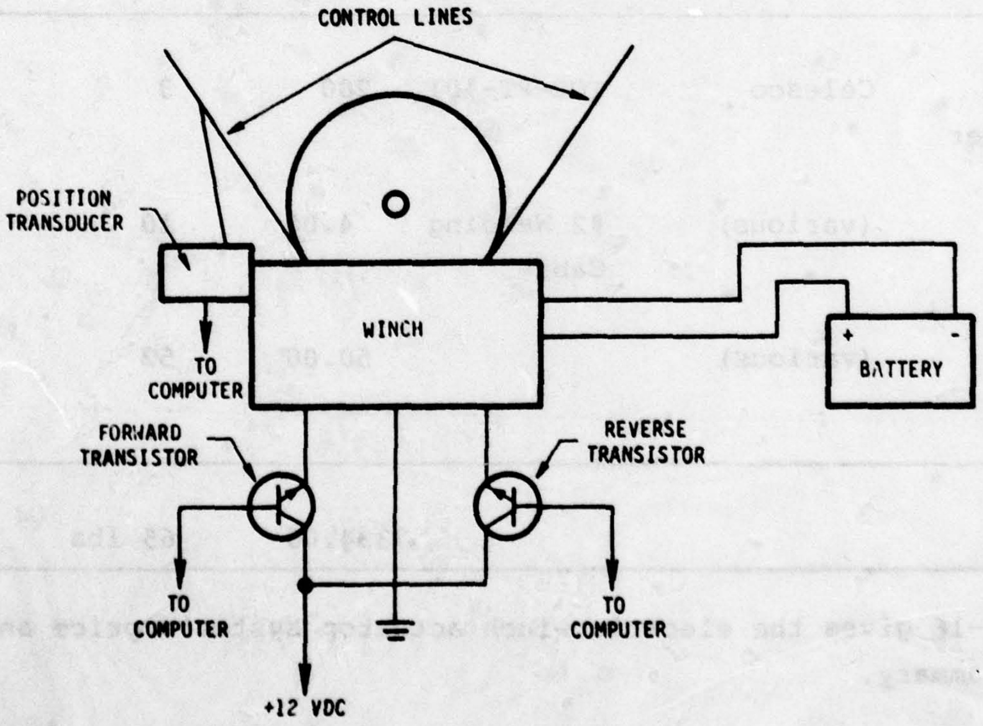

CONTROL LINES
POSITION TRANSDUCER
WINCH
TO COMPUTER
+
-
BATTERY
FORWARD TRANSISTOR
REVERSE TRANSISTOR
TO COMPUTER
TO COMPUTER
+12 VDC

Figure 10-12 - System Configuration (The Control Solenoids are Included in With the Winch)

The position transducer will be mounted on the winch. Its cable will attach to one of the control lines; as it is taken in or reeled out, the position transducer's line will do the same, and thus measure the control-line deflection.

Figure 10-12 shows the electric-actuator system configuration; weights and prices for the wire, position transducer, and battery are given in Table 10-15.

TABLE 10-15 EQUIPMENT REQUIRED WITH THE ELECTRIC WINCH ACTUATOR

Component	Manufacturer	Part Number	Price($)	Weight(lbs)
Position Transducer	Celesco	TCC-PT-101	280	3
Wire	(various)	#2 Welding Cable	4.00	10
Battery	(various)		50.00	52
Total			$334.00	65 lbs

Table 10-16 gives the electric winch actuator system's price and weight summary.

TABLE 10-16 ELECTRIC WINCH ACTUATOR SYSTEMS PRICES AND WEIGHTS

Winch Model	Payload Range (lbs)	Control Force (lbs)	Line Speed (fpm)	System Component Price (Dollars)	Winch Price (Dollars)	System Price (Dollars)	System Weight (lbs)
Ramsey DC246	7500-4500	2250-1350	13-16	334.00	560.00	894.00	193
Thern 486	4500-1500	1350-450	16-27	334.00	1082.00	1416.00	229

Although the line speed capability is not as high as might be desired, the electric actuator system offers a low weight, cost-effective system which requires minimal recycling efforts.

It does have a number of drawbacks in that due to the inherent nature, the electric motor and the solenoids will produce a good amount of electrical noise. This may very well interfere with the receiving signals which are guiding the airdrop vehicle. Since the system will operate at such a slow rate, this noise may last up to ten minutes of flight time.

The Thern winch has an electric brake to hold the load, while the Ramsey depends on its gearing. The Ramsey has a maximum load rating of 8,000 lbs. The gearing will easily hold a force of 2250 lbs.

11. CONCLUSIONS AND RECOMMENDATIONS FOR FOLLOW-ON WORK

This report describes five guidance subsystems that could be used for measuring required flight data, processing these data according to one of several guidance schemes, and activating control lines as required to guide a gliding airdrop system. It is intended that this report, along with NARADCOM's flight performance studies, will assist the Government in their selection of a specific guidance subsystem for fabrication and testing.

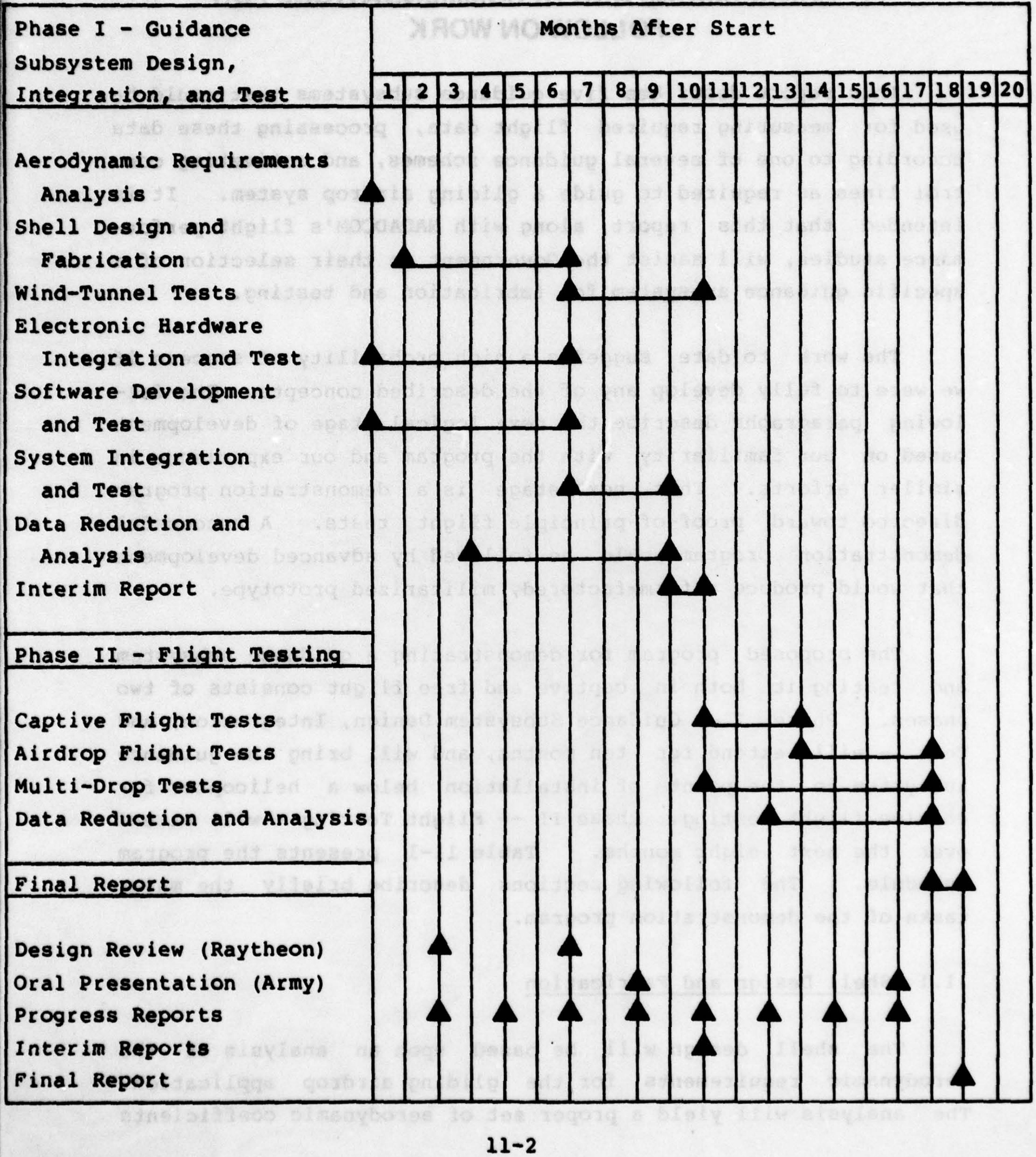
The work to date suggests a high probability of success if we were to fully develop any of the described concepts. The following paragraphs describe the next logical stage of development based on our familiarity with the program and our experience in similar efforts. This next stage is a demonstration program directed toward proof-of-principle flight tests. A successful demonstration program would be followed by advanced development that would produce a form-factored, militarized prototype.

The proposed program for demonstrating a guidance subsystem and testing it both in captive and free flight consists of two phases. Phase I -- Guidance Subsystem Design, Integration, and Test - will extend for ten months, and will bring the guidance subsystem to the point of installation below a helicopter for captive flight testing. Phase II -- Flight Testing - will extend over the next eight months. Table 11-1 presents the program schedule. The following sections describe briefly the major tasks of the demonstration program.

11.1 Shell Design and Fabrication

The shell design will be based upon an analysis of the aerodynamic requirements for the gliding airdrop application. The analysis will yield a proper set of aerodynamic coefficients

TABLE 11-1 PROPOSED DEMONSTRATION PROGRAM SCHEDULE



to assure a stable system suspended between the canopy and the payload. The design will minimize sideslip, if desired, and will include provisions for a flush-mounted static-pressure port for the barometric altimeter. For the purposes of this task, the shell will consist of an enclosure for the airborne electronics, and any externally-mounted sensors or actuators.

Design will be followed by fabrication and wind-tunnel testing. The total effort, including analysis and testing, will extend throughout Phase I.

11.2 Electronic Hardware Integration and Test

This task will bring together all ground-based and airborne electronics (mostly off-the-shelf equipment) required for the gliding airdrop guidance subsystem, with the exception of that associated with the actuator. It will also include the design of interface circuits. We will place a test package, containing what would be the airborne electronics, on a jeep or truck, and telemeter all sensed data to a fixed ground site. The vehicle will drive a predetermined course while its position is tracked from the gound site. Such a test would verify the operation of the position-measuring equipment, the data downlink, and all sensors except the altimeter.

11.3 Software Development and Test

This task will develop the software for implementing one or more of the guidance laws for a gliding airdrop system. We will write the software for a single-board computer for those guidance subsystems using an airborne computer, or for the MR-III data processor for those using the MR-III tracking system. This software will include coordinate transformation, position differentiation (for groundspeed), and filtering. The software tests will be based on simulated data inputs.

11.4 System Integration and Test

At the end of six months, we will be ready to integrate the sensors, tracking electronics, guidance computer, and shell into a single guidance package. The guidance software will be read from magnetic tape into the computer's random-access memory. A jeep or truck will carry the guidance package, driving a predetermined course while the guidance commands are being monitored from within the vehicle or from a fixed ground site. A simulated initial altitude and rate of descent will be programmed into the computer. We will correlate the resulting guidance commands with open-loop commands generated by the Army's computer simulation, in which the airdrop vehicle would follow the same course.

11.5 Captive Flight Tests

A helicopter will captive-carry the guidance package developed in Phase I, flying a pre-determined course while the guidance commands are being monitored from within the helicopter or from a fixed ground site. We will monitor the sensed data, the guidance commands, and the actuator motion and correlate this with open loop data generated by the Army's computer simulation, in which the airdrop vehicle would follow the same course.

11.6 Airdrop Flight Tests

In this task, we will suspend the guidance package from a government-furnished canopy that will be dropped from an aircraft, and track it under closed-loop control. As the airdrop vehicle comes within one mile of the desired landing zone, we will exercise the manual command override.

11.7 Multi-Drop Tests

This task will test the capability of the system to control multiple vehicles simultaneously. We will test this capability first on the ground with open-loop commands, using two land vehicles, then in free flight, with closed-loop commands to the canopy.

11.8 Final Report

The Final Report will include a detailed description of the guidance systems tested and the test results.

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