EXPLORING IN AEROSPACE ROCKETRY

13. TRACKING

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13. TRACKING

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The purpose of tracking is to establish the position-time history of a vehicle for observation, guidance, or navigation. The techniques employed are essentially the same for these various purposes. The required positional information consists of angular deviations from the line of sight between the tracker and the target and possibly angular rate deviations. From these data the position, range (distance from the tracker), altitude, velocity, and acceleration of the vehicle can be calculated. Extrapolation of the data can be used to predict the path of the vehicle and to provide guidance and control information to alter its flight. In the case of unknown satellites, successive observations can be used to determine the actual size, shape, and surface area of an orbiting vehicle. By using known orbital data it is possible to follow the satellite's path in reverse order and determine its actual launching point on the Earth.

Many tracking systems employ the technique of locating two or more trackers on well-established baselines and applying the principles of intersection and triangulation to obtain positional data. This method of tracking is most applicable to model rocketry and is explained in the excerpt from reference 1 given in the section TECHNIQUE OF TRACKING MODEL ROCKETS.

The two principal types of tracking systems employed by NASA at its launch sites at Cape Kennedy and Vandenberg Air Force Base are radar and radio systems and optical systems.

RADAR AND RADIO TRACKING SYSTEMS

These systems employ radio frequencies from 100 kilocycles to 30 000 megacycles. Below this frequency range, antennas with adequate directivity become unpractically large, and ionospheric propagation difficulties become severe. Above this frequency range there are practical limitations on the power that can be generated. There are also regions near the upper end of this frequency range that must be avoided because of water vapor absorption and attenuation due to scattering by rain. In tracking against a background of cosmic noise certain frequencies must also be avoided.

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Radar systems are classified into active and passive systems. An active system requires transmitting equipment in the vehicle, and this equipment is generally referred to as a beacon or transponder. Passive systems depend on the reflective properties of the vehicle to return the incident radio waves. These reflective properties may be enhanced by the use of special reflectors, or they may be degraded by special surface treatment. Active systems are generally superior to passive systems with respect to range capability and tracking accuracy, but their requirement of special equipment on board the vehicle is a disadvantage.

Depending on the method of measuring range, radar tracking systems are also categorized as continuous-wave systems or pulsed systems. Angle measurements are sometimes accomplished by a scanning technique in which the antenna position is moved either by mechanical or electronic means about the direction of maximum signal return. This method is employed by the more conventional types of radar and by some of the radio telescopes used in radio astronomy. Another method of measuring angles uses the principle of the interferometer to compare the phases of signals received in separate antennas on well established base lines. The frequency of the return signal from a vehicle being tracked depends not only on the transmitted frequency but also on the relative motion of the vehicle and the tracker. This change in frequency due to the relative motion of the vehicle and the tracker is known as the Doppler effect and necessitates designing the tracker to follow automatically the changing frequency. This frequency change, or Doppler effect, can be used to measure the relative velocities of the vehicle and the tracker. (Ref. 2 presents an excellent exercise on the use of the Doppler effect in satellite tracking.)

OPTICAL TRACKING SYSTEMS

Optical systems make use of the visible light portion of the electromagnetic spectrum. (Usually, ultraviolet and infrared systems are also included in this category.) All optical trackers consist essentially of a telescope mounted on gimbals to permit rotation about two axes. One type of tracker, the cinetheodolite, produces a photographic record of the position of the target image with respect to cross hairs on a telescope; it also provides azimuths, elevation angles, and timing indications on the film. With two or more such instruments on an accurately surveyed base line, the position of a target in space is obtained by triangulation. Tracking is usually manual or partially manual. Another type of optical tracking instrument is the ballistic camera, which determines angular position by photographing the vehicle against a star background. This instrument

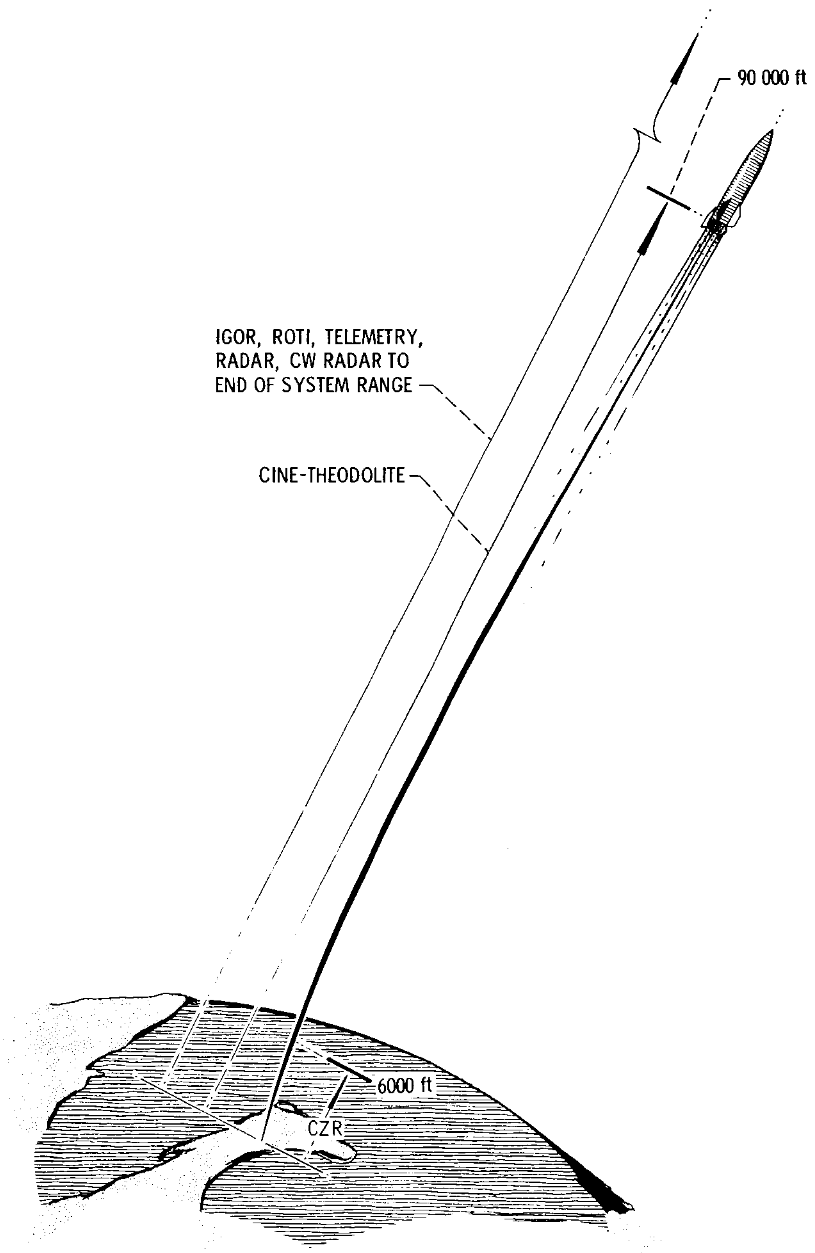


Figure 13-1. - Typical tracking coverage of missile launch. (CW, continuous wave; CZR, control zone radar; IGOR, intercept ground optical recorder; ROTI, recording optical tracking instrument.)

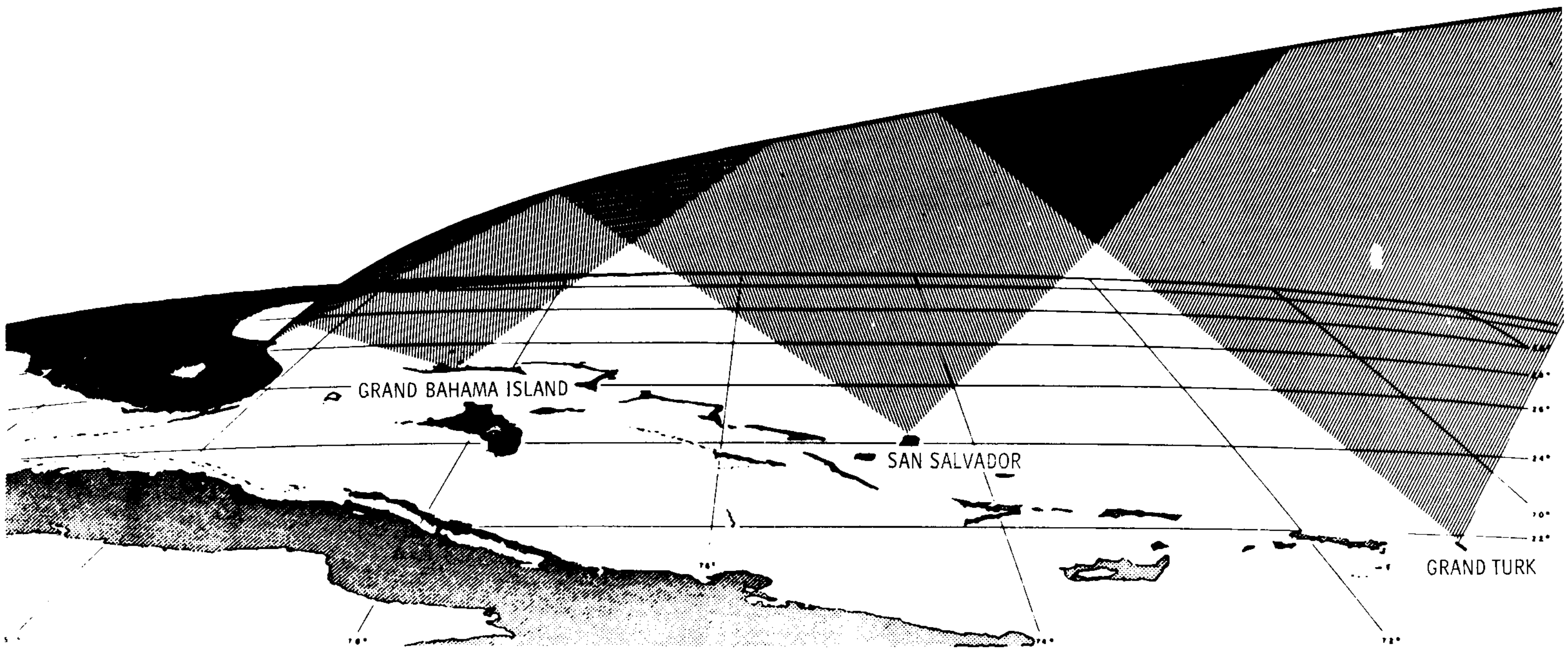


Figure 13-2. - Typical pulse-radar tracking coverage during midcourse phase of flight. (Midcourse phase extends from end of launch phase to some arbitrary point in space or time when terminal phase begins.)

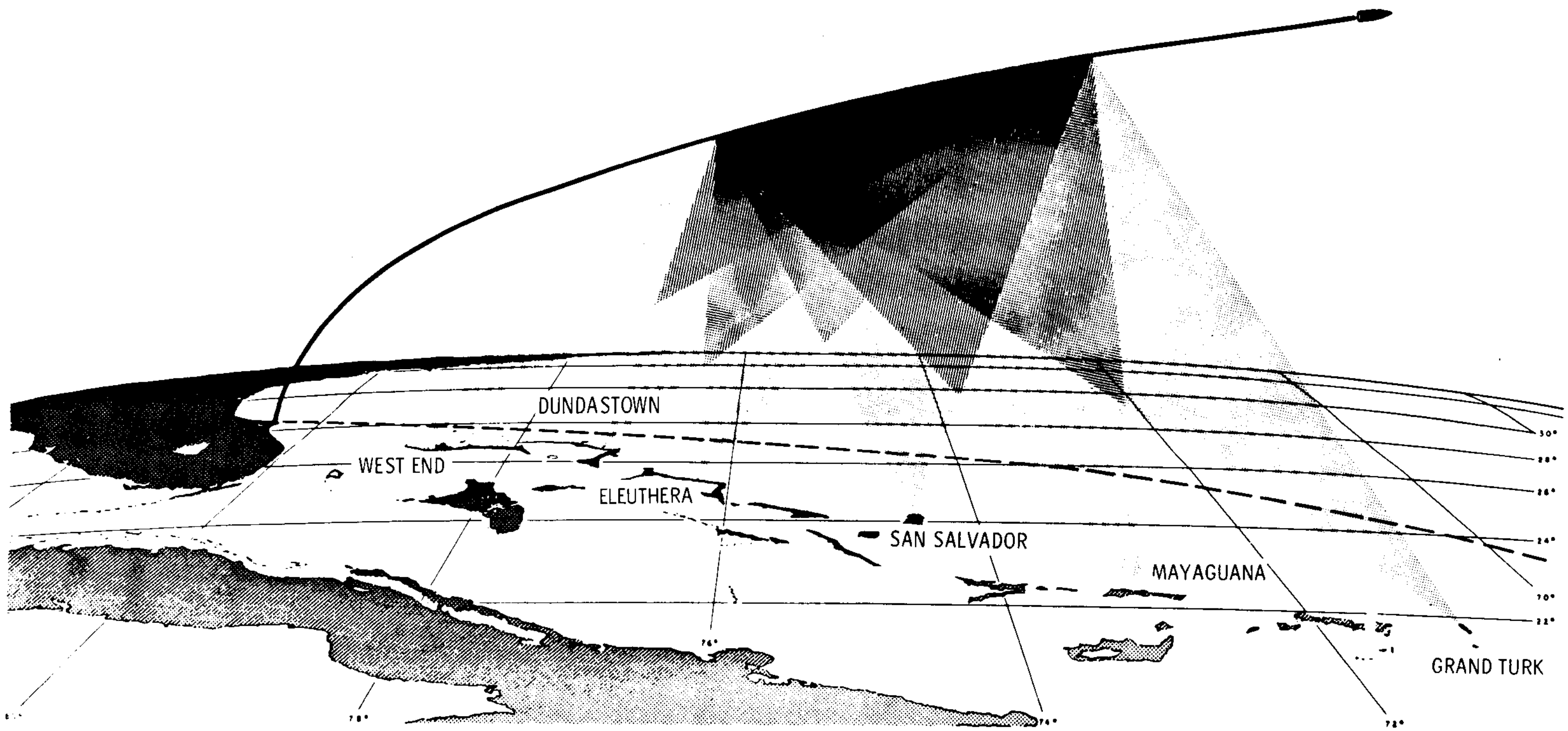


Figure 13-3. - Typical ballistic-camera tracking coverage during postburnout phase of flight.

is capable of a very high order of accuracy, but the data require special processing by skilled personnel, and the time delay involved is sometimes a disadvantage. Schemes for making some or all of the procedures automatic are under development.

Angle tracking with optical equipment can be accomplished with much greater precision than with radio equipment, but darkness, clouds, and haze limit the usefulness of optical equipment. Another important limitation of optical trackers is the fact that data reduction often delays the output beyond the period of usefulness. Automating procedures are under development.

For tracking certain objects some advantages may be gained by using ultraviolet or infrared radiation. Ultraviolet radiation in certain rocket exhausts and the infrared radiation from rocket engines may provide better contrast with the background radiation. Infrared radiation also penetrates fog, clouds, and haze more readily. Newer developments include the use of photoelectric detection and scanning techniques to permit automatic readout of angular position information. Television techniques to improve sensitivity, selectivity, and rapid readout are also in use. Laser trackers are being developed. An up-to-date review of optical tracking techniques and new developments is presented in reference 3.

Radar and optical techniques complement one another at NASA launch sites. In general, optical techniques are used primarily in the launch phases of flight and for exact permanent records, while the radar systems encompass the globe and are used for in-flight guidance corrections. Figures 13-1 to 13-3 show typical tracking coverage in the vicinity of Cape Kennedy. There are about eight different radar systems and 30 large tracking cameras capable of being deployed on this range. These systems are identified by their acronyms in the figures.

TECHNIQUE OF TRACKING MODEL ROCKETS

Tracking of model rockets utilizes the same principles of intersection and triangulation as those used by NASA. Because of cost and complexity, radar tracking methods are not used in model rocketry; instead, optical techniques with manual readout of data are employed. The main goal of tracking a model rocket is to obtain the maximum altitude of the rocket. Using two visual pointers - with or without optical aids - and employing trigonometry is the most practical way of obtaining this information.

Before choosing a measurement technique or a particular measuring instrument one must determine the accuracy required to fulfill the goal; judgment is the key factor here. If too high an accuracy is demanded, costs and complexity rise sharply. We have chosen to follow the guidelines of the National Association of Rocketry (NAR) in the adoption of the 10-Percent Rule. This rule and its application are described in the excerpt from the Handbook of Model Rocketry (ref. 1). The application of trigonometry to the determination of maximum altitude, the use of the NAR flight sheet, and the use of the NAR "Quickie Board" are also described in this excerpt. (The basic trigonometric functions - sine, cosine, and tangent - have already been defined in chapter 9.)

The excerpt from reference 1 is as follows:

> The tracking situation is shown diagrammatically in Figure [13-4].
>
> The theodolites are set up and leveled so that their azimuth dials are horizontal. They are zeroed in by sighting at each other along the base line. While zeroed in, their azimuth and elevation dials are set at zero.
>
> When the model is launched, both station operators follow it up in flight until it reaches maximum altitude. Tracking then ceases, and the scopes are locked in final position or left undisturbed. Azimuth and elevation angles on each theodolite are read. On some ranges, this data is communicated to the launch area by means of a telephone system. On other ranges, data is recorded at each tracking station and later taken to the launch area for final reduction.
>
> We now have a tracking situation with a known distance between two stations, plus an elevation and an azimuth angle from each station. To understand how altitude is computed from this data, let's derive the equations to be used. Refer to Figure [13-4].
>
> Given: Distance b
> Angle $\angle A$
> Angle $\angle D$
> Angle $\angle C$
> Angle $\angle E$

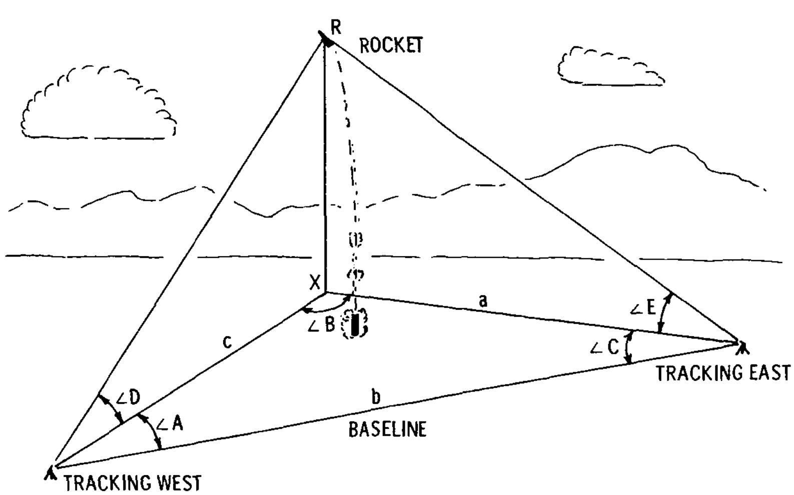


Figure 13-4. - Geometry of two-station tracking system. (From ref. 1.)

Point X is directly under the model R, and the distance RX is the altitude of the model. When we find distance a or c, we can then locate point X on the ground under the model and solve the triangles in the vertical plane to find RX.

There are two right vertical triangles (R-X-West and R-X-East). We can compute both separately and average the value RX obtained from both, thus giving a more accurate altitude reading.

The Law of Sines in trigonometry states:

$$\frac{c}{\sin \angle C} = \frac{b}{\sin \angle B} = \frac{a}{\sin \angle A}$$

Therefore:

$$c = \sin \angle C \frac{b}{\sin \angle B} = \sin \angle C \frac{b}{\sin[180^{o} - (A + C)]}$$

Since R is directly above X by definition, the angle R-X-West is a right angle. We can therefore compute the western triangle as follows:

$$\tan \angle D = \frac{RX}{c}$$

$$RX = c \tan \angle D$$

Substituting for c:

$$RX = \sin \angle C \tan \angle D \frac{b}{\sin[180^{o} - (A + C)]}$$

The other right vertical triangle is solved in a similar manner to give:

$$RX = \sin \angle A \tan \angle E \frac{b}{\sin[180^{o} - (A + C)]}$$

The two values of RX are then compared. If they are off by more than about 10 per cent, somebody goofed on tracking. If they are close, it means that "the triangles closed." By adding the two values together and dividing by two, or averaging them, the resultant altitude is very close to that actually achieved by the model.

However, since tracking is usually carried out to the nearest degree of arc, there are errors in the system, and the NAR has adopted a "roundoff" procedure to compensate for these. If the last digit of the average altitude is 1 to 4, it is dropped to zero. If it is 6 to 9, it is raised to the next 10-foot interval. In the case of the digit 5, the rule is: Keep it even. If the 5 is preceded by an even number, the 5 is dropped to zero. If preceded by an odd number, it is raised to the next 10-foot interval.

In addition to the "roundoff," NAR has also adopted the 10 Per Cent Rule for acceptable tracking data. According to the rule, there has been good tracking if the altitude readings from the two triangles are within 10 per cent of the rounded-off average.

To see how all of this works, let's take an example and work it through.

Given a 1,000-foot base line:
Tracking East azimuth: 23^{o} ($\angle C$)
Tracking East elevation: 36^{o} ($\angle E$)
Tracking West azimuth: 45^{o} ($\angle A$)
Tracking West elevation: 53^{o} ($\angle D$)

For one triangle:

$$RX = \sin \angle C \ \tan \angle D \frac{b}{\sin[180^{o} - (A + C)]}$$

$$= \sin 23^{o} \times \tan 53^{o} \frac{1,000}{\sin[180^{o} - (45^{o} + 23^{o})]}$$

$$= .391 \times 1.33 \times \frac{1,000}{\sin 68^{o}}$$

$$= .391 \times 1.33 \times 1,079$$

$$= 561 \text{ feet}$$

Solving for the other triangle by the same means, we get $RX = 555$ feet.

Averaging, the altitude is 558 feet. Rounding off, this is 560 feet. Ten per cent of 560 feet is 56 feet. Both 561 and 555 are within 56 feet of the average. The track is good.

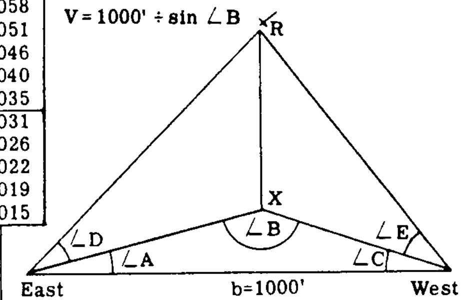
Since the complex term on the far right of the equation is the same when solving either triangle, it can be precomputed as a table of $1,000/\sin \angle B$.

A rapid method of this data reduction has been developed by John Roe, of Colorado Springs, Colorado, and used in the NAR for many years. Each model flown has a flight sheet on which is recorded the angles from both stations. Also printed on the sheet are the sine and tangent tables, plus the table for $1,000/\sin \angle B$. This flight sheet is shown in Figure [13-5], filled out for the flight we just reduced above. This fast method requires only some multiplication with the use of a slide rule. So it's a good idea to learn how to use a slide rule if you want to compute altitudes fast.

To provide even quicker data reduction, John and Jim Bonine, of Denver, Colorado, worked out their "Quickie Board" analog computer in 1960. This is shown in modified form in Figure [13-6]. It is set up for both 1,000-foot and 2,000-foot base lines. Although it is a graphical method, it is very accurate, even in small size. First, the azimuth angles from both stations are drawn out

∠	sin	tan	V	∠	sin	tan	V	∠	sin	tan	V	∠	sin	tan	V	∠	sin	tan	V
1°	.017	.017		21°	.359	.384	2790	41°	.656	.869	1524	61°	.875	1.80	1143	81°	.988	6.31	1012
2°	.035	.035		22°	.375	.404	2664	42°	.669	.900	1494	62°	.883	1.88	1133	82°	.990	7.12	1010
3°	.052	.052		23°	.391	.424	2559	43°	.682	.933	1466	63°	.891	1.96	1122	83°	.993	8.14	1008
4°	.070	.070		24°	.407	.445	2459	44°	.695	.966	1440	64°	.899	2.05	1113	84°	.995	9.51	1006
5°	.087	.087		25°	.422	.466	2366	45°	.707	1.00	1414	65°	.906	2.14	1103	85°	.996	11.4	1004
6°	.105	.105		26°	.438	.488	2281	46°	.719	1.04	1390	66°	.914	2.25	1095	86°	.998	14.3	1002
7°	.122	.123	8205	27°	.454	.510	2203	47°	.731	1.07	1367	67°	.921	2.36	1086	87°	.999	19.1	1001
8°	.139	.141	7185	28°	.469	.532	2130	48°	.743	1.11	1346	68°	.927	2.48	1079	88°	.999	28.6	1001
9°	.156	.158	6393	29°	.485	.554	2063	49°	.755	1.15	1325	69°	.934	2.61	1071	89°	1.00	57.3	1000
10°	.174	.176	5759	30°	.500	.577	2000	50°	.766	1.19	1305	70°	.940	2.75	1064	90°	1.00	-	1000
11°	.191	.194	5241	31°	.515	.601	1942	51°	.777	1.23	1287	71°	.946	2.90	1058				
12°	.208	.213	4810	32°	.530	.625	1887	52°	.788	1.28	1269	72°	.951	3.08	1051				
13°	.225	.231	4445	33°	.545	.649	1836	53°	.799	1.33	1252	73°	.956	3.27	1046				
14°	.242	.249	4134	34°	.559	.675	1788	54°	.809	1.38	1236	74°	.961	3.49	1040				
15°	.259	.268	3864	35°	.574	.700	1743	55°	.819	1.43	1221	75°	.966	3.73	1035				
16°	.276	.287	3628	36°	.588	.727	1701	56°	.829	1.48	1206	76°	.970	4.01	1031				
17°	.292	.306	3420	37°	.602	.754	1662	57°	.839	1.54	1192	77°	.974	4.33	1026				
18°	.309	.325	3236	38°	.616	.781	1624	58°	.848	1.60	1179	78°	.978	4.70	1022				
19°	.326	.344	3072	39°	.629	.810	1589	59°	.857	1.66	1167	79°	.982	5.14	1019				
20°	.342	.364	2924	40°	.643	.839	1556	60°	.866	1.73	1155	80°	.985	5.67	1015				

V = 1000' ÷ sin ∠B



Filled in by OWNER

Name Tom Rhue NAR # 50 Date 9-12-62

Model name Gargoyle Motor type ½A.8-4

SAFETY APPROVAL [signature]

Filled in by RECORDER

Tracking East: Azimuth (∠A) 23 ° sin .391 (1) Elevation (∠D) 36 ° tan .727 (2)

Tracking West: Azimuth (∠C) 45 ° sin .707 (3) Elevation (∠E) 53 ° tan 1.33 (4)

If ∠C + ∠A is less than 90°, read direct for ∠B.
If ∠C + ∠A is greater than 90°, subtract from 180° for ∠B.

68 = ∠B. Table value 1079 (5)

Recorder [signature] Track lost ☐

Filled in by DATA REDUCTION

(5) x (2) x (3)= 551

(5) x (4) x (1)- 561

1116

÷2 558 = average altitude

560 + 56 = 616 ok; 560 − 56 = 504 ok; 560

National Association of Rocketry

RANGE FLIGHT SHEET

Data reduced by 2/7

Launcher R-5 Misfire ☐

Launcher ______ Misfire ☐

Launcher ______ Misfire ☐

Figure 13-5. - NAR flight-sheet method of data reduction. (From ref. 1.)

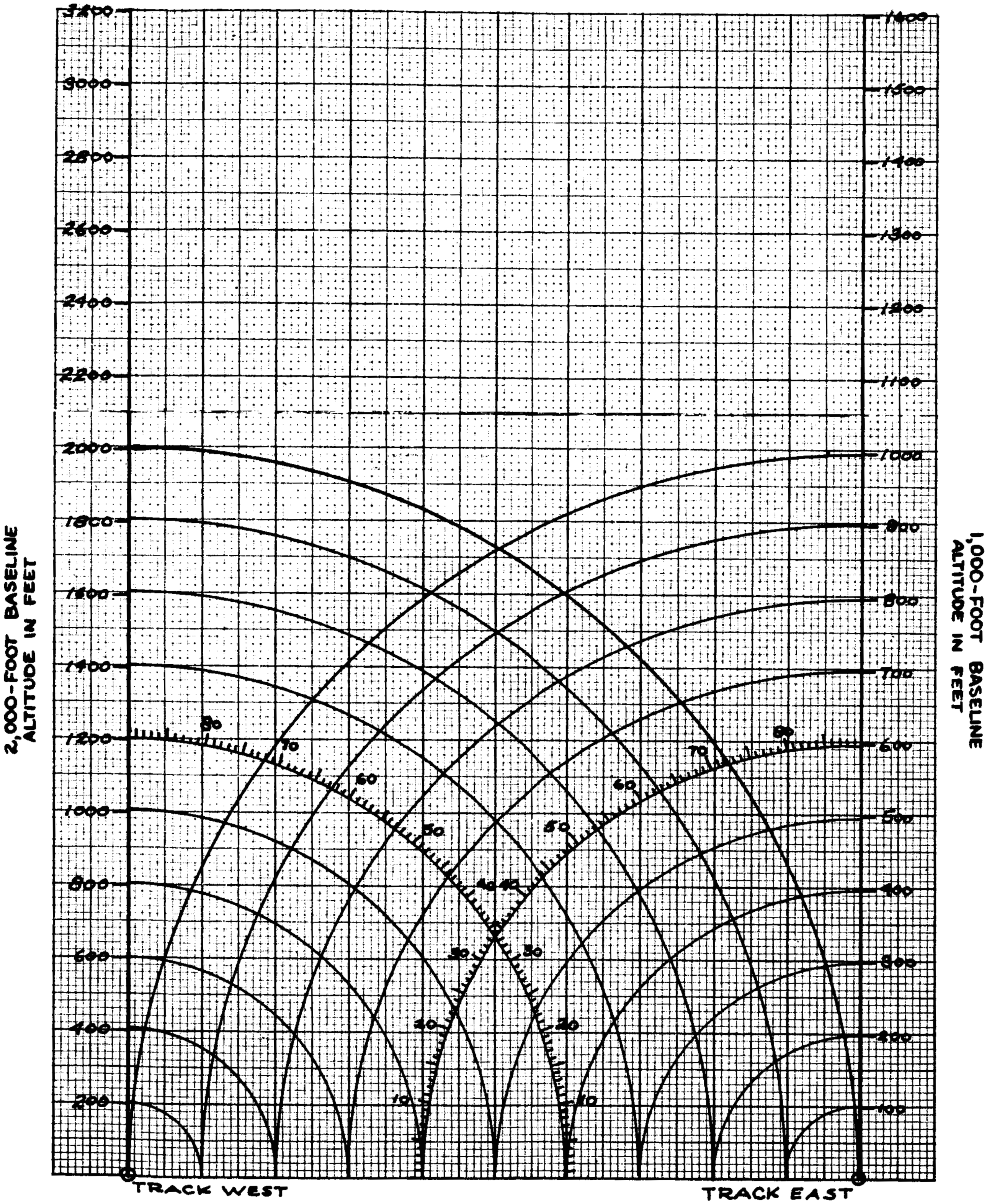


Figure 13-6. - NAR "Quickie Board" altitude computer. (From ref. 1.)

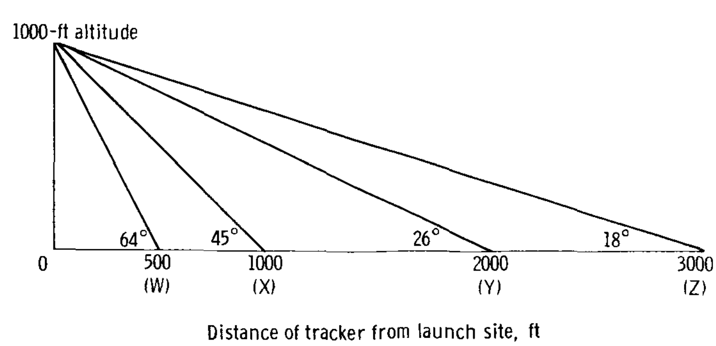
to an intersection. To compute the triangle for Tracking West, swing the intersection point down to the base of the graph with the Tracking West point as the center of swing. Draw a vertical line upwards from this intersection. Set up the elevation angle from Tracking West; where this line intersects the vertical line, read over to the edge for the length of base line, and read altitude directly. For Tracking East, carry out the same operations around the Tracking East point.

RANGE LAYOUT

The final layout of the firing range takes into consideration the various topographical features of the site, such as woods, hills, streams, roads, buildings, etc.; meteorological factors, such as wind direction and the position of the Sun, must also be considered. In addition to these considerations, the ideal elevation angles and azimuths are also determining factors in the positioning of the trackers.

Elevation Angle

Visual sightings, even with the use of aids such as telescopes, are only approximate, and the elevation angle read by an observer should be in the range which will be most conducive to the most accurate reading possible. Too small elevation angles (less than 25°) or too large angles (greater than 60°) increase the likelihood of a greater margin of error in determining elevation. Generally speaking, if the tracking stations are too close to the launch site, the elevation angles will be relatively large (approaching 90°) and, therefore, unreliable; if the trackers are too far from the launch site, the elevation angles will be small (approaching 0°) and equally unreliable. The sketch below shows that elevation angles taken from point W are approximately 64°, which is too large for accuracy. (When you look straight up, it is difficult to estimate how high in the air an object is.) For large elevation angles, a large difference in altitude is reflected as only a small



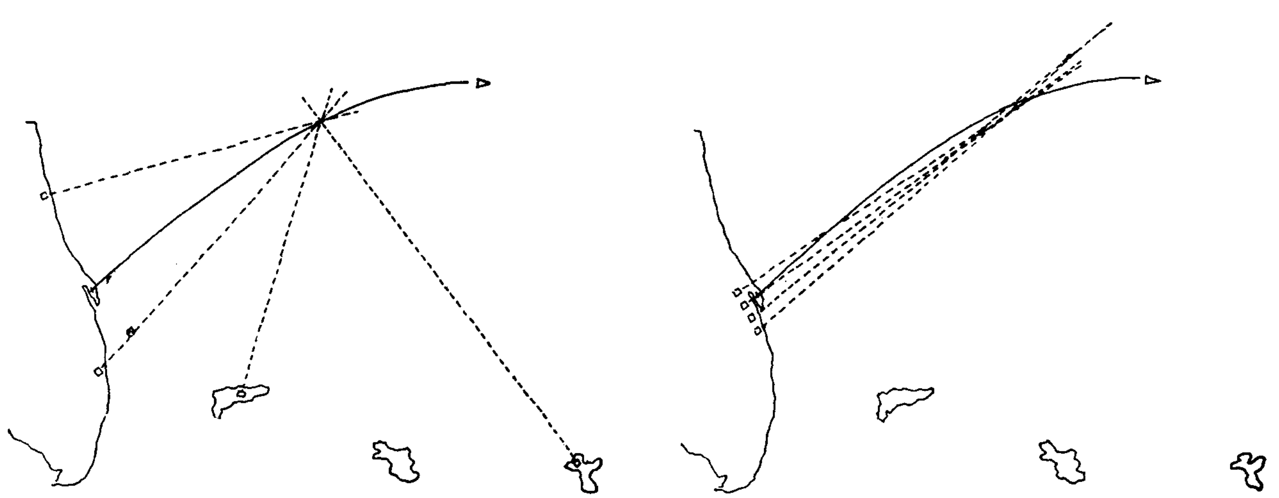
difference in the angle, because the angle is calculated from the tangent function, which increases to infinity as the angle approaches 90°. Also, readings taken from point Z are relatively inaccurate, because when the tracker is too far from the launch site and the elevation angle is small, even a substantial change in altitude does not cause a large enough difference in the elevation angle.

A rule of thumb is that the distance of the tracking station from the launch site should be at least equal to, but not more than twice, the expected altitude of the rocket. Positioning the tracking stations according to this rule will provide ideal elevation angles of 25° to 60°. Obviously, if rockets of greatly varied altitude capabilities are to be launched from the same site, several sets of tracking positions must be established.

Azimuth

The ideal intersection angle between the azimuths from any two tracking stations is 90°. If the intersection angle is too small (approaching 0°) or too large (approaching 180°), it is difficult to determine accurately the point of intersection. For full-scale launch sites, such as Cape Kennedy, where the missile range is basically a chain of islands, it is often impossible to set up tracking stations in the ideal locations. For model rocket launches, however, a site can usually be found which has the desirable topographical features and meteorological conditions, and the range can be laid out to approximate the ideal configuration from the standpoints of elevation angle and azimuth.

The importance of proper tracking-station positions and base-line layout is shown in figure 13-7. Figure 13-7(a) shows tracking-station locations which provide relatively



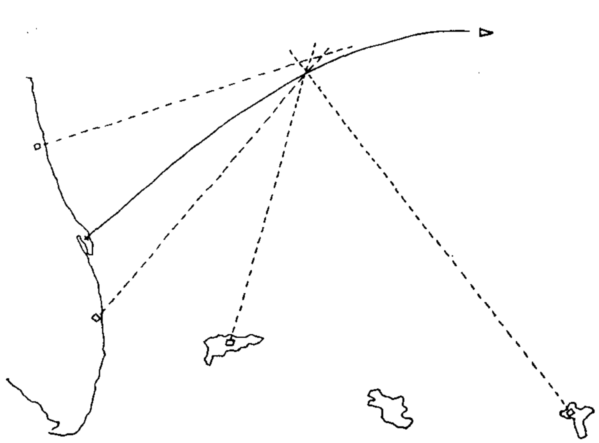
(a) Properly located tracking stations.

(b) Improperly located tracking stations.

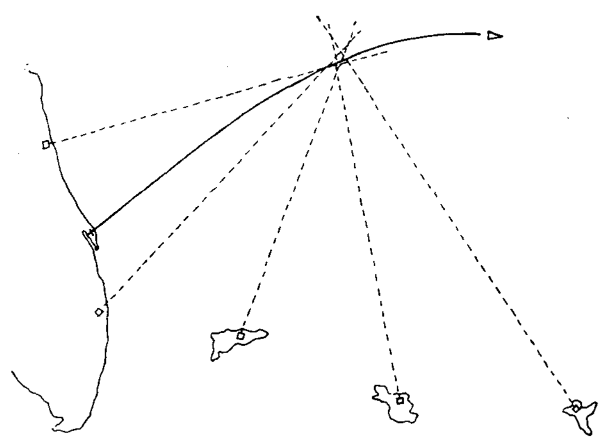
Figure 13-7. - Azimuthal location of tracking stations. (From ref. 4.)

good azimuth intersection angles. Here, the range layout cannot provide the completely ideal intersection angles of 90^0 because the range is a chain of islands and the trackers have to be located on these islands. However, the intersection angles are large enough to show clearly the point of intersection of the various azimuths. Four improperly located tracking stations are shown in figure 13-7(b). With such small intersection angles the azimuths are almost parallel, and their exact point of intersection is very difficult to determine.

Sometimes, imprecise intersections of azimuths may be obtained even from well-situated tracking stations. The azimuth from one tracking station may fail to pass through the common point of intersection of the azimuths from the other stations (fig. 13-8(a)). In such a situation, the azimuth which failed to pass through the common point of intersection would be disregarded, and a thorough investigation would be made to determine the cause of this stray azimuth. Figure 13-8(b) shows azimuths from various tracking stations intersecting at random. (For a postburnout, ICBM trajectory, typical separation of the various intersection points would be about 15 to 25 ft.) In this case, the most probable common point of intersection would be obtained by averaging.



(a) Failure of one ray to pass through common intersection point of other rays.



(b) Random intersection of rays.

Figure 13-8. - Typical tracking intersections. (From ref. 4.)

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