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System No. 2

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1-0. GENERAL.

1-1. During the period covered by this report, two major decisions regarding project orientation were made. The first was the decision to consider the communication functions of System No. 2 separately from the navigation functions. The second was the decision to discard the concept of a navigation system which depended on the radiations of existing low-frequency broadcast transmitters to generate position information.

1-2. The decision to consider the communication functions separately from the navigation functions was made in order to permit system design for each of these functions to proceed independently of the other and thus to achieve optimum performance in each function. This decision was necessitated primarily by the extra burden imposed on both functions by the increase in operating range to 4000 miles. It is believed that greater reliability and efficiency in the final product will result by designing system functions to meet specific communication or navigation requirements rather than by attempting the design of circuits which could be shared by both functions. System components will be shared by the two functions only when this does not compromise the requirements of either. Transmitters and receivers, both airborne and ground-based, for example, will be common to both the communication and navigation portions of System No. 2.

1-3. The decision to discard the concept of a navigation system dependent on the radiations of existing low-frequency broadcast transmitters was founded on a combination of factors. The principle objections to this dependance were the lack of rigid broadcast operating schedules, the possibility that countermeasures would be applied by unfriendly transmitters, and the lack of sufficient suitable broadcast installations in the Middle and Far East to provide reliable coverage of all areas. Further, an analysis of the propagation characteristics to be expected revealed that fluctuations of field intensity, due to various sky-wave modes, would make positive identification of the active mode extremely difficult since uncertainty in the downcoming wave angle would introduce an uncertainty in the effective wave length as observed by the aircraft in horizontal flight. This would require the introduction of an average effective wave length in the computations for these areas of uncertainty and would seriously compromise the accuracy of position measurements.

1-4. Since the fundamental principles of the navigation equipment described in this report have not yet been tested and

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proved, a concerted effort is being made to construct and assemble an experimental equipment intended to test the practicability of the system described.

1-5. In the case of the communication equipment described in this report, however, the fundamental principles involved have previously been tested and proved. For this reason, there is well-grounded confidence in the practicability of the communication equipment described and design of a prototype model has been started. Circuits are being breadboarded and tested only in those cases where performance requirements are special or unique.

2-0. FUNDAMENTAL PRINCIPLES OF THE NAVIGATION EQUIPMENT.

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3-0. ANTENNA ARRANGEMENT OF THE GROUND-BASED PORTION OF THE NAVIGATION EQUIPMENT.

3-1. The ground-based portion of the navigation equipment includes three grounded vertical radiators located at the vertices of an equilateral triangle. (A separate rhombic antenna will be used for reception at the base station.) First, a pulse will be transmitted from antenna 1, then a pulse will be transmitted from antennas 1 and 2 in combination, and finally a pulse will be transmitted from antennas 1 and 3 in combination. The ratio of the signal strength at the aircraft due to simultaneous pulse transmissions from antennas 1 and 2 to the signal strength at the aircraft due to pulse transmissions from antenna 1 is a function of the azimuth angle and elevation angle from the base station to the aircraft. (See figure 1.) This ratio is independent of mode of propagation or range as indicated by the following expression:

$$X_{12} = (2)^{\frac{1}{2}} \text{ Cos} \left[\frac{\omega_{12}}{2} + \frac{\pi D}{\lambda} \text{ Cos } \phi \text{ Sin } (\gamma - \beta_{12}) \right] \qquad (1)$$

where $X_{12} = \dfrac{\text{Signal strength at aircraft due to antennas 1 and 2}}{\text{Signal strength at aircraft due to antenna 1}}$

where ϕ = vertical angle (see figure 1)

γ = azimuth angle measured with respect to the reference line

β_{12} = angle formed by the perpendicular of a line connecting antenna 1 to 2 with the reference line

ω_{12} = phase angle by which the current in antenna 2 leads current in antenna 1

By the same method:

where $X_{13} = \dfrac{\text{Signal strength at aircraft due to antennas 1 and 3}}{\text{Signal strength at aircraft due to antenna 1}}$

$$X_{13} = (2)^{\frac{1}{2}} \text{ Cos} \left[\omega_{13} + \frac{\pi D}{\lambda} \text{ Cos } \phi \text{ Sin } (\gamma - \beta_{13}) \right] \qquad (2)$$

An explicit expression for the azimuth angle γ is given by:

$$\gamma = \text{Tan}^{-1} \left[\frac{K_{12} \text{ Sin } \beta_{13} - K_{13} \text{ Sin } \beta_{12}}{K_{12} \text{ Cos } \beta_{13} - K_{13} \text{ Cos } \beta_{12}} \right] \qquad (3)$$

$$\text{where } K_{12} = \text{Cos}^{-1} \left(\frac{X_{12}}{(2)^{\frac{1}{2}}} \right) - \frac{\omega_{12}}{2} \qquad (4)$$

$$\text{and } \quad K_{13} = \text{Cos}^{-1} \left(\frac{X_{13}}{(2)^{\frac{1}{2}}} \right) - \frac{\omega_{13}}{2} \qquad (5)$$

The quantities on the right of equations (4) and (5) are known. It is to be noted that β_{12} and β_{13} are fixed by the geometry of the antenna positioning. The form of equation (3) suggests a possible mechanical analogue for finding the azimuth angle γ. Figure 2 shows the geometry which represents the azimuth angle in terms of the fixed angles β_{12} and β_{13}, and the variables K_{12} and K_{13} which are determined by the signal ratios according to equations (4) and (5).

3-2. Once having a value for γ, equation (1) or (2) yields the vertical angle ϕ by use of an equation of the form:

$$\phi = \cos^{-1} \frac{K_{12}}{\sin(\gamma - \beta_{12})} \cdot \frac{\lambda}{\pi D} \qquad (6)$$

The range of the aircraft is determined from a knowledge of the path length of the radiation from the transmitter to the receiver and the vertical angle ϕ obtained by use of equation 6. Thus far, only one-hop propagation modes have been considered.

3-3. The range r for the one-hop mode is given by $2R\theta$. (See figure 3.) Expressed in terms of ϕ and the path length L, this becomes:

$$r = 2R \tan^{-1} \left[\left(\frac{L}{2R}\right) \frac{\cos\phi}{1 + \left(\frac{L}{2R}\right) \sin\phi} \right] \qquad (7)$$

The error in the range due to an error in ϕ is given by:

$$\left| dr \right| = 222.5 \text{ km} \frac{\sin\theta}{\cos\phi} \sin(\theta_1 + \phi) \left| d\phi \right| \qquad (8)$$

Table 1 is a tabulation of the errors in r due to an error of one degree in ϕ for different ranges and different heights of reflection h.

Table 1. Errors In Range For One Degree Errors in ϕ as Function Of h

r (km)	dr (km)			
	h = 100 km	200 km	300 km	400 km
1000	4.43	7.7	10.8	13.8
2000		10.1	12.9	18.0
3000		12.8	15.8	19.4
3500			18.5	21.1

By way of explanation, for the 2000 km range, there is a 10.1 km error per degree error in ϕ for a height of reflection of 200 km and an 18.0 km error per degree error in ϕ for a height of reflection of 400 km.

3-4. The fact that the receiving antenna is not at ground level introduces an error if r is obtained using equation (7) directly. The correct ground range is obtained (See figure 4.) from:

$$r = 2R \tan^{-1}\left[\left(\frac{\ell_1 + \ell_2 + \ell_3}{2R}\right)\frac{\cos\phi}{1 + \left(\frac{\ell_1 + \ell_2 + \ell_3}{2R}\right)\sin\phi}\right] - \frac{h_a}{\tan\phi} \qquad (9)$$

where $\ell_1 + \ell_2$ = the actual path length

h_1 = the correct height of reflection

h'_1 = the height of reflection implicitly assumed in using equation (8)

h_a = height of receiving antenna

ℓ_3 = the path length from the receiving antenna to ground maintaining the same ray direction as from the point of reflection at h_1 to the receiving antenna

In terms of central angles, the correct range is given by:

$$r = 2R\theta_1 - R\theta_a$$

where neglecting the height of the receiving antenna, the range is given by:

where: $2R\theta_2$

$$\theta_2 = \tan^{-1}\left[\left(\frac{\ell_1 + \ell_2}{2R}\right)\frac{\cos\phi}{1 + \left(\frac{\ell_1 + \ell_2}{2R}\right)\sin\phi}\right] \qquad (10)$$

As a numerical example, let us choose, $\ell_1 + \ell_2 = 2042$ km

$h_a = 60{,}000' = 18.29$ km

$\phi = 12^{\circ}$

The correct r = 1911.0 km from equation (9)

The incorrect r = 1919.0 km using equation (10). This is a difference of 8 km.

3-5. No mention has been made of the errors due to the fact that the ionosphere is not a smooth reflecting sheet. These errors may be represented as uncertainties in X_{12}, X_{13}, and will be minimized by averaging over a sufficiently large number of measurements.

4-0. GROUND-BASED NAVIGATION EQUIPMENT.

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7-0. FORM-FACTOR CONSIDERATIONS.

7-1. The size and configuration of the space available in the airplane for installation of System No. 2 equipment leaves much to be desired. The configuration of this space necessitates packaging of the equipment in a manner which will contribute undesirably to its weight. Also, the cockpit instrument panel space available for control and operation of the system is less than that required for the control unit of the ARC-34 equipment, yet the System No. 2 equipment must perform functions of far greater complexity than those involved in the operation of the ARC-34.

7-2. These factors are of importance from an engineering standpoint primarily because they tend to increase the difficulties of equipment component design and because they necessitate the use of form factors which are ill-suited to minimizing size and weight, or to simplifying test and maintenance of the equipment. By way of example, it may be mentioned that the space available is long, narrow, and of irregular cross-section; accordingly it will probably be necessary to incorporate a cast-magnesium-alloy "backbone" as the basic support for system components. Space conforming more nearly to equipment requirements would permit assembly of the components in more conventional form, with a consequent saving in weight of eight to ten pounds through elimination of the backbone structure.

7-3. Preliminary estimates suggest that System No. 2 will employ a total of about 300 vacuum tubes and transistors. The total volume occupied will lie in the neighborhood of 2.5 to 3.0 cubic feet, and the weight may be expected to approximate 60 pounds. Average power input will be on the order of 500 watts, with instantaneous peak values in the vicinity of 1500 watts. More refined estimates of such data will be available for inclusion in a future report.

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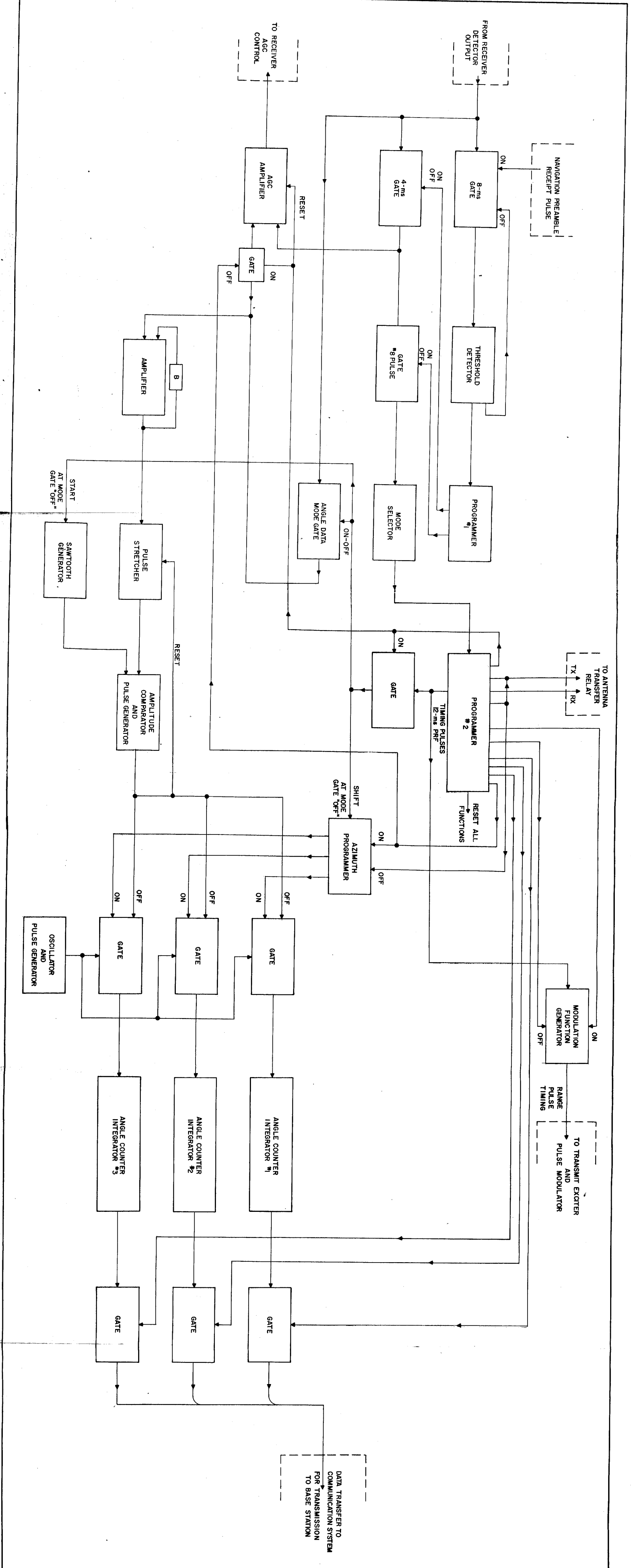

Figure 9A. Navigation Data And Timing Unit, Block Diagram

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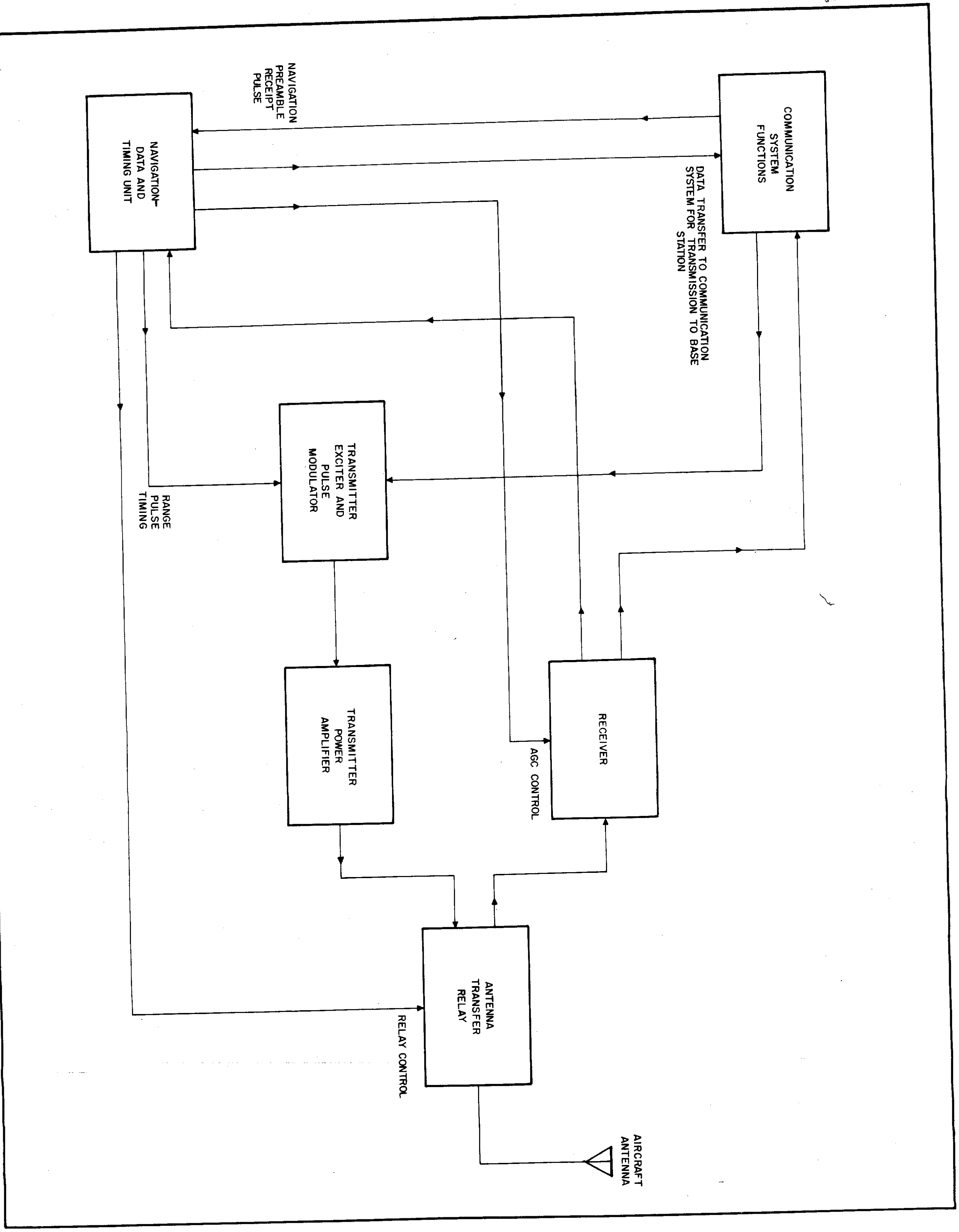

Figure 9. Basic Airborne Navigation Equipment, Block Diagram

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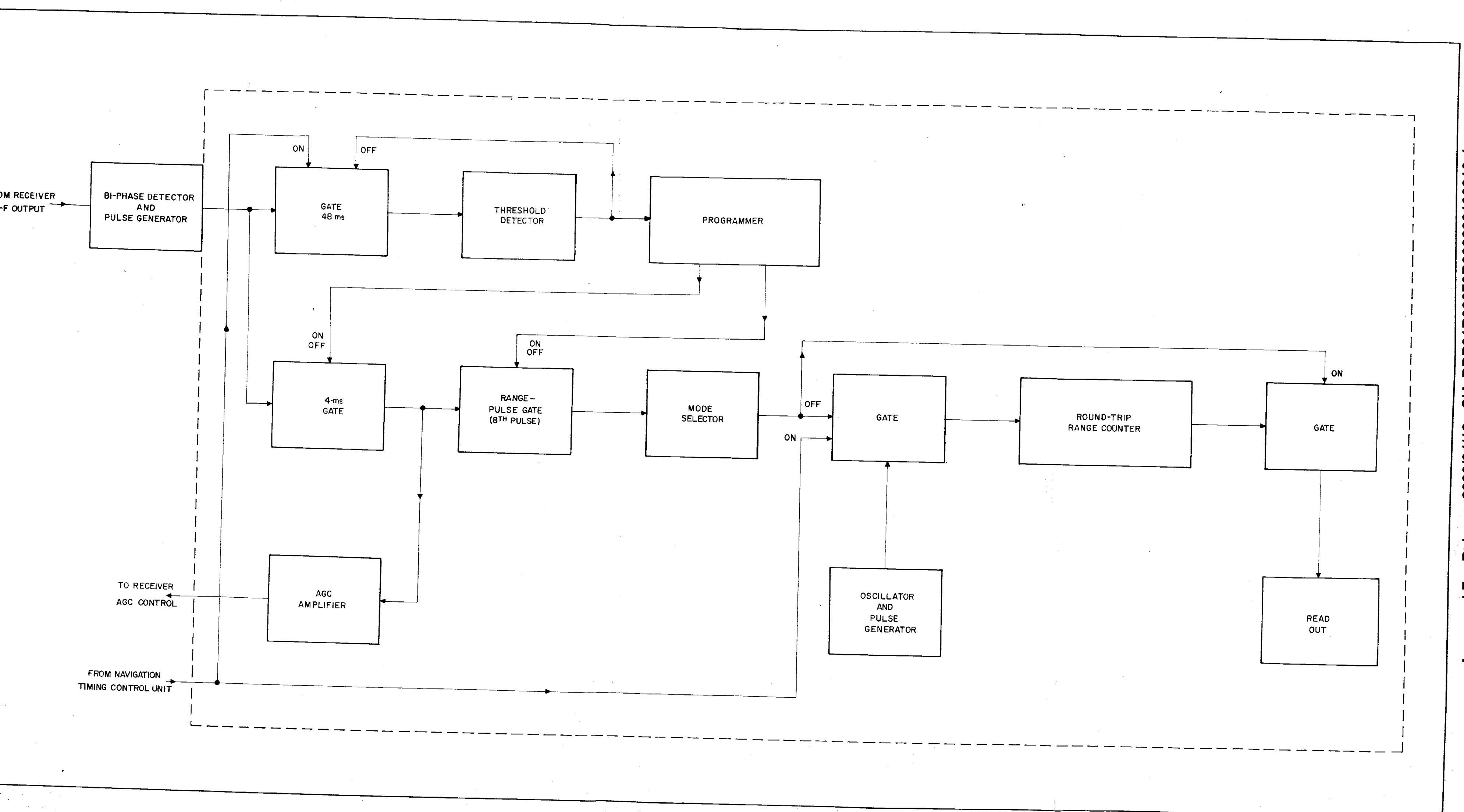

Figure 8. Navigation Range-Data Unit, Block Diagram

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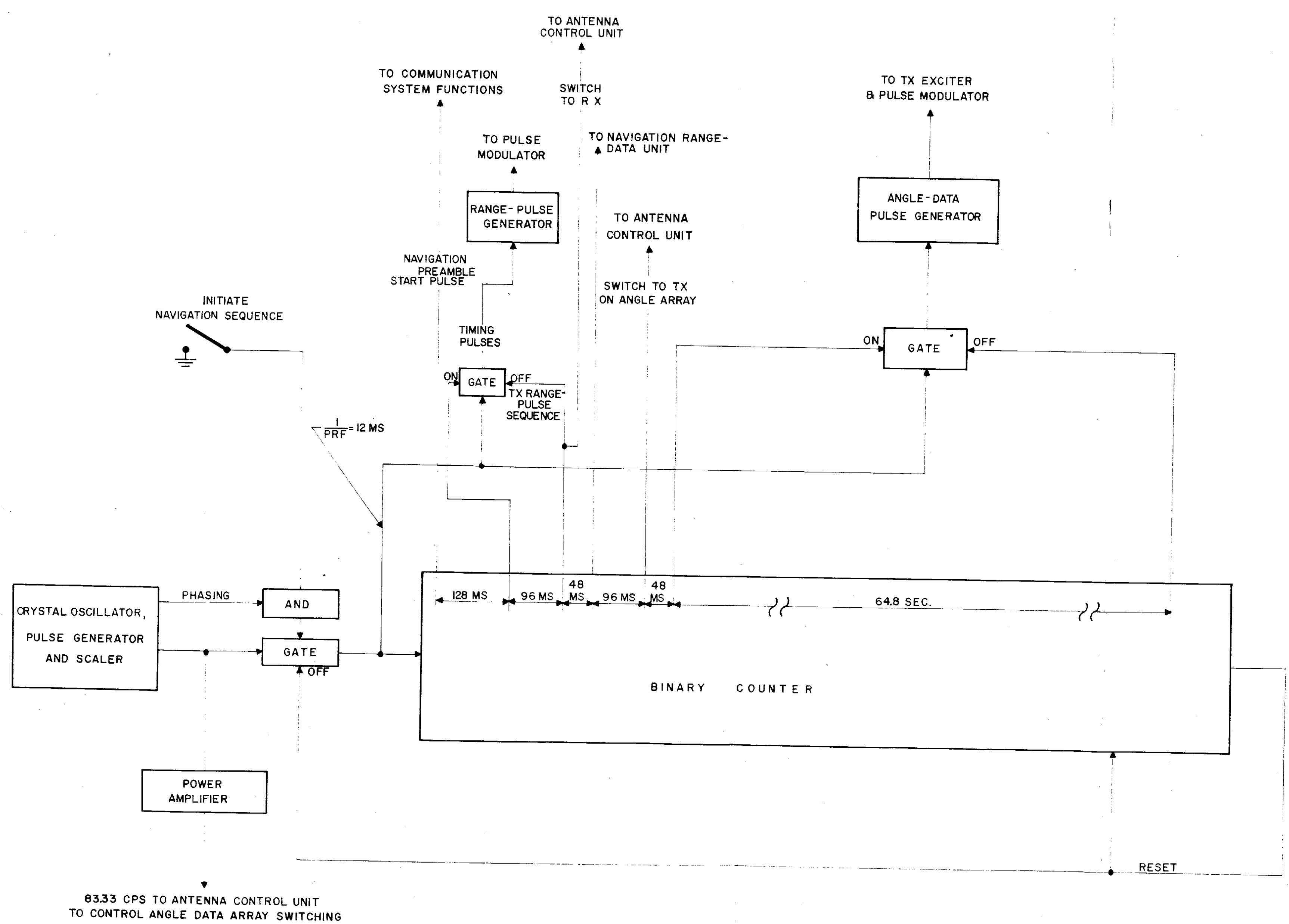

Figure 7. Navigation Timing & Control Unit (Ground Based), Block Diagram

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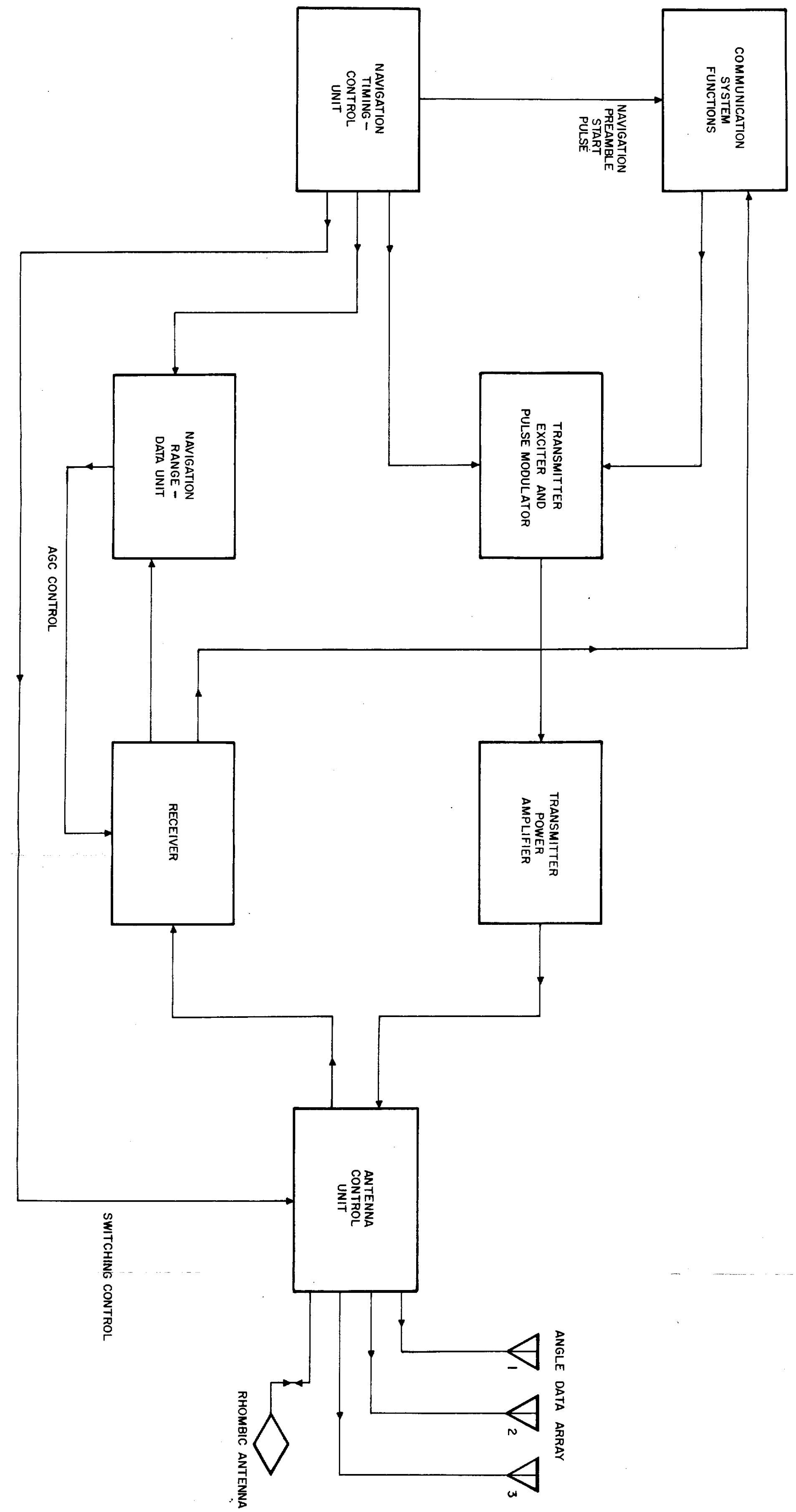

Figure 6 - Base-Station Navigation Equipment, Block Diagram

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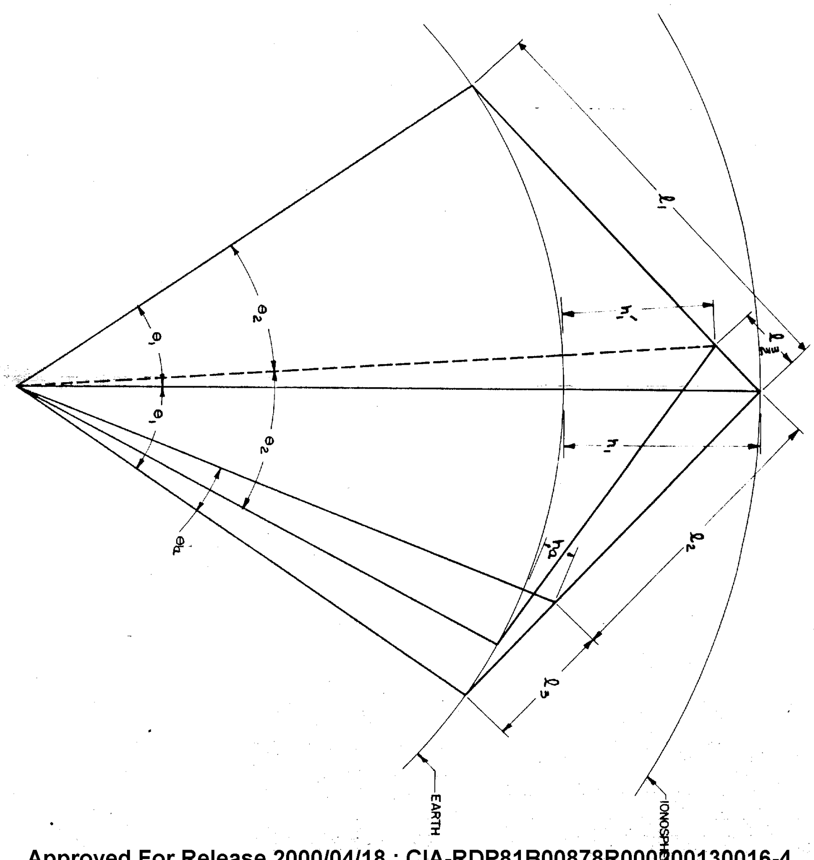

Figure 4. Error Due To Neglecting The Height Of The Aircraft

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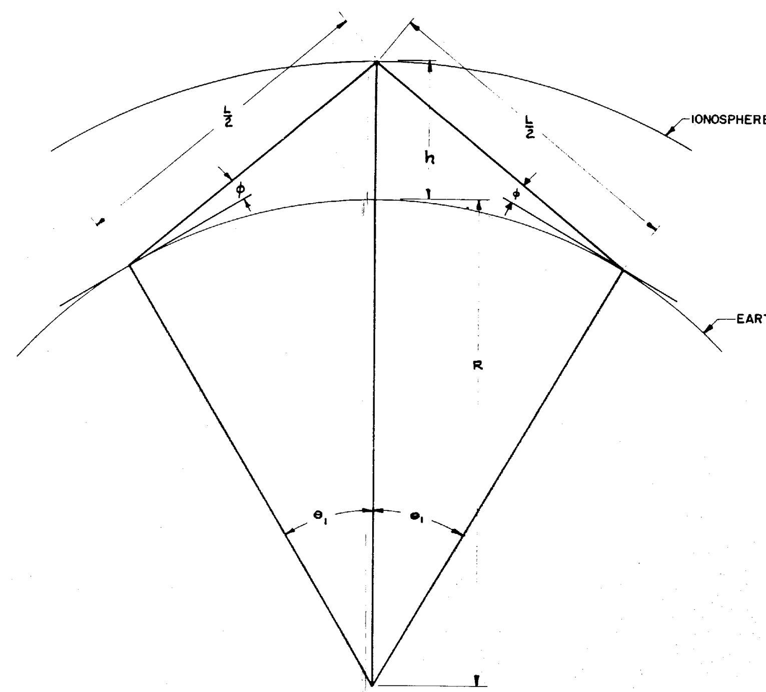

Figure 3. One-Hop Mode

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$$a = K_{12}\ \mathrm{SIN}\ \beta_{13} - K_{13}\ \mathrm{SIN}\ \beta_{12}$$

$$b = K_{12}\ \mathrm{COS}\ \beta_{13} - K_{13}\ \mathrm{COS}\ \beta_{12}$$

$$\mathrm{Tan}\ \sigma = \frac{a}{b}$$

$$\mathrm{Tan}\ \sigma = \frac{K_{12}\ \mathrm{SIN}\ \beta_{13} - K_{13}\ \mathrm{SIN}\ \beta_{12}}{K_{12}\ \mathrm{COS}\ \beta_{13} - K_{13}\ \mathrm{COS}\ \beta_{12}}$$

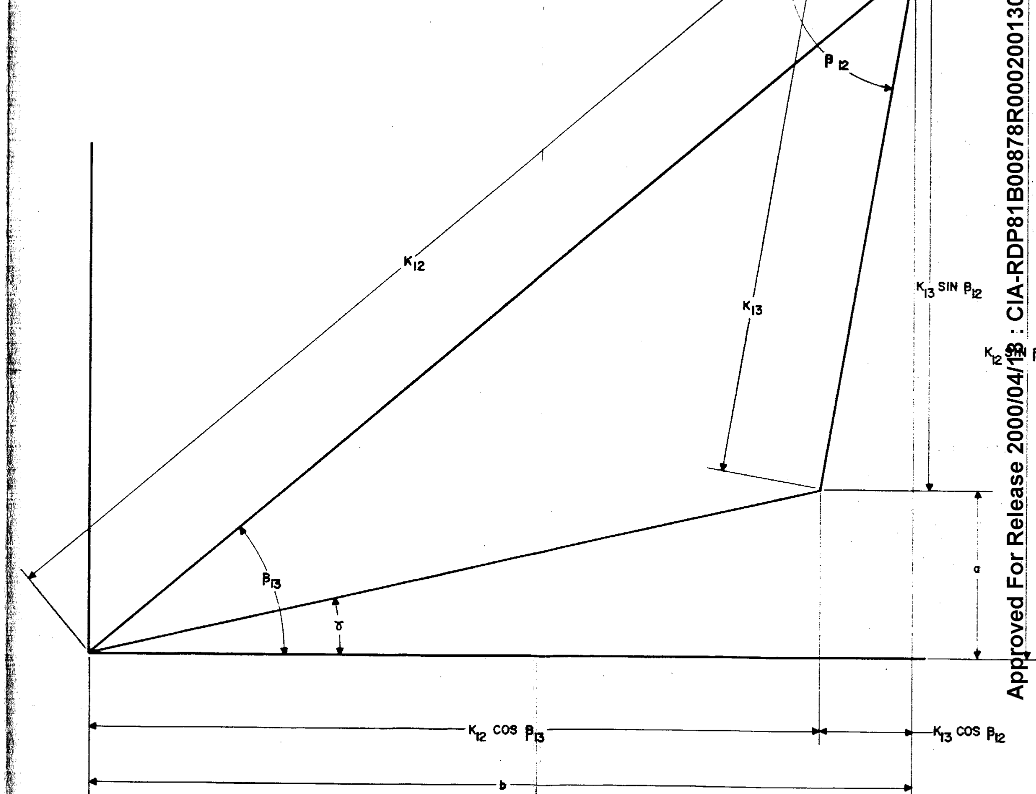

Figure 2. Geometric interpretation Of Equation 3

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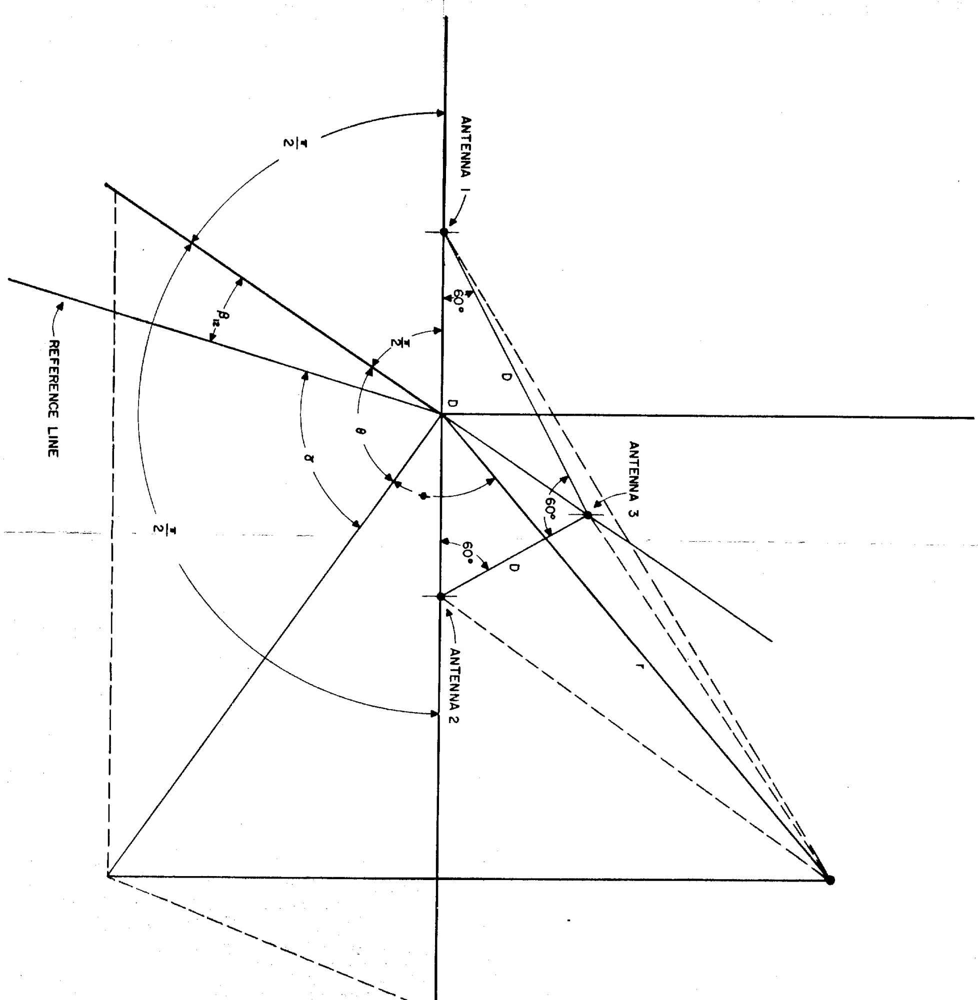

Figure 1. Geometry Of Antenna System

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