The control and tracking of modern high-speed aircraft, guided missiles, and the giant vehicles of the space age require visual display systems of far greater flexibility than are now available. The development of an experimental integrated data display system having two- and three-dimensional capabilities and a controllable memory using coherent fiber optics is a major advance in this field. Used in conjunction with advanced data-gathering systems, such equipment will reduce the chance of errors in operator judgment and will accelerate decision-making.

Experimental

Radar technology has advanced to the stage of development where we may realistically postulate a single radar that can simultaneously and automatically search for, acquire and track with precision a large number of aircraft, providing accurate data as to their dimensional position and velocity. High-speed digital computers that can assimilate large volumes of coordinate information from such radars and from other data-gathering devices will permit the construction of integrated automatic data-gathering, processing, and decision-making control systems. However, it will prove impossible to predetermine all possible operational situations in air traffic environments of increasingly high density and speed and to supply the "canned" answers that will be required by such systems. Consequently, there exists a requirement to develop new visual display devices that can work with advanced data-gathering equipment. Such devices must display quantities of coordinate data in a form suitable for rapid, intelligent monitoring and evaluation by a trained operator in order to allow him to override the automatic control system in times of malfunction or when it is confused by a particular operational situation.

An experimental three-dimensional (3-D) display that exhibits trajectories of both aircraft and satellites has been built at APL (Fig. 1). This is the first step toward demonstrating the technical feasibility of a display system that can display coordinate data in three, as well as in two, dimensions.* A device like this, with trained operators, can perform the key functions of a general-purpose display system for both advanced-weapon and commercial-air-traffic control systems.

The system is also suitable for use with sonar and could be used in a Naval Combat Information Center to display simultaneously both sub-surface and surface tactical situations for evaluation.

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* Success of the display system described herein is due in large measure to J. B. Garrison who conceived many of the basic requirements and techniques used.

A. C. Schultheis

3-D Radar Display

Also, as the requirements for space control systems become better defined, we believe that the display system will find uses in such areas as surveillance, navigation, and orbital rendezvous.

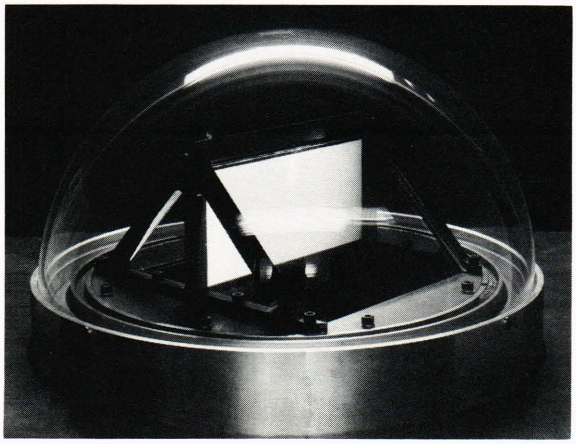

Fig. 1—Experimental three-dimensional display mounted under a plastic dome. Trajectories are displayed on the rotating, vertical, translucent screen.

Display System Characteristics

Because we see the world in three dimensions, it is natural that a 3-D display will provide an operator with information that he can assimilate and evaluate intelligently in the shortest possible time. Furthermore, in a heavily-populated, high-speed air situation, it will be highly advantageous for an operator to watch only one display for all his information rather than to be forced to make a composite mental picture from several 2-D displays, each giving only two categories of information, e.g., range-azimuth, range-elevation, etc. The higher the degree of saturation and the higher the air traffic speeds, the more critical will be his need of such equipment. To be effective, the display must present a large volume of information, have good resolution, and be able to present a controllable time history of a particular situation.

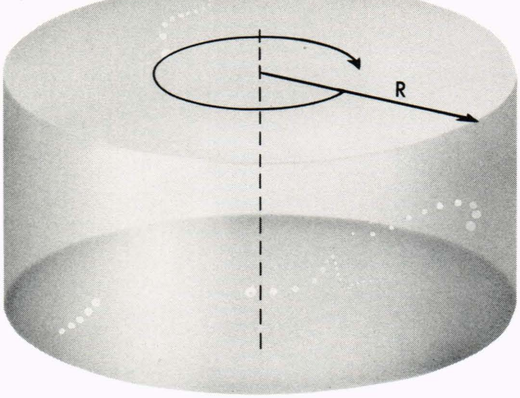

Fig. 2—Cylindrical volume with several trajectories suspended within it to illustrate the 3-D display concept.

To illustrate the concept of a 3-D display, a series of points forming individual trajectories suspended within a volume (arbitrarily chosen to be cylindrical) are shown in Fig. 2. The heaviest point in each trajectory represents the current position of the object under observation, while the others form a selected portion of its past-time position history—a variable for time periods from seconds to hours. With this ability to control the time-history display of an operational situation, an operator can avoid excess data display and more easily detect and evaluate operational trends.

The time lag for display of data after being received must be minimal. Also, the data insertion system must have access to all volume resolution elements within a minimum reaction time since there is no possible control over where objects will appear. A data access time of 1.0 sec was selected as being reasonable and practical, thus permitting all displayed data to be updated every second.

Displayed data must also be easily broken down into categories of information; color coding was therefore selected as being of greatest use to an operator. A capability of inserting symbols and cursors was also provided. With such tools as these an operator can intervene effectively in a fast-changing, high-density, operational environment.

Display Technique and Principles of Operation

Among several ways of generating a 3-D effect of the character shown in Fig. 2, a rotating vertical display screen (Fig. 3) of a semitransparent light-diffusing substance (e.g., frosted glass) was selected. As the screen rotates, it scans the entire volume of a sphere of radius *R*. For example, at each revolution of the screen, we turn on a small spot of light at the same angular position ϕ of the screen; the spot is then imaged on the screen at location x_o, y_o. The time duration of the spot is very short so that it appears to hang in mid-air at that location. Rotating the display at 20 revolutions per second removes any noticeable flicker as the spot is turned on and off once each revolution; the observer is not aware of the screen itself since its rotational speed makes it invisible.

There are several important advantages inherent in this type of 3-D display. It is truly three dimensional to the *naked* eye and requires no aids to vision. Because of the semitransparent material of the screen, it can be observed from any position. The light spot (data point) is diffused by the screen surface so that it is scattered almost equally in all directions, with the exception, perhaps, of a small angle defined by the plane of the screen and its thickness.

This type of display has a four-color potential. At any angular position of the display screen, four independent quadrants—two at an azimuth angle of ϕ and two at an angle of $(\phi + 180^\circ)$ on opposite sides of the screen—are available to image light spots of different colors that may be viewed simultaneously. (Note in Fig. 3 that only a semicircular screen is needed to generate a spherical volume about the axis of rotation; the light spots need be imaged on only one side of the screen.)

One thousand such vertical planes distributed equally in angle (which is consistent with the

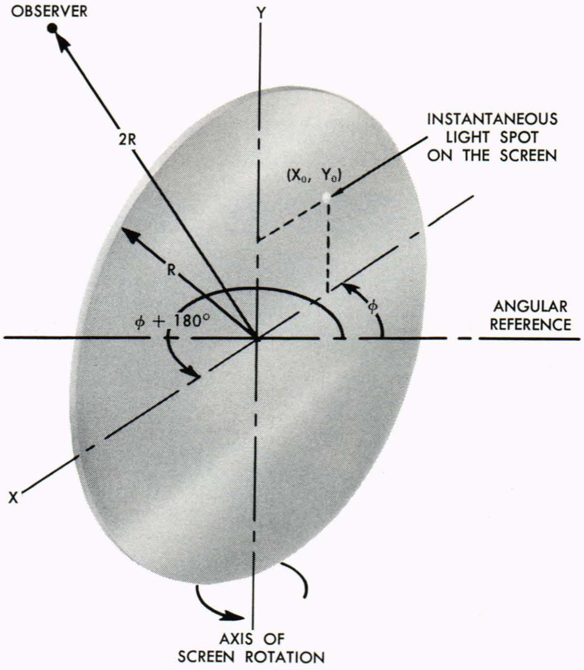

Fig. 3—Rotatable, vertical display screen that scans the complete volume of a sphere of radius *R*.

resolution stated) define a system angular resolution (azimuth) of 0.36°. Since each circular plane contains 10^6 resolution elements, the entire display volume will therefore contain 10^9 volumetric resolution elements regardless of the radius of the display volume.

Data Processing and Insertion

During each of the 20 revolutions of the screen per second, there are 1000 azimuth locations at which we wish to see all objects (light spots). Thus, the screen spends a total time of 0.05 sec/1000 (50 μsec) at each discrete angular position during a single revolution. In this instant there are 10^6 resolution elements that conceivably could require illumination. This means that a single light spot could spend approximately only 10^{-11} sec at each one of the million resolution cells in order to illuminate them all sequentially in 50 μsec at that location. A realistic example might be to assume 100 objects, at a particular azimuth angle, each being updated with latest position information every second. If we wish to display about 10 minutes of time history on each object, then the light spot must illuminate 60,000 different positions each revolution of the display (100 objects $\times$ 60 points per object per min $\times$ 10) in 50 μsec. This means, assuming they were equally distributed in time, that a single light spot could, on the average, dwell at each position for only about 10^{-9} sec.

The factors important to design of the data-processing and insertion portions of the system were determined from these considerations. The total number of data points that must be displayed in the short times involved (10^4 or 10^5 points in 10^{-5} sec) makes single-channel, sequential, lightspot scanning systems using cathode ray tubes and digital memories appear impractical. Hence, analog techniques allowing use of many parallel channels, each with a controllable memory, appeared to provide a potential solution. It was decided to investigate the use of 2-D, opaque, data memory surfaces that simultaneously could store data and be used to provide a controllable parallel channel light readout to the display.

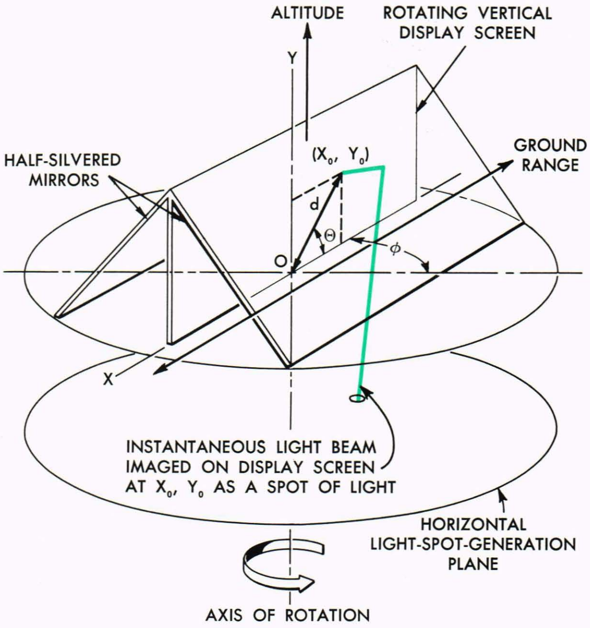

Fig. 4—Diagrammatic representation of the rotating experimental display shown in Fig. 1 and the display principle presented in Fig. 3.

Display Implementation

The technique chosen to image light points on the display screen (a rectangular screen rather than the circular screen in Fig. 3 that generates a cylindrical display volume) is shown in Fig. 4. The horizontal plane generated by the rotating *X*-axis represents the surface of the earth. If we take the bottom center of the display (*O*) as the coordinate origin, then the position of any object is determined by its height y_o above the earth and its ground range x_o at any azimuth of ϕ or $(\phi + 180°)$ on the screen. Assuming a minimum resolution cell of radius $R/1000$, where R is the radius of the cylindrical volume, we can place 500 such cells side by side along the X and Y axes of the screen. This establishes resolution of the display in both ground range and altitude of 1 part in 500 for the display system.[*]

Rapid on-off gating of the light spots in synchronization with the display rotation at the desired azimuths is accomplished in a horizontal light-spot-generation plane located directly under the display volume as shown in Fig. 4. At any instant, the picture on the horizontal plane is imaged on both sides of the vertical display screen by means of a simple projection-lens system and semitransparent half-silvered mirrors. These mirrors deflect the light rays projected from the horizontal plane so that they are imaged as spots on the vertical display screen without distortion; because they are semitransparent, they allow the observer to see the spots of light through them.

2-D Display System

The characteristics and operating principles of the analog memory data storage, insertion, and processing system can be described by referring to Fig. 5. Figure 5A shows a simple 2-D display system having two closely-spaced data surfaces of

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[*] Target altitude and ground range can be easily derived from object radial range d and elevation angle θ.

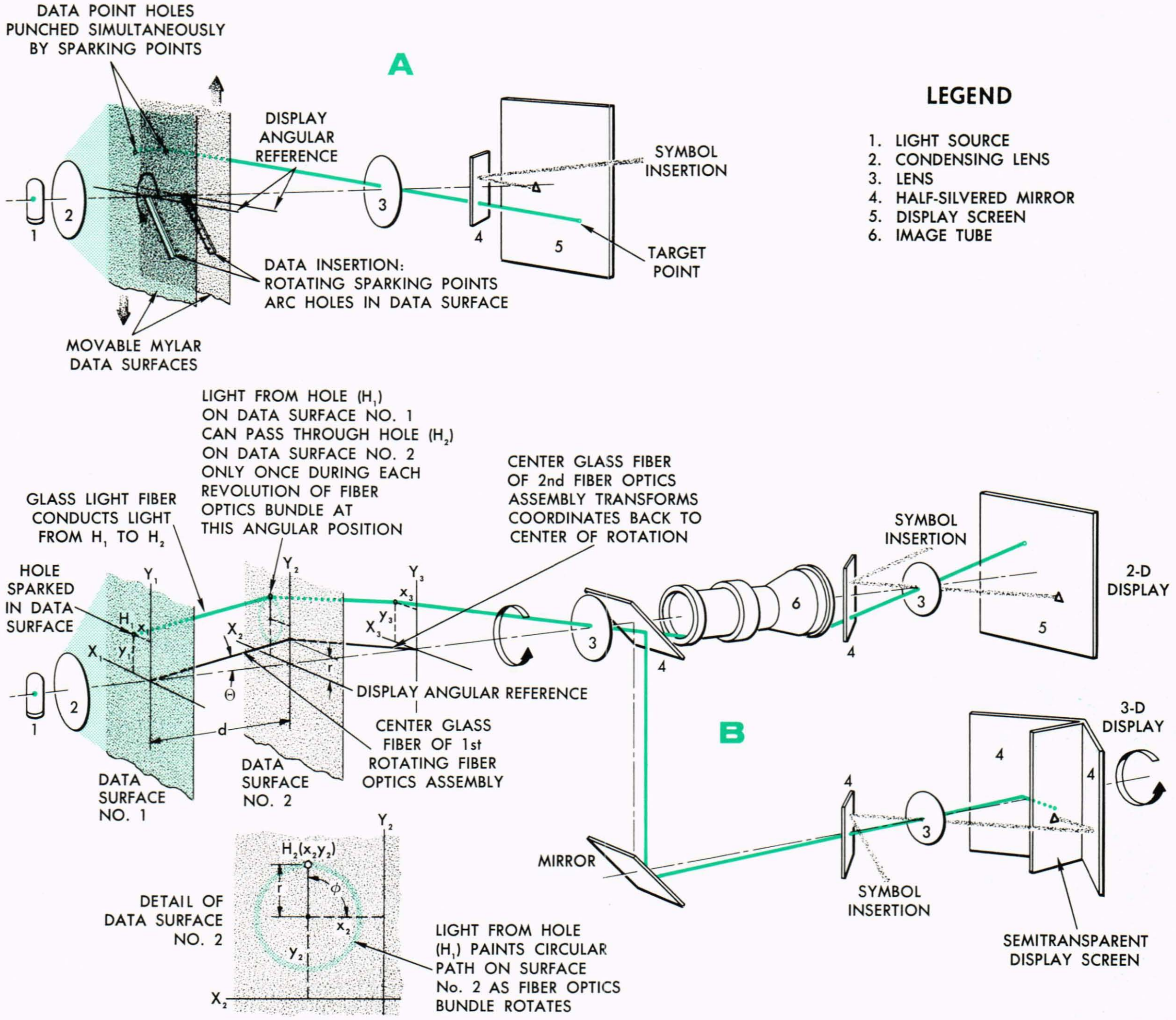


Fig. 5—(A) Simplified 2-D system showing principles of data insertion, storage, and display. (B) Principles of combined 2-D and 3-D displays. Note that fiber optics bundles are represented by a single glass fiber.

aluminum-coated Mylar tape. With aluminum coating on one side, this normally-transparent flexible plastic film forms an opaque memory surface. After making a data point hole in each surface (by removing spots of the aluminum coating) so that these holes are directly aligned, light can pass through both holes and be imaged on the screen via the lens and half-silvered mirror to represent a target coordinate point.

Data Insertion—To make the data point holes, we use an electric discharge from a rotating set of sparking points onto the aluminum surface of the Mylar. By controlling the total energy in the sparking pulse (width, voltage, etc.), the hole size can be controlled quite easily. Typical pulse widths of approximately 0.2 μsec and 5000 volts in amplitude are being used. The spark generator is a simple modulator that can be triggered readily from an external source. To reduce the number of sparking points required to scan the complete data surface, radial motion is applied to the sparking arm as it rotates. If the desired accuracy of data insertion is one-half a minimum resolution element, then in 20 revolutions, or one second (the required system access time), each point is made to move a distance of 10 resolution diameters.

If the data point holes are to align properly in angle, the timing accuracy must be related to the maximum usable radius of the data surface and to the minimum resolution element of radius $R/1000$. Since the circumference of the usable display area is $2\pi R$, there are about 3000 resolution elements scanned every 0.05 sec by the outermost sparking point. Thus, to locate the holes in angle to half a resolution cell requires system timing accuracy of approximately 8 μsec.

Display Persistence—The purpose of the two Mylar data surfaces is to permit control of the variable memory (display persistence) by moving the display surfaces at a controlled rate in opposite directions, as shown in Fig. 5A. This serves two purposes. It erases old points from the display by destroying hole alignment between the two surfaces (thus, new data points on a trajectory are perfectly aligned and old points gradually disappear), and it introduces new data surface to the system, thus preventing the system from becoming saturated.

The rate at which the surfaces must move relative to each other is determined by the required memory time and the size of a minimum resolution cell (or hole diameter). If the minimum resolution cell is 0.005 in. in diameter on the display data surface and the memory time required is 5.0 min, the rate of tape usage would be 0.001 in./min. If the full display capacity must be available at all times, the Mylar film speed must be $2R$/memory time, or 1000 times as fast as that required to erase points. If complete independence is required between desired memory time and display capacity, it would be possible to have a double channel memory system in which either or both systems could display points on the screen.

3-D Display Systems

The implementation shown in Fig. 5A is not suitable for the 3-D display, however, since there are no provisions for independently controlling light spot readout from the memory as a function of azimuth angle and in proper time synchronism with the 20-cps rotational speed of the 3-D display screen.

Figure 5B shows the basic operating principle of the combined 2- and 3-D display system. In order to gate the light spot on and off, a rotatable light spot nutator made of coherent fiber optics is inserted between the two data surfaces. Coherent fiber optics are a solid mass of many parallel glass fibers, each approximately 0.001 in. in diameter. When bundled together, these fibers act as independent light guides.

If, for example, we image small spots of light on one face of a coherent bundle (ends of the individual fibers), the light will be conducted almost perfectly and with negligible loss and will appear as light spots imaged precisely in the same location on the opposite face. If, as shown in Fig. 5B we place a fiber optics bundle between the two data surfaces so that the center glass fiber (and consequently all other fibers in the bundle) is not parallel but is at an angle to the axis of rotation, the following results are obtained.

1. If the bundle is rotated about the rotation axis defined by a dotted line connecting the intersections of X_1 and Y_1 on data surface No. 1, and X_2 and Y_2 on data surface No. 2, any hole such as H_1, continuously illuminated by light on data surface No. 1, will paint a light spot (via the fiber optics) on data surface No. 2 having a locus forming a circle of radius r (Fig. 5B).

2. The position x_2, y_2 of the light spot on surface No. 2 at any angle of rotation defined by ϕ can be determined from the simple transformation equations, $x_2 = x_1 + r \cos\phi$, and $y_2 = y_1 + r \sin\phi$, where $r = d \tan\theta$, and ϕ is defined by the angular position of the center glass fiber with respect to the display angular azimuth reference. These equations show that the center of the light circle painted on data surface No. 2 is located at the same position x_1, y_1 of hole H_1 on data surface No. 1.

3. If we place a second hole H_2, as shown in Fig. 5B, at some position (x_2, y_2), defined by the above equations and thereby located at some position on the circular path, the light spot will trace as the fiber optics bundle rotates; we can very effectively control the parallel light readout of the memory as a function of time or angle. The continuous light beam from H_1 can pass through H_2 only once during each revolution of the fiber optics bundle.

By rotating this bundle in synchronism with the 3-D display, the light spot can be imaged only via lens, mirrors, etc., on the display screen at one angular azimuth position, for each altitude and range (determined by x_1, y_1) once each revolution. The second fiber optics bundle shown in Fig. 5B is required to transform the coordinates (x_2, y_2) back to the original coordinate positions (x_1, y_1) with respect to the center of rotation, before projection to the display screen. Since we defined 1000 discrete azimuth locations for display resolution, the circumference of the scanning light circle must contain at least 1000 minimum-resolution cell diameters or be equal to $2R$.

Figure 5B also shows the manner of adding a 2-D display. The process is self explanatory.

Complete Display System Implementation

Figure 6 is the planned complete 3-D display system, with a third data surface added to eliminate false trajectories which may be generated in a two-surface system as different trajectories cross one another. With a third surface, the possibility of a false trajectory is minimized since only scattered false points can occur. We expect that by

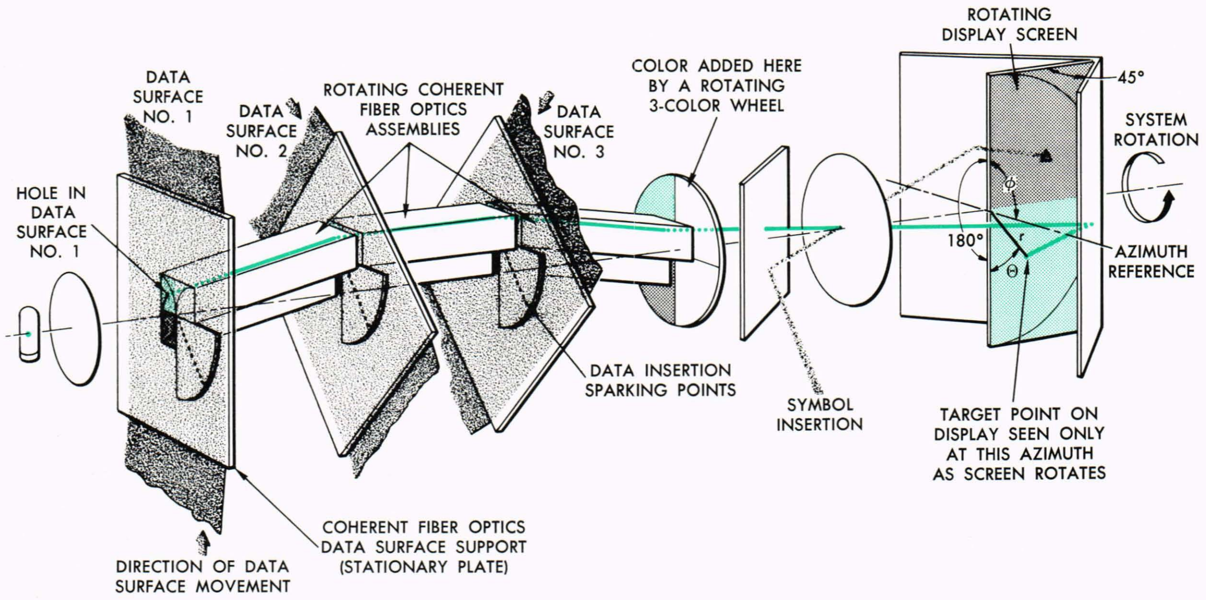


Fig. 6—Proposed complete 3-D display system showing use of a third data surface to eliminate false trajectories, and also showing three skewed fiber optics assemblies.

using 10% of the data surface area, or about 100,000 target points, the number of false points will be about 0.1% of the total number of points displayed. Since we are only interested in displaying trajectories, this level of false target information can be tolerated.

The operating principle of the rotating fiber optics assemblies is the same as in Fig. 5B. Color is inserted by a transparent three-color wheel (red, green, and white) that rotates synchronously with the fiber optics and display. Light spots appearing on the last data surface must pass through the color wheel before being imaged on the screen. This can be better understood by remembering that an image on the display screen at any azimuth position is really a vertical image of the last horizontal data surface at that instant of time via the projection lens and half-silvered mirrors inclined at a 45° angle.

This technique of color insertion utilizes the four-color capability in the display and permits division of the rotating fiber optics assemblies into four imaginary longitudinal sections. Each section is always reserved for a single color. Note that one fiber optics section is eliminated to allow insertion of sparking points. This prevents the sparking points from passing in front of the data surface at a time when they would interfere with the passage of light and prevent projection of data points. A typical, skewed, experimental, coherent fiber optics assembly is shown in Fig. 6. The assembly is 1.0 in. square and has fibers about 1.5 in. long and 10 microns in diameter.

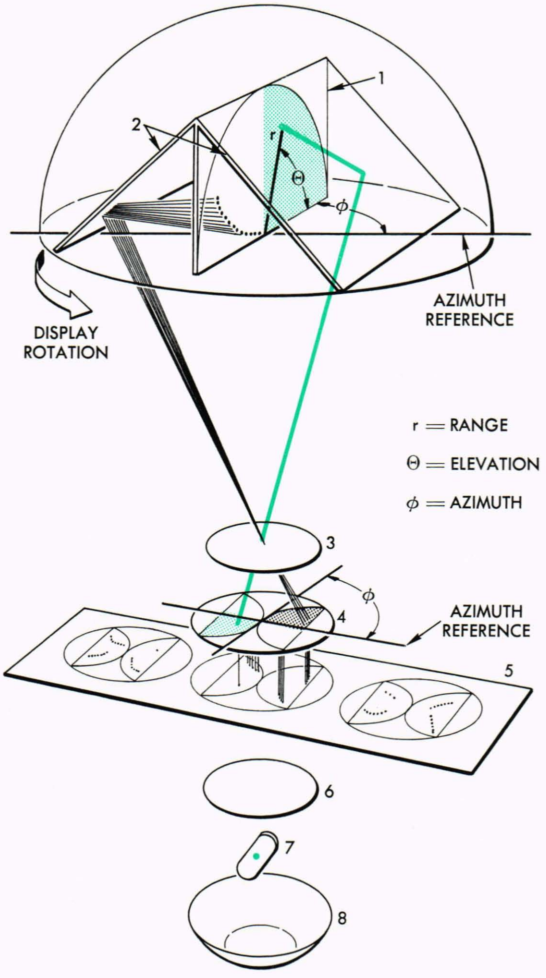
Alternative Data-Insertion Techniques

Investigations have been made of the use of a moderate-power ruby laser to supply energy via the fiber optics to burn a data point hole through the three data surfaces simultaneously. This technique of data insertion, in lieu of the rotating sparking points described previously, was successful, but the duty factor of the laser is still too low to make such a system practical. Investigations of this possibility are continuing. Another interesting possibility is the use of photochromic materials that change from an opaque to a clear state when exposed to light of certain wavelengths.

Experimental Display

Figure 7 illustrates the experimental system that has been successfully used to display synthetic aircraft and satellite trajectories. The display screen itself is 7.0 in. wide and 3.5 in. high. A 3.5 magnification is supplied by a projecting-lens system having a focal length of about 6.0 in. and light-gathering aperture of about 2.8 in.

Two memory surfaces are used to generate the simulated aircraft and satellite trajectories. The circular memory surface in the object plane of the projection lens is attached to the lens and rotates with the display. Fixed data point holes representing discrete range and elevation coordinates have been made in this surface. Beneath the rotating data surface, and separated from it by about 0.01 in., a second fixed data surface has been placed which has data point holes that match the rotating set at certain angular (azimuth) positions of the display. Light continually floods the underside of this second fixed memory surface so that when two holes align themselves as the display rotates the light is imaged as a spot on the display screen at that angular position. By moving the rectangular fixed data surface, trajectories in the display volume can be made to appear and disappear to simulate a dynamic situation.



LEGEND

1. VERTICAL FROSTED GLASS PROJECTION SCREEN
2. HALF-SILVERED MIRROR
3. PROJECTION LENS
4. ROTATING DISPLAY SURFACE WITH COLOR QUADRANTS AND DRILLED COORDINATE HOLES
5. ADJUSTABLE DATA SURFACE FOR DISPLAY OF FIXED SYNTHETIC TRAJECTORIES
6. CONDENSING LENS
7. LIGHT SOURCE
8. REFLECTOR

Fig. 7—Experimental 3-D system that has successfully demonstrated aircraft and satellite trajectories.

Holes from 10 to about 4 mils in diameter have been successfully used in the memory surface and displayed in three dimensions. A 4-mil hole results in an altitude and range resolution of 1 part in 250. If the maximum range of the display is set at 100 nautical miles and altitude at 50,000 ft, this gives a range resolution cell of 2400 ft and an altitude resolution cell of 200 ft.

Through magnification, a 4-mil hole on the data surface yields a 14-mil light spot on the display screen. The minimum discernible spot size, as derived earlier, would be $R/1000$ where R is 3.5 in.; this would give a 7-mil-diameter spot.

There has been no difficulty in observing trajectories on the screen using the 14-mil resolution cell which subtends about 2 angular mils at the eye when viewing the display at 7.0 in. from the center. Light from a 750-watt projection bulb has been found adequate in a room that is only moderately darkened. Data points separated by about a resolution cell in a trajectory are discernible.

A number of screen materials other than frosted glass have been tried, and the most satisfactory material found so far is ordinary drawing vellum. Synthetic memory surfaces of thin metal with holes drilled in them, and surfaces of aluminum-coated glass sparked manually, have been successfully used to place points in the display. Color identity codes of red, green, blue and white have been used.

As predicted, the display described is easily visible from all sides, and the angle at which vision is restricted by the plane of the screen is of no consequence. Display trajectories are easily distinguishable from false noise points. There is a small amount of blocking of light from the posts supporting the half-silvered mirrors, and there are some slight refraction effects when part of a trajectory is viewed through the half-silvered mirror and the other part through air. These effects have been completely eliminated, however, in a newer display similar to that shown in Fig. 1 but which uses a single full-silvered mirror on one side of the screen only.

Actual results obtained from the experimental equipment have verified that the display technique and the basic principles of data insertion are feasible and meet predicted display performance objectives. The experimental system is severely limited in flexibility because of the synthetic method of inserting data points and the fact that only two surfaces are available. However, a more flexible, dynamic data insertion and processing system is planned which will allow more detailed testing and evaluation of the overall design objectives.