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LITCHFORD SYSTEMS

AUGUST 1969

SUGGESTED TEST OF A SELF-CALIBRATING BARO-HEIGHT REPORTING CONCEPT FOR GENERAL AVIATION AND AIRLINE SSR

Figure I illustrates the principles of the concept. The aircraft flies over a normal Marker Beacon signal, and in so doing, a relay is closed to activate the cockpit light or tone indication of the marker signals to the pilot. This is a standard output from existing 75 Mc marker receiver, however, this relay, in addition, initiates a short series of measurements of actual aircraft height during the time the aircraft is in the marker beam. For example, the marker beacon receiver relay activates the aircraft's VHF transmitter for a short time and a tone-data signal representing the height as established by the barometric sensor unit is transmitted to the ground. The barometric sensor is quantized to perhaps 100, 200, 300,or maybe even 500 foot heights so that height reporting from sea level to, say, a maximum of 15,000 or 20,000 feet is contained in a simple code structure bringing the cost to a few dollars for the sensor and tone encoder. Several details of this code (100 quantized elements or 256 quantized elements?) have been discussed before.

At the time the aircraft passes over the marker station the signal is received on the ground from the aircraft on the VHF "unicom" frequency, and decoded with a BTL tone-decoding unit to represent the height sensed by the airborne baro-sensor. Obviously this baro-sensor and particularly a very, very low cost unit may be in error, needing adjustment just as a pilot adjusts his baro-sensor manually today. This is accomplished in a proposed "proof of concept" test by use of a direct radar height measurement using a ground unit. At this time an "X" band (modified marine) radar "looks" at the underside of the aircraft. With a 50 kw pulse only 0.1 microsecond wide (repeated 1,000 times a second) it is expected that more than adequate signal can be obtained by reflections from even the smallest aircraft. This strong signal return is expected since the radar beam will be a narrow zenith beam with no ground reflections or other disturbing radar targets.

The marine radar's usual rotating antenna is replaced by a microwave horn or "pillbox" antenna pointed at the zenith. The beam is shaped into a fan shape to match or improve on the 75 mc marker beam shape.

The radar cathode ray display with special retentivity characteristics is offset so that the 3/4 mile scale, or 4,500 feet, represents the full 12 inches across the display. A series of photocells (many choices of tiny ones) are placed in series on a line positioned over the PPI static line. Each photocell monitors discreet distances (now, of course, heights). The radar has two ranges of interest to the test: 3/4 mile and 1½ mile, and by available range switching the photocell signals can represent twice the height values for simple tests. One inch of the (12") display represents about 400 feet of height. It is possible to utilize small photocells so that at least four can be located per inch and would be placed directly over the cathode ray beam (line) established by the 12" radar display (remember the radar is not rotating but is being used as an "inverse radio altimeter" so the cathode ray sweep of the screen will be a stationary straight line offset so that "0" represents "0" height and 12 inches represents 4,500 feet, or 9,000 feet as determined by the range switch. Large photoelectric signals suitable for selected units will be obtained from the bright emissions.

Figure 1 represents the overall system and shows the photocells electrical outputs going to a set of relays (or solid state switches) that represent heights. Since there are no air or ground targets in the radar beam area, and the output of the radar can be ignored (or gated out) except when a VHF signal comes from an overhead aircraft indicating it is in the marker beam, and thus also in the radar height measurement beam, the relay outputs are only electrically activated at the time of the measurement. No signals need exist unless activated by the "presence" of an aircraft in the marker beam, eliminating many problems of channelization, interference, etc.

If 4 photocells per inch are used (could possibly be more, say 5 or 6 if need be), then there will be a height quantization into 48 units. At the 3/4 mile range (4,500 feet maximum range) this is every 100 feet approximately; and at 1½ mile range (9,000 feet maximum range) this is every 200 feet; and on the 3 mile range (18,000 feet maximum range) it is every 400 feet. These values can obviously be changed once the "proof-of-concept" is established. Thus, coming from the radar is the 48 electrical contacts representing the 48 quantized height elements.

Similarly, the VHF "Comm" receiver on the ground receives the BTL tone data signal and can also read out quantized height data from the aircraft. About a 40-milisecond burst can provide any one out of 100 possible height codes, using the triple-tone data equipment of BTL, or two (16 X 16 = 256) bursts of 40 miliseconds each can achieve this with the simple dual tone (4 X 4 = 16) equipments. Either will probably do for testing purposes.

Now, we have a similar number of wires available from the air-to-ground signal to be compared to the radar-sensed height. The comparison circuits merely examine the quantized data and determine if the heights agree (say each is quantized exactly the same, then say wire #21 represents 2,100 feet (at the 4,500 foot maximum height range)). If, however, a signal appears on wire #21 from the radar data and wire #24 of the BTL tone data output, then the comparitor recognized that a height reporting error of 3 quantized elements, or 300 feet, exists. This is accomplished by simple relay logic and is inexpensive to built (can be done in house at NASA as well as the other items).

The difference* signal, provided by the comparitor circuit, is now transmitted to the aircraft. By use of tone signaling to the aircraft, this can be such that a plus and minus value in 100-foot steps can be transmitted for the error data. For example, if 16 codes were used in the (low-cost) commercially available

* Quantity and polarity; for example, the error above is +300 feet and the corrective difference signal would be -300 feet, causing the 2,400-foot report to now read (2400-300) or the correct 2,100 feet.

BTL tond (4 X 4 tones) system, we could have a +800 and -800 foot range of error corrections in 100-foot increments. The pilot can be provided a readout directly in height error and then can reset his baro-sensor so that it is corrected. Similarly this error can automatically correct the output of the baro-sensor in one of many ways.

Since all of this occurs in a second or two, the airborne readout would be in a stored circuit so that error data is stored.* Error could be transmitted by tone message, such as the morse code, still used in many aviation facilities, so that 26 to 30 steps would be available (actually in 75 mhz signal cover for about 30 seconds). Error data could be used to automatically correct the altimeter by a closed loop circuit (merely shifting the encoder contacts or the code itself).

Some Needed Lab Data

It would be good to measure some data on photocells as to their sensitivity to cathode ray tube phosphorus (good retentivity) typically used for radar displays. Also, it may be necessary to use some circuit gain after the photocell pickup of the phosphor signal so as to provide power to actuate relays or logic circuits. It is also possible that the photo sensitive device's output itself will be an adequate switching signal. The reason for this assumption is that the radar is really working at fairly close range, by its usual standards, against a rather large target (aircraft underside cross-sections are much larger than "head-on"

*This permits the pilot to correct at his convenience and to note the amount of error for replacement of the baro unit ($10.00) if it is beyond the specified limits. The stored data would be de-activated, say in 2-3 minutes, permitting the system to be automatically initiated again by flying over another height sensor.

profiles of aircraft), and there is no other target to cause noise or other electro-luminescence of the phosphor of the radar cathode ray tube. Furthermore, some 500 to 1,000 radar "hits" exist during the brief time the aircraft is in the radar beam. The tube phosphor "integrates" and "stores" this repetitive signal, enhancing signal to noise enormously.* Thus the signal-to-noise ratio should be very good and the target is only sensed when it is known that the target is in the beam (via the marker beam signal causing the aircraft to emit its tone height data).

If the photocell system does not work for some reason, then a direct use of delay-lines and typical range-decoders would be used. The latter is a more direct type of engineering but can be more complicated with the number of range or height outputs desired, and it is desirable (if at all possible) not to cut into the radar circuitry or to modify it. Further, there is a visible display of the height of the target (with the cathode ray photocell readout) to the ground observers, and this would be the makings of good visual data source. Each photocell would be mounted in its own light-shield box so it is exposed only to the light source of the radar strobe-line directly beneath it. Adjacent areas would be similarly shielded as they would be separated by ¼ inch. The smallness of the photocells is important but many exist that can do this job. Perhaps some photo-sensitive, solid-state devices will give direct, current switching, replacing mechanical relay functions.

* special "Storage tubes" exist with special "memory" designed into the phosphors, and electrical means to read out; tests of these tubes is suggested after this early"proof of concept" stage where a multiple photo-cell unit is used for economy and expedition..

The basic elements for this significant experiment are the VIZ baro-sensor with modified baro-switch plates, BTL tone-data equipment, marine radar (Sperry unit costs about $14,000 to $15,000 when one considers the offset features, spares, shipping and maybe some small modification). The "in house" work would be the Zenith pointing X-band antenna, photocells, and the comparitor of the radar height outputs with the BTL outputs. The equipments suggested should permit a low-cost flight test and evaluation of the "proof-of-concept" type. Since the items are all commercial items, and utilized well within their performance limits, there should be little stretching of any engineering. Admittedly, the ten-dollar VIZ sensor may be low-cost, but it can be corrected to within 50 feet if data for this correction is available in the cockpit during flight, creating results equivalent to a $1,000 baro-sensor. Further, the radar would report automatically the presence of the aircraft, its identity, and establish if excessive (hazardous*) height errors actually exist.

This latter function is now a national necessity even with current SSR baro-sensor units utilizing the 4,096 codes of SSR. The identical ideas and equipments herein described would work with the SSR and should be tested as such, since the "floating" height references between aircraft <u>without any inflight monitoring</u> or ability to correct height errors can be fatal in dense air traffic. Further, the ability to conduct "inflight-calibration" makes a very, very low cost sensor practical, since it can be

*All the elements for an automatic reporting (of large errors) to a central point (via land wire) exist, so that a fully monitored system is possible; thus permitting full use of vertical separation criteria for <u>ALL</u> users of the airspace.

corrected at the exact time of its use, in the exact environment of its use, and at the exact height at the time of the reporting (not with a bell-jar test every 9 months in a remote, sea level, ground laboratory environment).

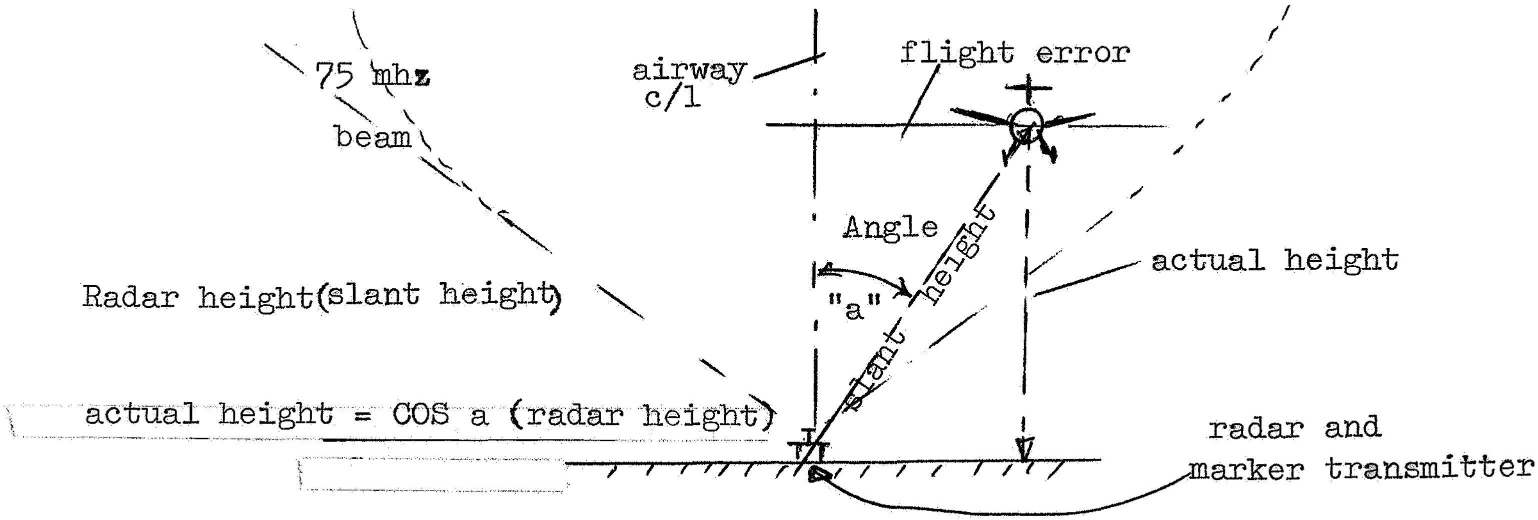
Radiation Patterns

Although the foregoing material explains the principle of the auto-calibration of baro-sensed height information, several questions arise as to how wide the beams are (both 75 Mc and radar beams), whether the aircraft is in the beam long enough for data exchange, the likelihood of two aircraft in the beam, the serious fact that the aircraft may not pass through the actual zenith line from the beam emitter because of flight errors (off the VOR track slightly, etc.).

The best way to approach this matter is to first examine the coverage diagrams of the 75 Mc markers. Most 75 Mc beams are basically the same, but have some variations in the minor and major axis dimensions depending upon their application. The attached diagram from the FAA Flight Inspection Manual illustrates these dimensions and some tone identity and done code signals combinations now in use. Typically, if an aircraft is 5,000 feet in altitude, it will pass through the minor axis (normal to the airway direction) in ±2 NM of flight, or 4 miles duration (see 219 B). At 120 knots, this is a time duration of almost 2 minutes depending upon the sensitivity of the receiver. Since this varies (probably on the low side) the time of reception of the 75 Mc signal will probably be between 1½ and 2 minutes at this height. If the speed is 240 knots, this is cut in half (45 to 60 seconds), and at 480 knots, this is about 23 to 30 seconds of time.

In any case, the marker signal is present long enough to attract the pilot's attention and so that he can hear the tone signals and tone codes several times. Also, this is more than adequate time for the exchange of height data as described previously. With increased height the time is greater. However, typically, the lower altitudes have lower speeds so that some compensation takes place. For example, at 1,000 feet the signal is 2 miles in width, or 1 minute at 120 knots, and 30 seconds at 240 knots (the latter being typical, low altitude, terminal area speed of jets). Thus, it is concluded that at least 30 seconds, or at worst perhaps 20 seconds, of signal is available on the normal airway marker. This is more than adequate to alert the height measuring equipments and to assure the radar will measure the most accurate height and minimize "slant-height" measurement errors.

If the aircraft is not over the zenith of the marker beam emitter (passing through the vertical beam axis), then some means of assuring that a height error is not incurred by the radar measuring that range.



This general error is less than 2% if the aircraft passes within 11° or less of zenith. At 5,000 feet this is a track error of about 1,000 feet. In most cases the flights will be within the track error, if the pilot has maintained the standard (two sigma) ±4.5 degree total VOR system error just prior to passing over the station and if near a VOR at the time of height measurement. However, at greater distances this (±4½°) can be more than 1,000 feet, and in fact can be 3,000 to 4,000 feet, so that some consideration must be given in the tests to ways and means of correcting for slant-height range measurements.

Crossed-Beam Concept

Since the radar microwave beam is readily controlled and shaped at X or C band, and directed in any manner we desire, we can cause it to provide data not possible with the wide, poorly controlled patterns of a 75 Mc marker beacon emission. The wide width of the 75 Mc marker is advantageous to this concept as it assures the tone (data) transmission of height from the aircraft always occurs. But, we must assure ourselves that the radar reads the actual, correct height of the aircraft, not merely the slant-height of the aircraft. By crossing two flat planar beams, each generated by a simple "pill-box" or microwave horn (see pages 459-464 of Vol. 12 of the Radiation Lab series), we can simply achieve interesting, and most useful results.

The geometric principles of the crossed beams are shown in Figure II. Two planar beams are crossed at 90° (maybe 60° is better). Each beam is quite narrow in one direction and quite wide in the other, creating a vertical "fan" shaped beam. Typically, a beam 3° X 90° as measured at 3 db points would be a good first experiment. At 5,000 feet, 3° is 250 to 500 feet in radar (beamwidth) coverage, providing about 1,000 "hits" (pulses) as the aircraft traverses (flies through) this fixed beam. It will be noted that if the aircraft is to either side of the airway, two distinct beam returns exist since the antennas are merely in parallel, both fed from the single radar. The width (duration) of each beam return (count the pulses) is determined primarily by speed. The separation between the two returns (dimension Y) is related to the amount of off-course piloting error.

This off-course error is of a track parallel to the airway direction at this point, and the crossed beams are oriented according to Figure II. Thus, if the aircraft is a goodly distance off the airway at the time of height measurements, then dimension (time units) "Y" will be large. A simple clock running at the radar PRF (1,000 pulses/second) counts the times X, Y and Z in units of "hits" and time between "hits". This output is a simple digital signal readily processed to obtain the correction factor.

This is used to correct the actual slant range height measurement*. Since in most cases we will be dealing with a cosine function (of angle "a"), the corrections will be small percentages of the slant range height (10° is 1½%; 20° is 6%, 30° is 14%). Thus, the dimension Y, if measured to an accuracy of 5%, creates a final geometric error of height of only 1/20 X 6% or 0.3%, well within our design objectives. 0.3% typically at 5,000 feet is but a 15-foot error due to the slant range measurement, well within the nationally standardized 100-foot quantized system (SSR of 4,096 codes each representing 100 feet of quantized height.

Without a crude means of slant-height corrections, some serious off-course errors would create false height errors. Further geometric analysis of the crossed-beam concept will show that near the center of the cross the errors due to slant-range or off-track flight errors decrease markedly because of the "cosine-function" influence. It is likely that a vast majority of the air traffic will be on course or close enough that slant range errors would be minimal. Initial tests of this concept can assume this, knowing a simple slant correction will be tested as a second phase. However, even in the adverse case of airway traffic off-course sufficient so as when viewed vertically from the measuring site it is 30 degrees from the zenith; the dimension "Y" is readily measurable to 1 part in 20, and thus correct the 14% error to 1/20 of that error, so that the geometric error is down to about 0.7%. Even in this highly exaggerated case, height monitoring data used for vertical separation,

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*It can be shown the airway or a track parallel to it is a vertical plane intersecting the two crossed microwave planes and that a constant ratio of beamwidth and beam separation (x/y or z/y Fig. 2) represents angle "a" as viewed from the ground.

etc., is still within the quantized values of our national standard. the higher the aircraft, the less the slant correction for a given airway track error; another compensation aiding the concept above 10,000 feet.

Technically, the crossed-beam concept is easily installed by merely using two horns or pill box antennas fed with a microwave "T" from the radar. Crossed-beam tests occur after some single-antenna flight tests to determine widths, etc. The flight tests would record with tape, scope cameras, etc., the shapes of beams A and B, their widths, number of pulse "hits", and the dimension Y. Simple electronic geometric correction can be applied to correct the radar range (height data) so that effectively the data is a vertical line equivalent to a zenith altitude measurement directly beneath the aircraft, even if the aircraft is not over the facility. Flight tests of this data will establish the best beamwidths, angles, and likely errors, however, all these values seem well within desired engineering tolerances.

By simply determining A and B dimension (Figure II) in terms of count of radar pulses (X and Z) as well as Y, then a <u>ratio</u> exists between the average of A and B and the dimension Y. If a fast aircraft traverses the beams A and B, the number of radar pulses received may be smaller than a slow aircraft. If, say, a 120-knot aircraft returns 2,000 pulses, a 240-knot aircraft will return 1,000 pulses since his occupancy of the beam is half the time (under the same conditions). Also, Y, in terms of beamwidths A or B, is half, but the ratio of A/Y or B/Y is constant for both speeds. Knowing this, and the slant range, the dimension Y is determined in terms of the beam occupancy time and a <u>ratio</u> of the time Y and the average occupancy time (of beam A and B) determines the extent the aircraft is off course and establishes the angle "a" from zenith as viewed from the ground site*.

Flat planes must be used for this geometry, but it is well known that a microwave beam can be kept flat to 1 part in 100 (or a thousand), with the simplest of design. The height solution must utilize this crossing flat planar beam geometry to succeed; yet it is the easiest geometry to obtain with the simplest of static microwave antennas.

The above speed variation can occur similarly with height variation since the beam is an angular beam and the crossing planes are angular. Again, this is compensated by the ratio of beamwidth vs sector Y width (angles O and M in Fig. IV), the ratio establishing the value of the cosine of the off-zenith angle. The same concept as speed occurs if the aircraft samples are at the same speed but at height differing by two to one (see Fig. III). The elapsed time of the higher aircraft (while in the beam) will be twice that of the lower aircraft. Remember we have exact slant range to utilize in our computation with the ratios of A/Y and B/Y. With these dimensions readily available from the radar video output, it is easy to compute the slant range correction factor. This concept is equivalent to the famous "V-beam" height measuring radar concepts of World War II, wherein the two beams (in a "V" configuration) rotated. Here, we use a low-cost, static beam concept and the aircraft flight through

*Figures III and IV are illustrations of the 3 dimensional geometry involved. Fig. III shows that variation in height does not change the ratio, making angle "a" constant. Fig. IV illustrates that the extent of track error varies Y and angles M and O proportionally with viewing angle "a", establishing the cosine correction of the radar slant range.

the narrow, flat beams creates the equivalence of the scanning function of the V-beam.

In Figure IV it is shown that the angles O and M are equivalent or proportional to the angle "a" made by an off course flight as viewed from the marker and radar (co-located) site. Thus, the electrical measurement of angle "a" is the simplest of matters. A pulse counter counts the number of received pulses in the radar video output as the aircraft traverses the first beam (of the crossed beams), that it intercepts. The crossed beams may be at 60° or 90° meaning that the axis of the cross is symmetrical with the direction of the airway. Thus, the aircraft flies through the plane of the radar beam at an incident angle of 30° or 45° causing some effective widening of the beam, but no changes in the computation of the above mentioned ratios. Thus, the pulse counter continues to count during the time Y and then counts again the second beam intercept. Since this counting is at the PRF of the radar which is available directly to the counter input, the counter is started with the first reception of the beam signal and continues to count until the passage of the second beam signal and no more pulses are available. One beam starts this counter; the other terminates its count. (We could use beam switching and slightly different PRF for each beam.) A second counter counts the number of pulses in each beam and divides by two to give an average count (improving accuracy since both beams are identical but a pulse or two might be lost). The outputs of the two counters then represent the beamwidth and angle between the beams. The <u>ratio of the counts of the two counters</u> is taken (and used to compute cos a) and they are then reset for the next flight to pass overhead.

G. B. Litchford
August 1969

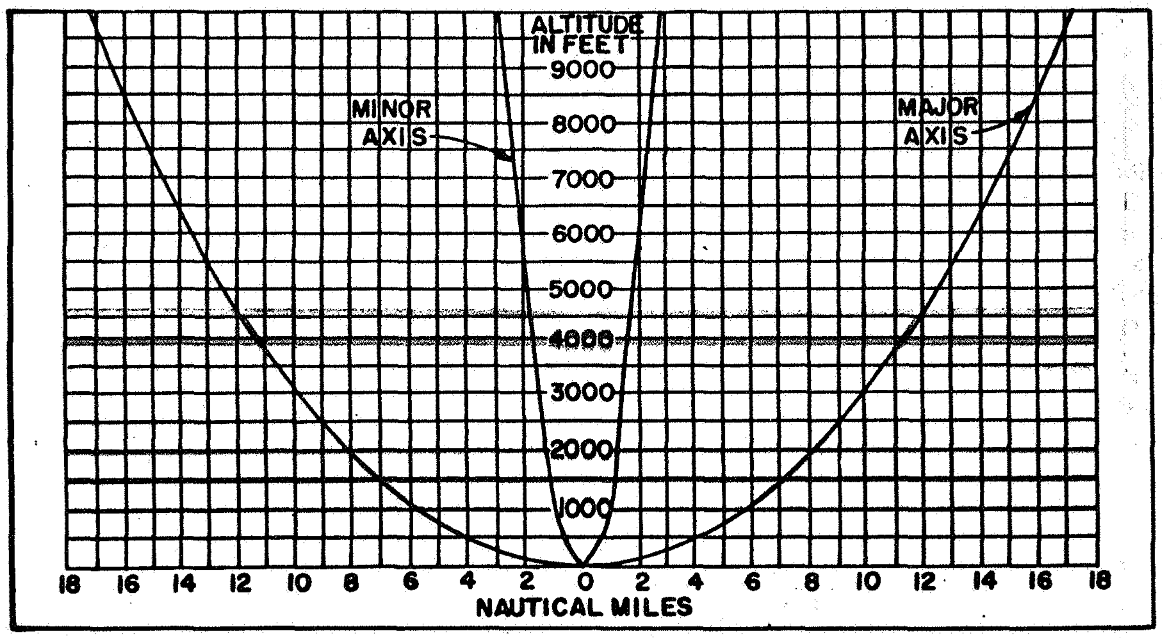


FIGURE 219–B Vertical patterns obtained from a Class FM fan marker having an impoved type antenna array, receiver sensitivity "High".

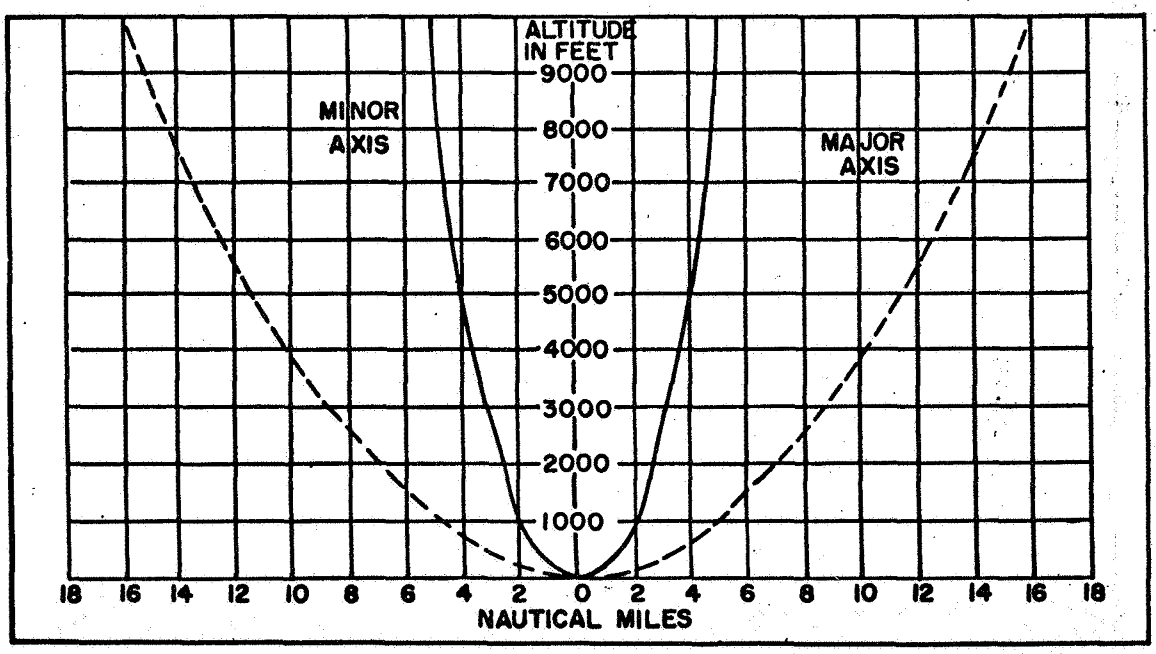


FIGURE 219–C Vertical field patterns obtained from a Class FM fan marker having a standard type antenna array, receiver sensitivity "High".

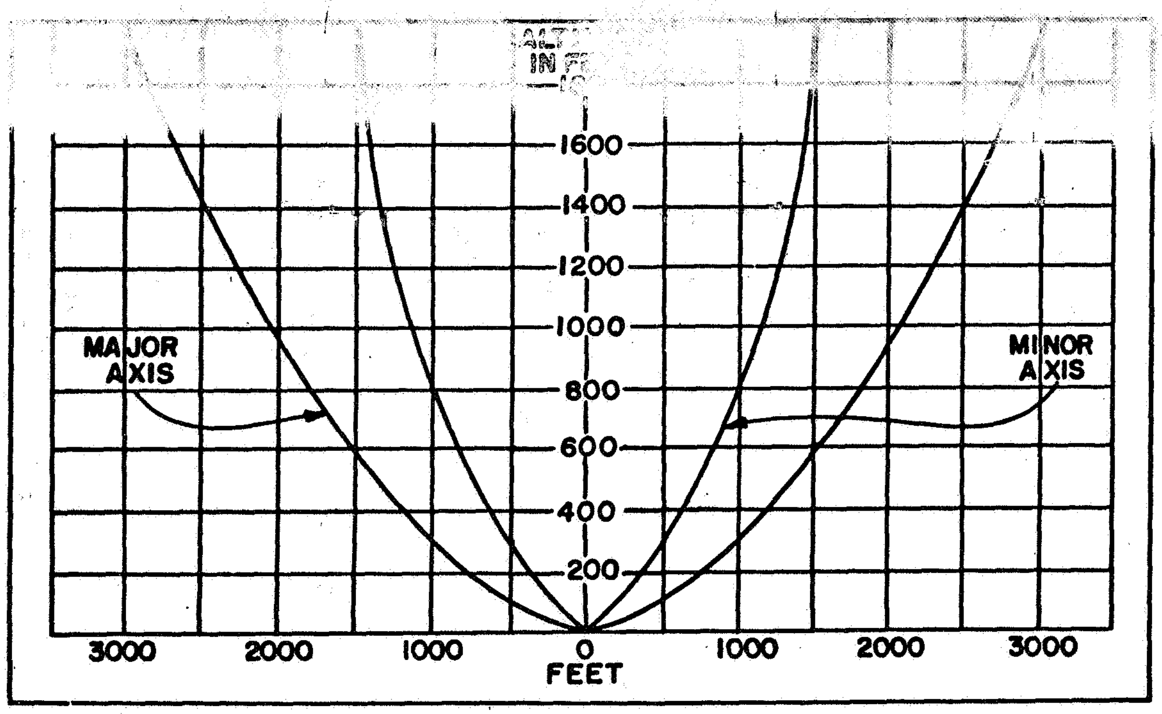


Figure 219–F Vertical field patterns obtained from an ILS marker beacon. Receiver sensitivity "Low".

cps and identified with continuous dots at the rate of 6 dots per second.

d. *Back Course Marker (BCM).* A 75 MC marker might be installed along the localizer back course to serve as a final approach fix. It will be modulated at 3,000 cps and identified with two dots at the rate of approximately 95 two-dots combinations per minute. Where earlier type equipment is installed, the keying rate may be approximately 72 two-dot combinations per minute.

Summary of Marker Beacon Data by Functional Use.

Type Marker	*Functional Use*	*Modulation Tone (cps)*	*Receiver Sensitivity for Check*	*Ident.*
Z	LFR–Station Location	3000	LOW	None—Continuous tone
ILS	OM	400	LOW	Continuous dashes
ILS	MM	1300	LOW	Alternate dots and dashes
ILS	IM	3000	LOW	Continuous dots
ILS	Localizer back course	3000	LOW	2 dots
FM/LFM	En route or approach (LFR)	3000	HIGH	To indicate LFR leg—see figure 219–A
FM/LFM	Approach (other than LFR)	3000	HIGH	Code letter R (• — •) See par. 219.11

AIR BORNE ELEMENTS

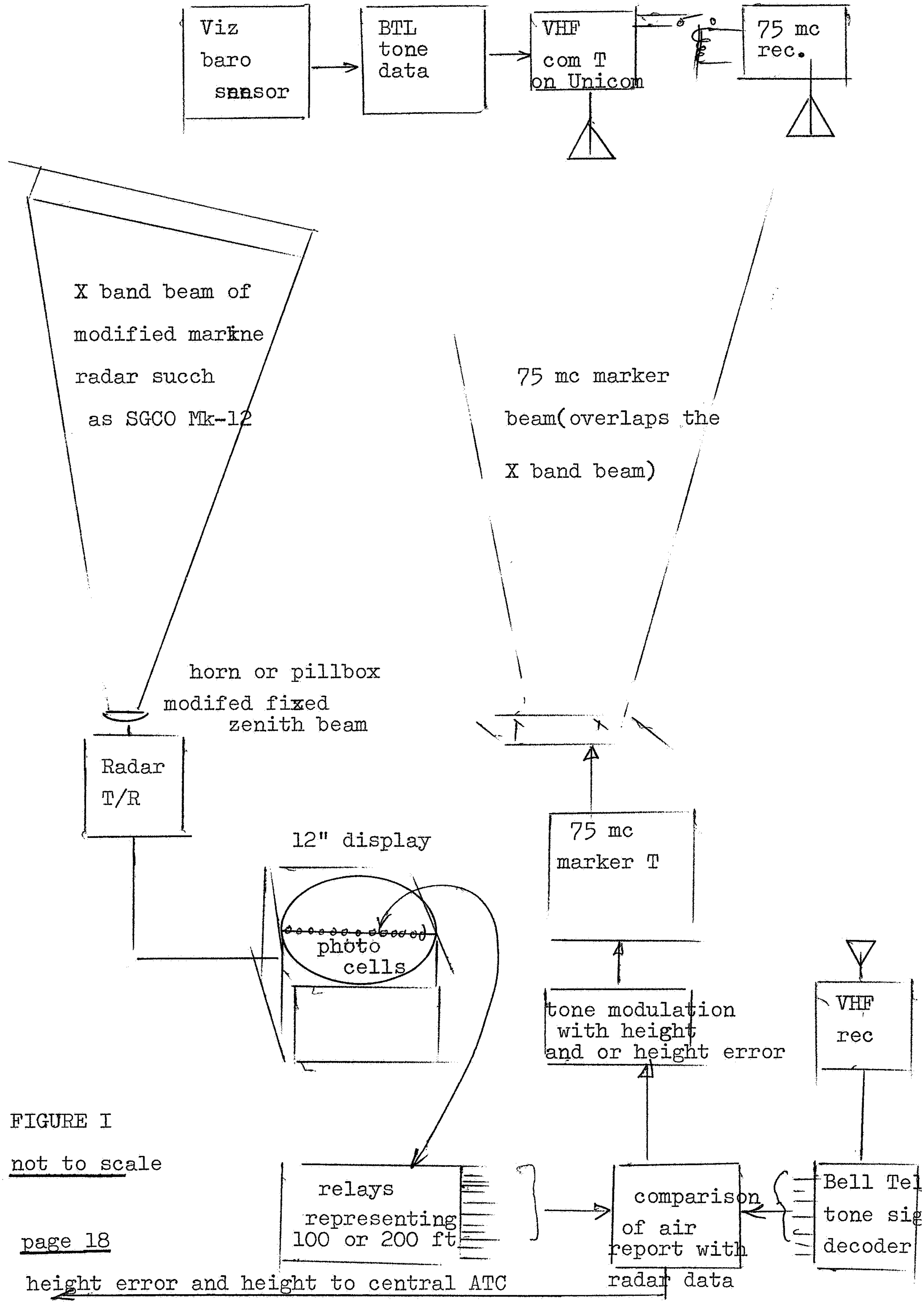
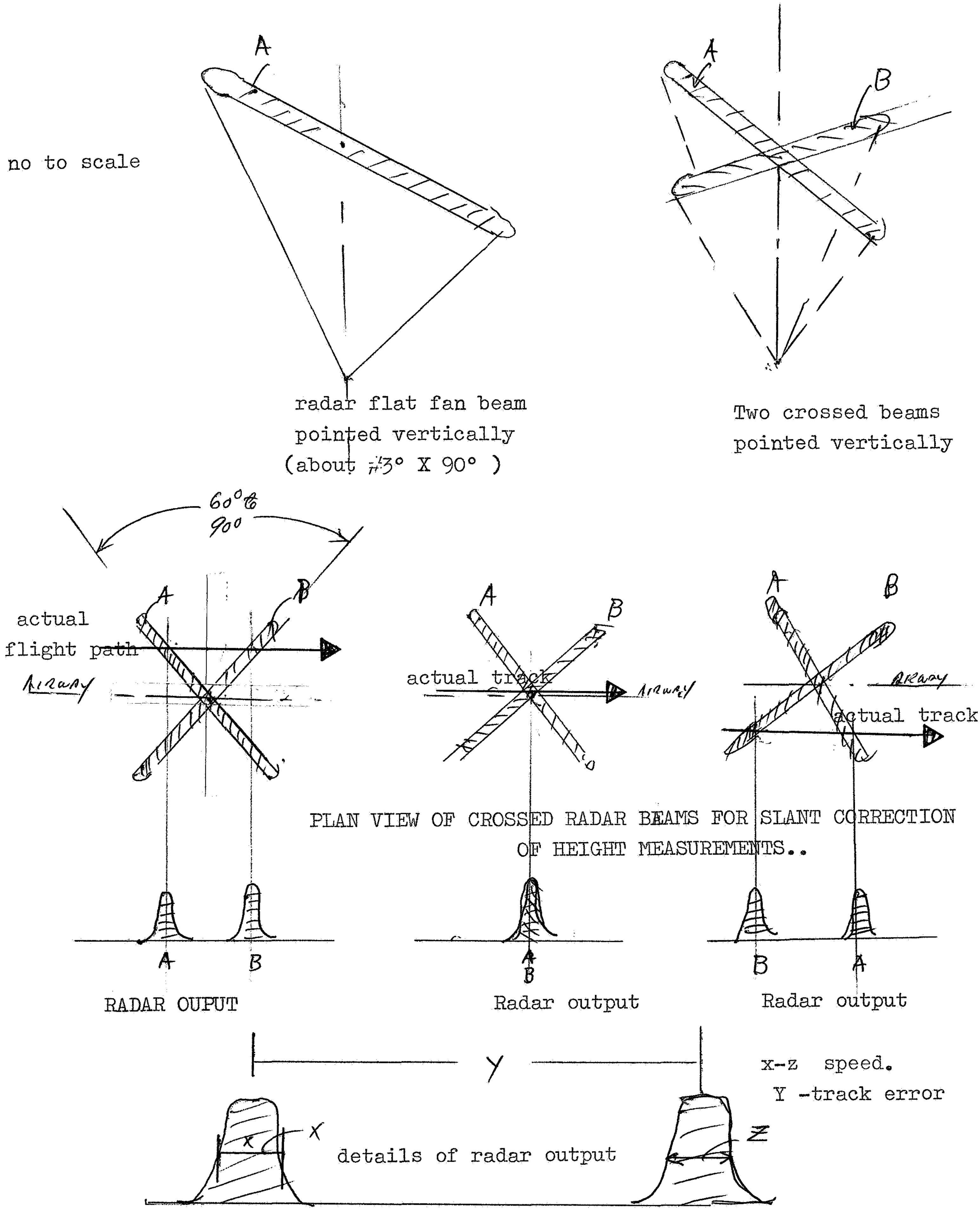


FIGURE I

not to scale



----- FIG II-------

CONCEPT OF CROSSED BEAMS FOR CORRECTION OF HEIGHT ERROR..

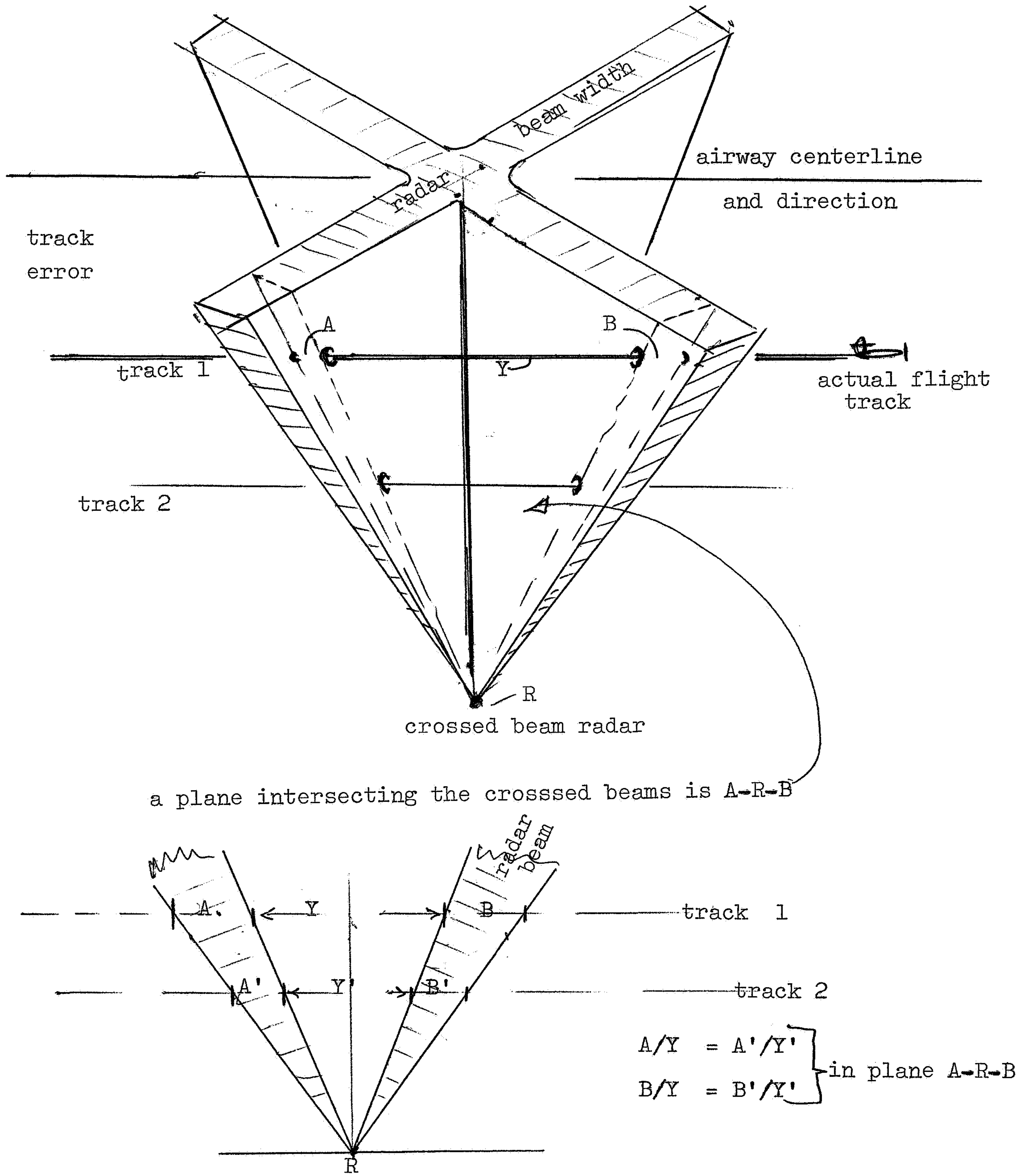
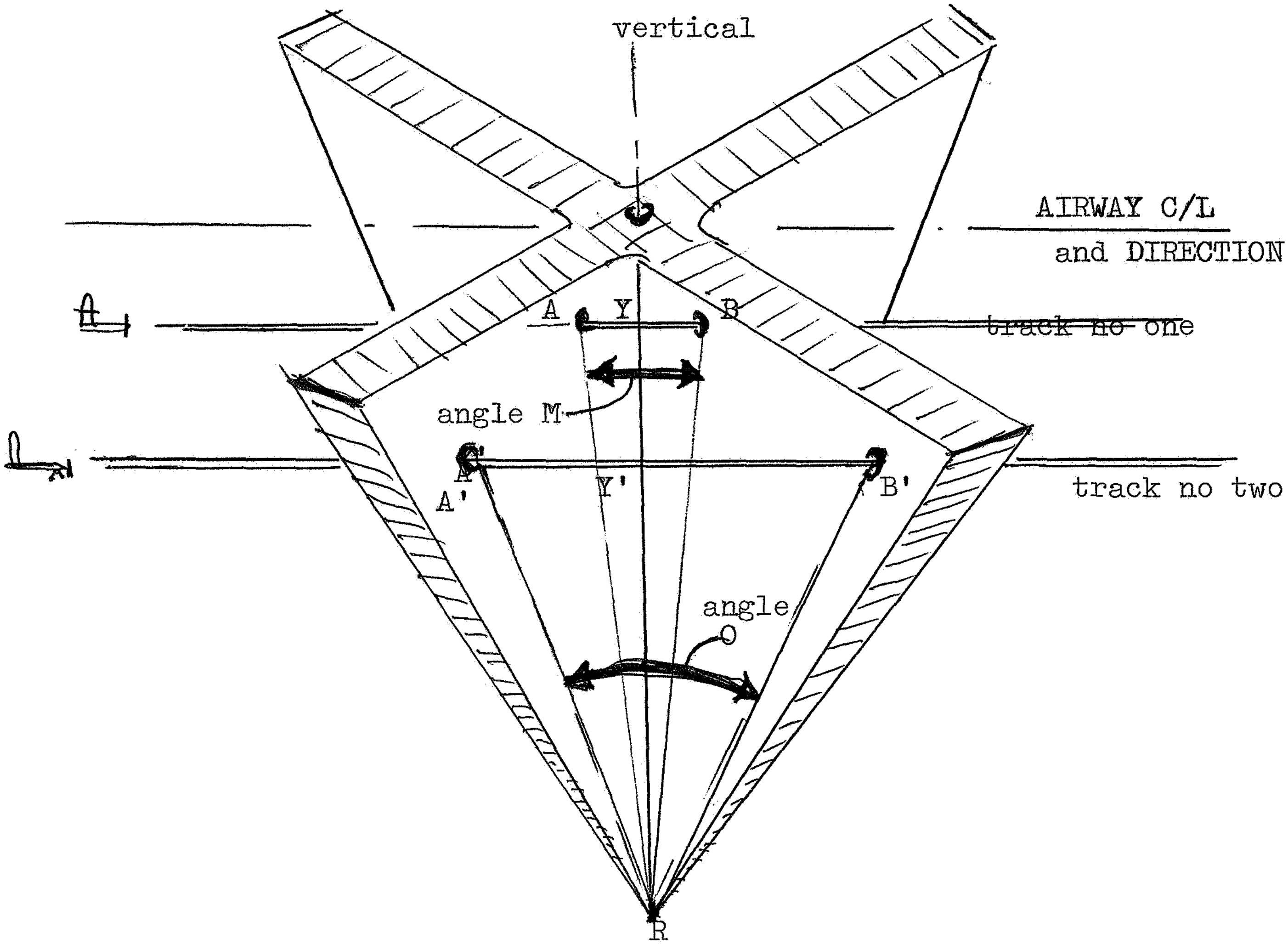


FIG III

MEASUREMNT OF COSINE "a" IS BY RATIO
OF BEAM WIDTH AND ANGLE BETWEEN CROSSED BEAMS



crossed-beam radar

note that track no. one passes through the crossed beams with less track error than track number two.

the plane RAB is defined by track no. 1
the plane R'A'B' is defined by track no 2

Angle M is the intersection of the plane RAB with Crossed beams

Angle O is the intersection of the plane R'A'B' with crossed beams

Angles O and M are proportional to the viewing angle "a".

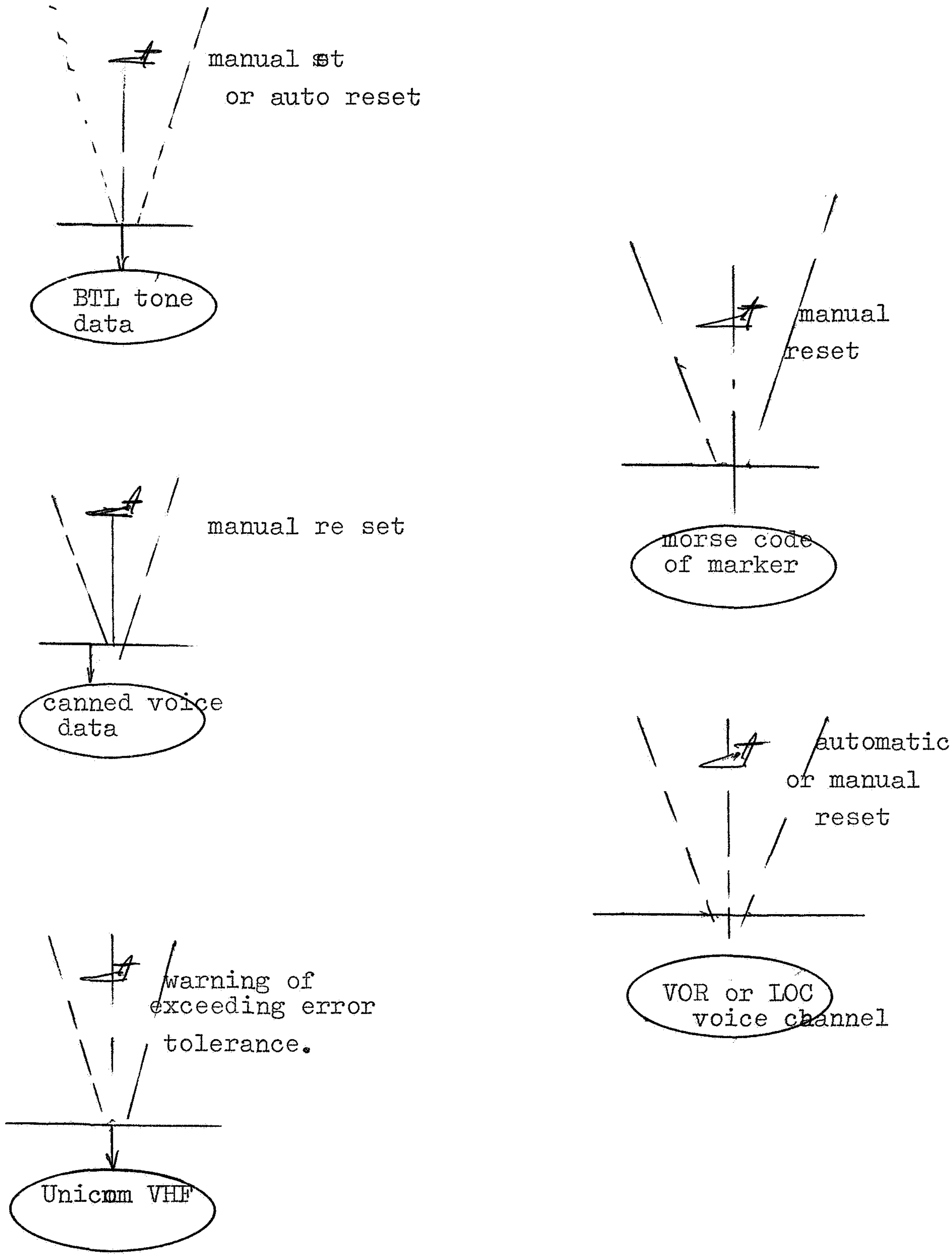
therefore: angle "a" is proportional to ratio Y/A of fig III

Therefore:

actual aircraft height = radar slant height X COS "a"

or $H_a = H_r \times \mathrm{Cos}\,\frac{Y}{A}$

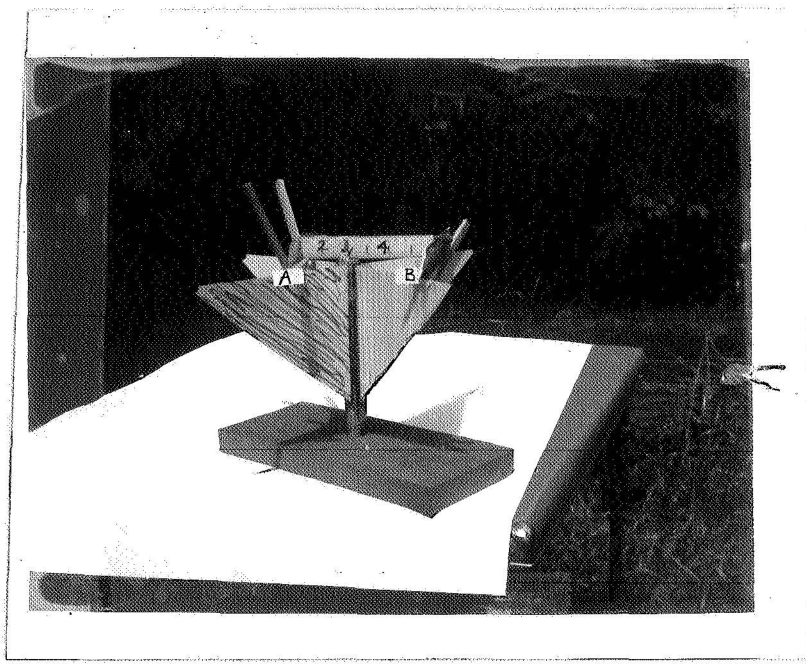
Figure IV



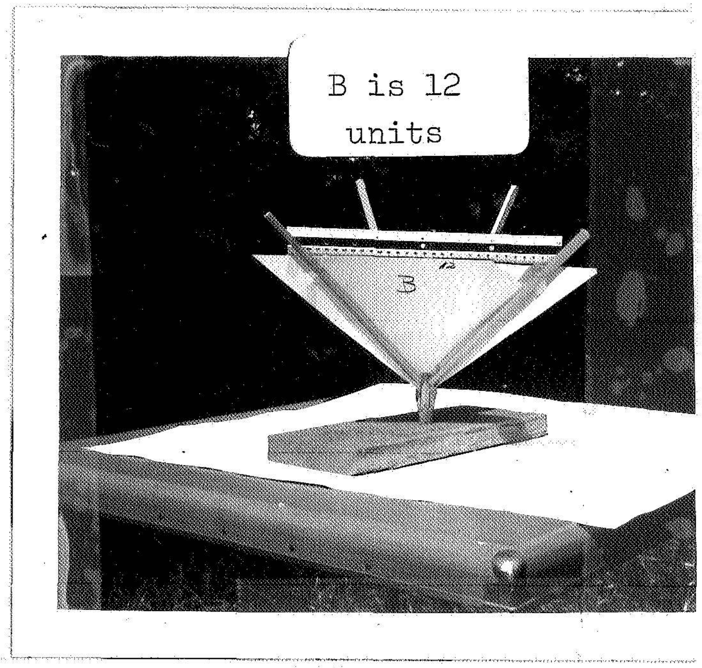
SOME OF THE MANY METHODS OF RELAYING THE

ALTITUDE HEIGHT ERROR BACK TO THE AIRCRAFT

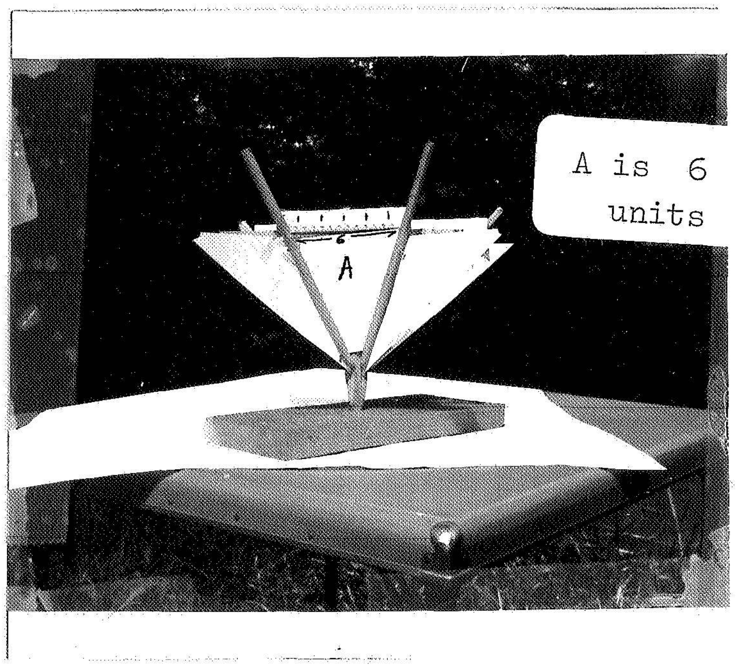
FIG V



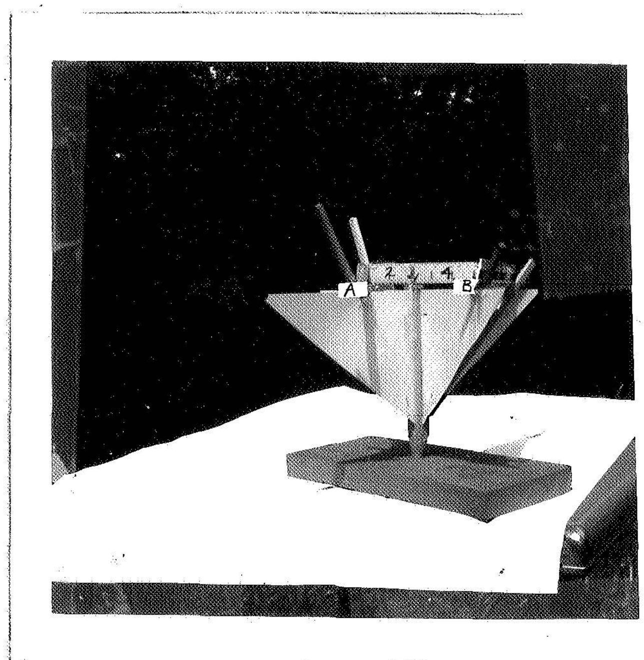
I
Two aircraft A and B pass through the crossed vertical beams.
Note: A is 2 units off course
B is 4 units off course



III
Viewing the track of B from 90° (side view) its intercept of the crossed beams creates angle B.

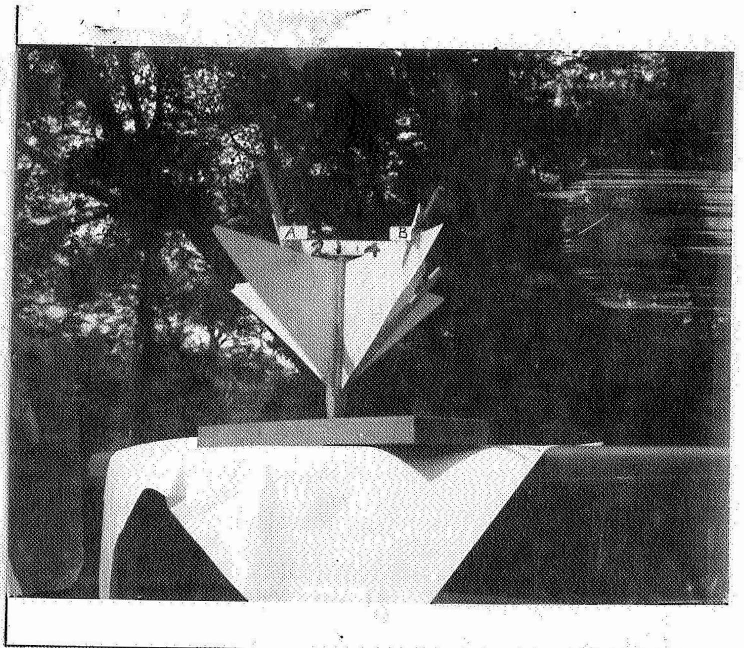


II
Viewing the track of A from 90° (side view) its intercept of the two crossed beams creates angle A.

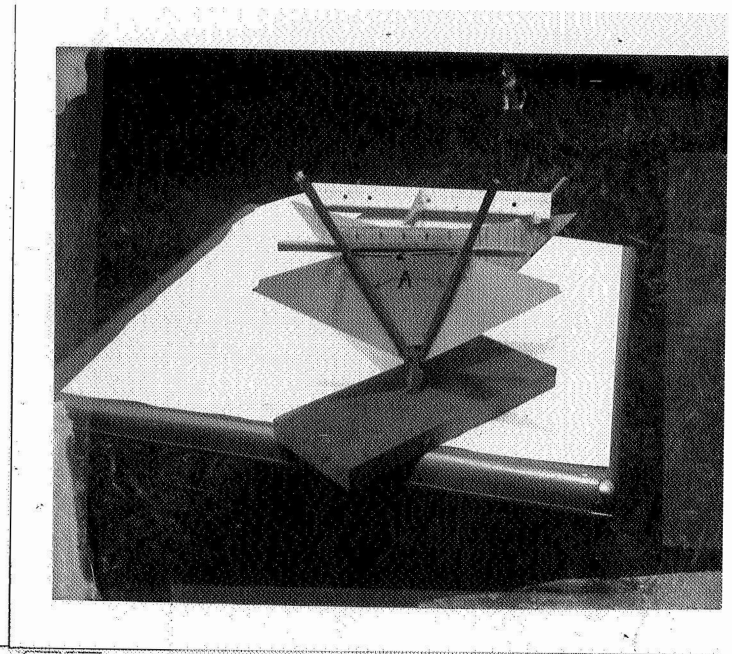


IV
Alternate view for Fig. 1 above.

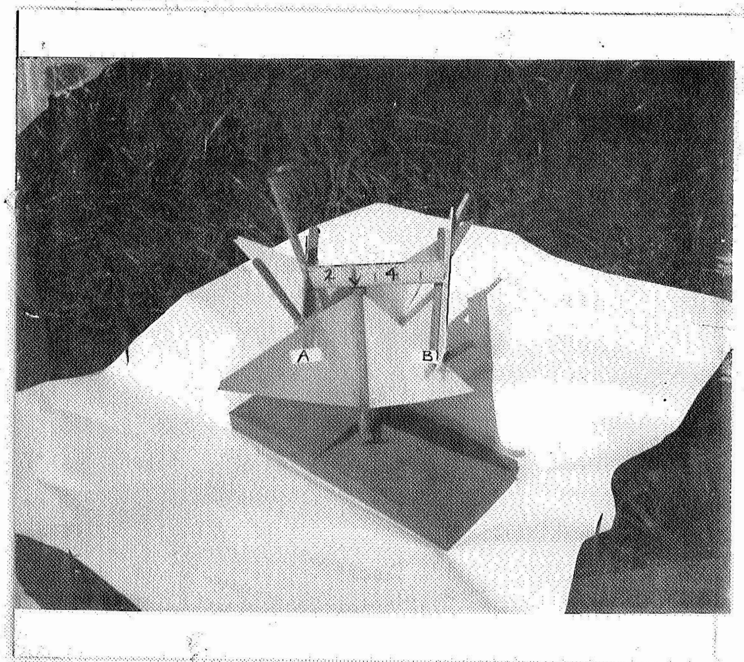
PHOTOS OF MODEL OF ALTITUDE MEASUREMENT
CROSSED BEAM CONFIGURATION



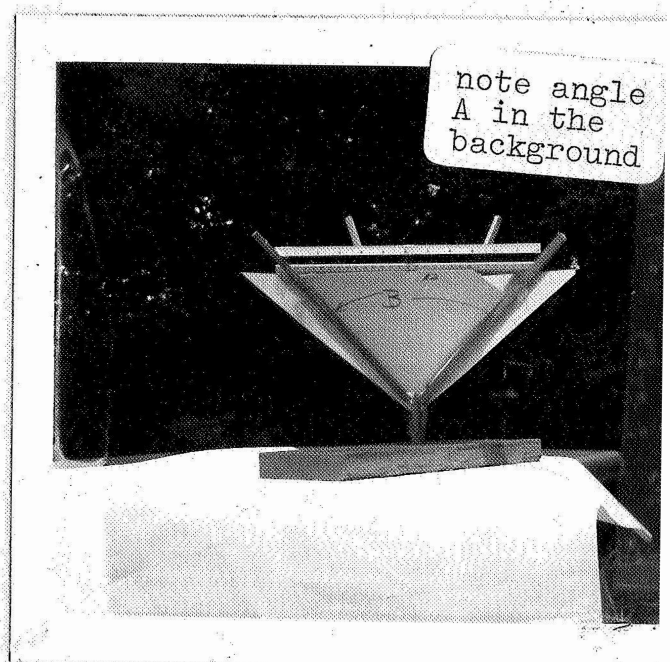
View of model showing two tracks A & B passing through the crossed vertical beam radar. Note: A is 2 units off course and B is 4 units off course.



Track A viewed from the side showing angle A is 6 units wide or proportional to error A.



Alternate view of the model showing the A track error of 2, B track error of 4.



Track B viewed from the side showing angle B as 12 units wide-proportional to track error of 4 of track B as shown above.

Note that the model shows that a track error of 2 units creates an angle (A) of 6 units, and that a track error of 4 units creates an angle (B) of 12 units. This illustrates the geometric relationships of the two crossed beams of the height measurement radar described further in the text. Basically, any track error is proportional to the angle created between the radar antenna and the two beam intercepts. If the track error is zero, the angle is zero; if the track error is 2, the angle is 6; if the track error is four, the angle is 12; etc.