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Satellite Prediction and Display

A Review of SPAD

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ABSTRACT

A satellite position prediction and display device (SPAD) has been conceived, constructed, and operated at the Naval Research Laboratory. Experience with the research equipment has shown that it is technically feasible to implement the SPAD concept in several ways, using a digital computer for prediction and using both a geographic display and a tabular readout to present predicted positions of selected satellites at arbitrary times.

Other conclusions include the following. Predicted satellite positions should be computed at the user's location, using orbital elements and orbit decay information so that prediction can continue even with stale data. The general features of the SPAD computer control panel should be retained, since they provided a great deal of flexibility in presenting predicted positions at arbitrary times for a number of satellites selected either individually or according to category, as fast as such information was requested of the AN/UYK-1 computer.

Such flexibility and speed was achieved at the expense of equipment complexity. It is difficult to assess the merit of achieving this performance in view of the attendant expense, since there is no known operational requirement for a shipboard prediction and display device similar to SPAD.

This discussion leads to the following tentative recommendations. For further system studies, the SPAD concept should be implemented on an NTDS-equipped ship, using the Naval Tactical Data System computer and display console on a time-shared basis. Thus, with some sacrifice in operator convenience, SPAD design becomes essentially the software problem of programming the NTDS computer and reassigning functions to the controls and indicator lamps on the NTDS display console. This modest investment using available hardware will facilitate further studies to provide answers to such questions as how satellites should be categorized, how many can be viewed at once, how fast should accelerated time be varied, the need for hard-copy readout, and what information and format is needed for the tabular readout display.

For a service version of SPAD, use of a modern computer-driven display is recommended. For system efficiency, the computer should be time-shared among several functions. Doctrine at the SPASUR station should be changed to permit the satellite updating message to be prepared in the SPAD format prior to transmission to the user.

PROBLEM STATUS

This is a final report. The problem was terminated on Dec. 31, 1967.

AUTHORIZATION

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SATELLITE PREDICTION AND DISPLAY – A REVIEW OF SPAD

INTRODUCTION

The prototype version of the Satellite position Prediction And Display equipment (SPAD) has been constructed and demonstrated at the Naval Research Laboratory. Previous reports have described assumed performance objectives, the hardware and computer software, and experience gained in using this research tool to determine the Navy's requirement for a shipboard satellite display of modest accuracy but considerable versatility and speed. While a formal evaluation was not conducted, and while the Navy's requirement has not yet been established, the experience thus gained has provided considerable insight into possible performance and equipment configurations.

The present report reviews SPAD both as a concept and as a research tool. Tentative conclusions are briefly presented, as well as a list of the design decisions which study and experience have shown to be significant. The overall objective of this report is to present a review of what has been learned regarding the possible need and nature of a relatively simple but versatile satellite position prediction and display equipment.

HISTORY OF SPAD

Although the NRL satellite display SPAD has been described in previous reports (1-15), this section on its history is presented to show how study of earlier satellite displays led to the SPAD concept, why a particular configuration (Fig. 1) was implemented, and how experience with this hardware led to the conclusions and appreciation of the design decisions which are discussed in this report.

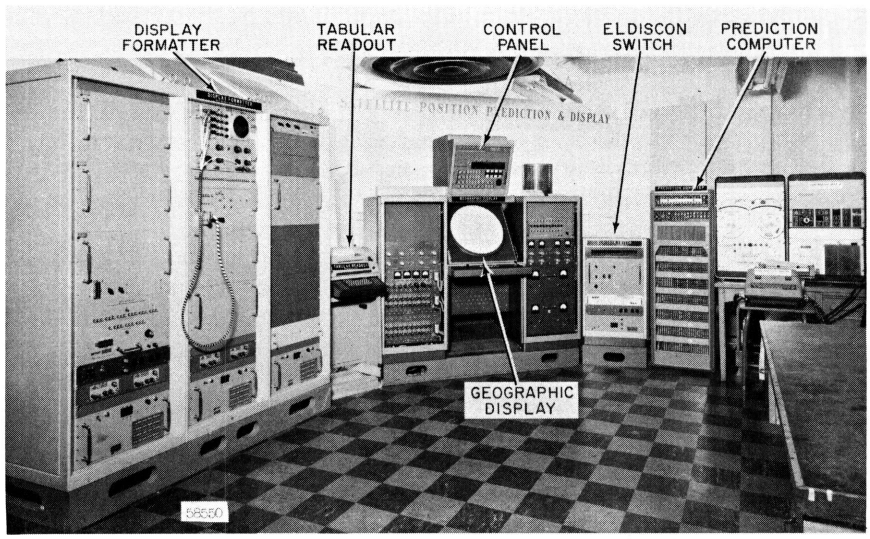

Fig. 1 - Laboratory installation of SPAD

Other Display Approaches

The position of a satellite is commonly known by prediction, since it is not practical to track an orbiting object continually. At first, one or more orbits were plotted on a Mercator map projection. Then a more flexible display was provided by means of a film strip and projector, with each film frame showing the precomputed positions of several satellites at a given moment of time printed on that frame. Each film strip was then carried to the user point, where the frames could be either advanced in real time at one-minute intervals or rapidly moved forward or backward until the desired time was reached. However, the film-strip display became more difficult to interpret as the number of orbiting objects increased. Furthermore, the display was dependent on receiving the next film strip from the space surveillance station.

The film-strip method was discarded, and the sophisticated central prediction computer was reprogrammed to prepare a printed satellite data message. Following transmission, this message would permit orbits to be plotted and displayed at the user site. For each satellite the message would include an orbit portion listing several positions and corresponding time increments for a given orbit. These data would be plotted on a transparent overlay, with the equator crossing being slid east or west on the map to the desired crossing point selected from the second part of the message. This equator crossing portion provided longitudes and corresponding times for a number of crossings. Thus, by interpolation and other mathematical manipulation, the position of a given satellite at a given time could be somewhat laboriously determined by means of comparatively simple equipment. The method was suitable for satellites with stable orbits such that the ground track did not appreciably change shape during this time interval of several days.

This manual method was followed by an electronic device for storing, plotting, shifting, and interpolating orbit points (16-19). The device still used the Mercator map projection, secured desirable improvements in response time at the expense of equipment complexity, and, like the manual method, ceased operating if the updating data messages were not received from the central computer. Serious position errors could be expected for satellites with decaying orbits, since there could be no continuous compensation for temporal variations in the orbital elements. That is, regardless of orbit decay, the shape of the displayed suborbital path necessarily remained constant for the week between data updatings, and this shape was electronically shifted east or west corresponding to the orbital period bracketing the desired prediction time.

Another satellite display (20,21) has many of the features of SPAD, using orbital elements and electronic analog simulators to generate the functions representing predicted orbits. The display uses cathode-ray tubes with two types of map overlays: orthographic projection and Mercator projection. Thus, only a portion of the earth's surface is shown.

Certain orrery displays, referred to only in passing, depict one satellite orbiting about a rotating earth globe. The orreries are relatively simple and inexpensive and appear to be intended for illustrative purposes only. For practical reasons they are limited to but one satellite at a time.

SPAD Concept

Consideration of these and other approaches to the prediction and display of satellite positions (22, 23) led to the supposition that in time there would arise an operational requirement for a rather different display, capable of great flexibility, convenience, and speed, but with moderate accuracy and complexity in displaying selected information on selected satellites from a growing repertoire of orbiting objects. It was hoped that information gained from study of possible display configurations and experience gained with design and operation of a plausible configuration would prove helpful in reducing lead time should it become necessary to produce an operational equipment.

Thus, there was generated the proposal of Ref. 1 for study and development of such a satellite display, with tentative performance specifications being given. The question of how and where to compute position data was considered in Ref. 2, which also included a proposal for a prediction computer to be located at the user site on board ship. This location seemed desirable, since it would lighten the load of satellite data to be sent over a radio communication circuit. The special-purpose computer appeared to be relatively simple, employing precision magnetic resolvers to perform multiplications and to generate trigonometric functions (24). The desire for greater flexibility and capability, combined with the growing complexity of the digital front end of the hybrid computer, led to a decision to utilize a general-purpose digital computer. Then a tentative plan was devised to evaluate SPAD on the USNS KINGSPORT, using the AN/UYK-1 general purpose digital computer installed on board. This ship, the TAG-164, was being modified as a seagoing satellite terminal. It was planned that with regard to SPAD the ship would serve merely as an evaluation site, and that SPAD would not be involved in the ship's mission.* While the AN/UYK-1 computer proved to be satisfactory, it is likely that many other computers would have done as well, providing they had comparable speed and memory capacity.

Various display design questions as well as a proposed display configuration were described in a companion report (3). The referenced report considers the following: there was to be a map overlay showing the entire earth's surface, including the poles. The world-map display in conjunction with this overlay was to depict positions of up to ten satellites selected by category, although provision for selection and deletion of individual satellites was later incorporated in the computer programming. For a satellite designated at the computer control panel (Fig. 2) there would also appear an orbit on the world-map display (Fig. 3).

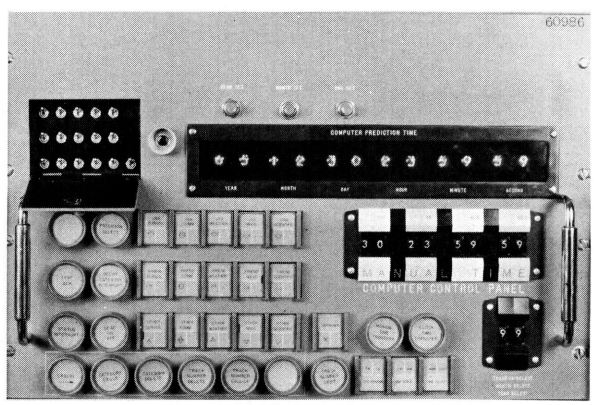

Fig. 2 - Computer control panel

When operated as described previously, the geographic display is said to be in the world-map mode. The display can also be off-centered and expanded about this satellite (alternatively, about own-ship) and is then said to be operated in the expanded mode. The one satellite would then appear on a rectangular expanded display 20° in latitude by 30° in longitude (Fig. 4), or on a polar display 40° in diameter (Fig. 5) when the satellite was within 15° of either pole. A velocity vector as well as an area-of-view circle for this satellite also appears on the expanded display. The significance of this circle can be as desired. The circle might, for instance, represent the area seen by cloud-cover cameras.

*SPAD was never installed on this ship, however.

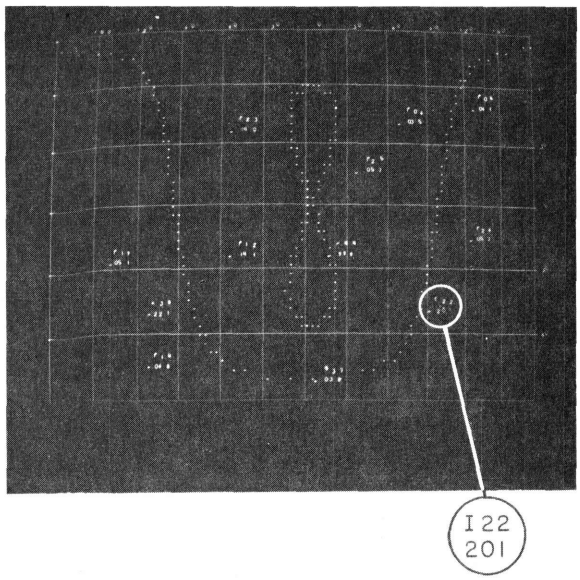

Fig. 3 - Two orbits, eleven satellites and own ship on the world map display

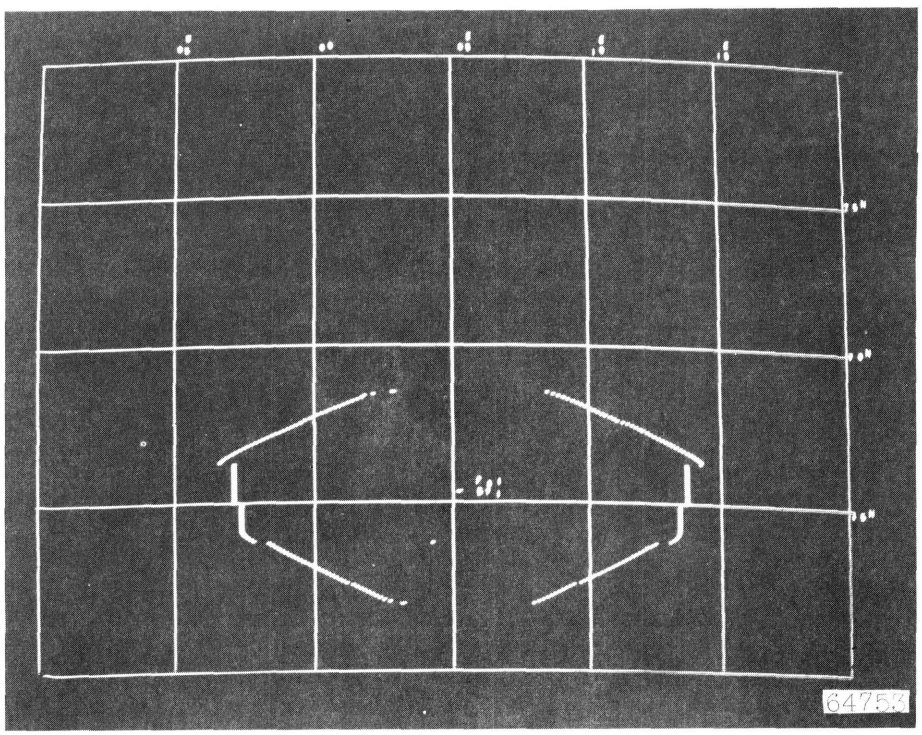

Fig. 4 - Approximation to a circle compensated for convergence of the meridians

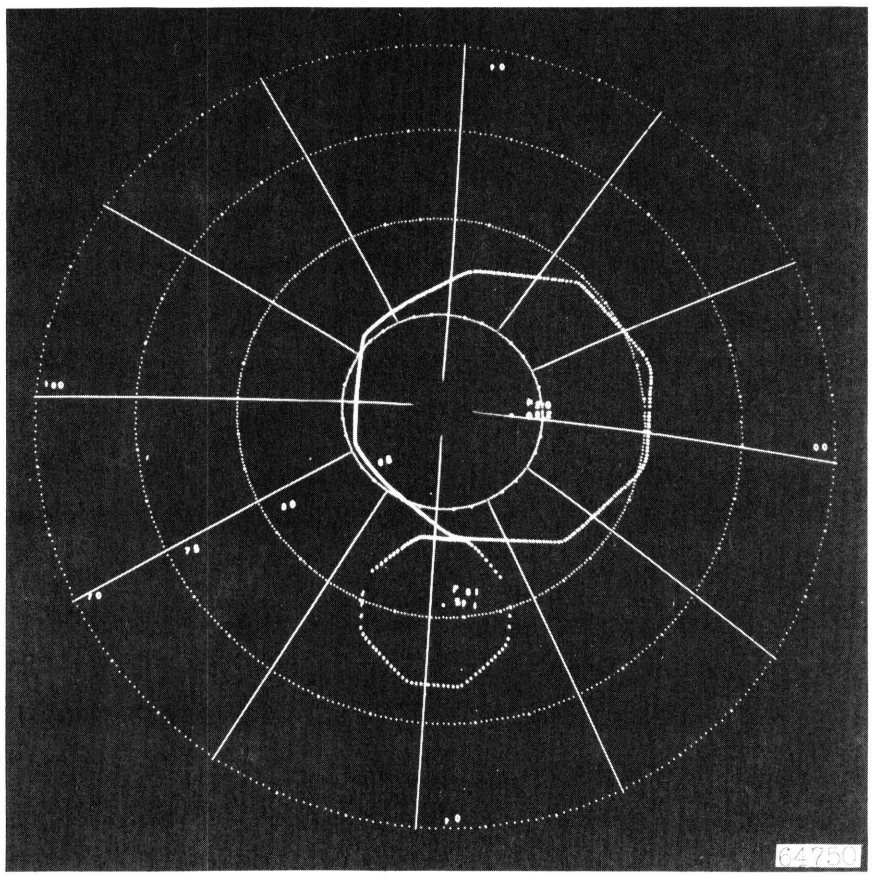

Fig. 5 - Polar expanded display with own ship, selected satellite, and areas of view

The circle if painted about own-ship might represent the distance which a ship could steam in, say, 24 hours. With the facility provided, the significance could later be established by doctrine and could be altered whenever necessary. Thus, SPAD was regarded and constructed as an experimental device, with many features such as accelerated time being included for evaluation.

SPAD Hardware

Constructed as a research tool with emphasis on ease of construction, ready maintenance, and convenience of modification, SPAD appeared as shown in Fig. 1. Its operation is described in terms of the units shown in the photograph.

The two-unit controller to the right has a tape reader used to load the adjacent prediction computer with both the program and the list of satellites with their orbital elements and related data. Satellite positions are then calculated by means of equations based on those derived in Refs. 4 and 5, but modified to include the "a-dot" term (where $\dot{a}$ denotes rate of change of a, the semi-major axis, as discussed in Ref. 9). A computer control panel above the geographic display is used to select the satellites for which predicted positions are placed in the display formatter, where they are stored and presented to the geographic display at the display frame rate. Additional information for one selected

satellite at a designated time is presented in tabular form by the page printer visible between the formatter (to the left) and the geographic display console. An electronic disconnect switch (the "Eldiscon" switch of Fig. 1) was added to permit time-sharing of the computer (e.g., for the KINGSPORT installation) as well as to provide interfacing between SPAD digital circuits and those of the AN/UYK-1 computer.

Much of the complexity of the formatter (housed in the three-bay rack cabinet) was a consequence of the decision to paint positions on the geographical display (a 19-inch Charactron* cathode-ray tube) by means of a raster so as to avoid the effect of hysteresis errors in deflection. Such hysteresis errors lose their significance when all information to be compared is painted during the same raster. The formatter also contains circuit exercising and other trouble-shooting circuits as well as a real-time generator and a data-entry panel for manual entry of own-ship's position, course, and speed. (While time and own-ship data were to be automatically provided by the KINGSPORT, the shipboard installation was never made.)

Much of the versatility of SPAD can be described with reference to the display control panel and the computer control panel, both located at the geographic display. Once the information for display has been selected at the computer control panel, the various controls on the display control panel permit the operator to temporarily inhibit selected video so as to resolve any ambiguities due to overlap. Operation of the computer control panel (Fig. 2) is described in Ref. 7, and only its more salient features need be mentioned here. The complexity of both this panel and the consequent computer program was influenced by two broad objectives: the desire for great flexibility, and the investigation of control features which appeared to have some merit and which could be readily implemented.

Although a formal requirement did not exist, it seemed important to be able to select satellites by category. A 3×5 category matrix was chosen, based on countries of origin and five functions as shown in the push-button array of Fig. 2. To this a sixteenth category, Unknown, was added. This partitioning is quite arbitrary and can readily be changed. Following such a selection, individual satellites can be deleted or called up by track number, an arbitrary bookkeeping number significant only within SPAD. In general, the operator will not know how many satellites have been selected by category. Thus, there are store overload lamps to indicate which selected categories have satellites waiting to be displayed and a cycle button to instruct the computer to select another ten satellites according to a programmed priority sequence.

To avoid the possibility of any confusion, six pairs of numerical indicators on the computer control panel serve to indicate the current computer prediction time, which can be either "clock" time or "manual" time. From left to right, these pairs of indicators represent year, month, day, hour, minute, and second. Upon accepting this information, the computer converts time to a binary word representing the number of seconds elapsed since the beginning of 1960. As the computer is now programmed, valid years are 1960 through 1975, a span which can be covered in one-second increments using the 30-bit word length capability of the AN/UYK-1 computer.

One pair of thumb-wheel dials is used with appropriate "execute" buttons for transmitting to the computer three kinds of two-digit numbers: month, year, and track number information. As a matter of circuit economy, there are no counting circuits to automatically handle month and year information; thus, these numbers are set manually.

The same pair of thumb-wheel dials (located in the lower right hand corner of the computer control panel) can also be set to designate a satellite track number. Several

*"Charactron" is a trademark of General Dynamics Corp.

track-number execute buttons are available for instructing the computer to delete this satellite from the display, to call it up, to generate an orbit, or to activate the tabular readout as may be desired.

Valid track numbers are from 00 through as high as 87, depending on how many satellites are included in the weekly message updating the orbital elements. With additional memory capacity, the computer could easily handle more than 88 satellites.

As shown in Fig. 3, each satellite position is identified by a group of six symbols, as follows. One of 16 category symbols appears in the first position of the top line. Next appears the two-digit track number. The second line of three digits denotes satellite height in tens of miles. A computer output word of 30 bits uses four bits to designate each symbol and five bits to address the proper formatter store, which receives a given 24-bit symbol word. In this application, it was possible to so constrain the six-symbol format that each set of four bits could be converted to the six bits needed to select the desired symbol from the 8×8 array within the Charactron cathode-ray tube.

While an edge-lighted optical map overlap was planned, time did not permit this feature to be implemented. A modified cylindrical equal-spaced map projection (25) was chosen because it included the poles.

Demonstrations and Tests

SPAD was installed at NRL and demonstrated to a number of interested Department of Defense personnel. These demonstrations provided some experience with operation of the equipment in addition to that incurred during the technical evaluation. (Results of the evaluation are discussed later in this report.) There was no formal operational evaluation, due to limitations in time, money, and available manpower. However, the experience gained in thus operating the equipment led to a number of conclusions which are discussed later in this report.

EXPERIENCE WITH SPAD

For practical purposes the prototype version of SPAD described previously met the tentative specifications and performed as described in Ref. 7. However, the computer with its 8192-word memory could store data on only 88 satellites, rather than the specified 100. Other performance data will be briefly stated in preparation for a discussion of possible future versions of SPAD.

Position Updating Speed

The AN/UYK-1 computer, with its clock period of 3 microseconds, could predict positions of 11 satellites in 1.1 sec. This cycle time went up to 1.36 sec during the tabular printout, with one tabular character being interleaved with each updating of a position. In the expanded mode the one satellite position was updated each 0.16 sec. An orbit represented by 128 positions was computed in 5 sec, with no updating of position stores taking place in this interval. For storage and display these positions were quantized to 4° in both latitude and longitude, so that fewer than 128 points appear (Fig. 3) to represent an orbit.

These updating speeds were more than adequate for clock-time predictions, since in the limiting case (Ref. 2, p. 3) for a highly eccentric orbit at perigee the satellite will travel about 60 naut mi in ten seconds. Thus, position stores should be updated at least every five seconds to allow for some error in computation and display. Computation

errors were usually negligible, compared to the display quantization error of 0.5° in longitude, or 30 naut mi at the equator.

Prediction for Manual and Accelerated Time

The manually designated time feature proved to be a convenient and rapid means for determining what satellites would be in a given neighborhood at some designated future or past time. Further, starting from some arbitrary time it was possible to vary time manually at an accelerated rate either forward or backward in a search to determine when a communication satellite, for example, would pass over own ship. It was equally easy to determine when and where a group of satellites would tend to bunch. Only an electronic, dynamic display could permit one to answer such questions in so brief an interval. The search time spent answering such questions was minimized by using fast time to secure an approximate answer and slower time to secure a refined answer.

Accelerated time could be varied continuously from 1X (normal time) to 3600X, corresponding to a one-hour increment each second. The latter speed, while suitable for synchronous and other long orbits, was too fast for low-altitude satellites. For instance, at 3600X accelerated time a 90-min orbit would be represented by three position predictions every two orbits (approximately). Such meager data are hardly adequate for depicting a suborbital path! This worst-case situation could occur with 11 satellite positions being updated each 1.1 sec, since the prediction time would change 1 hr (3600 sec) each second of real time.

There are several ways to generate more points per orbit for low-altitude satellites viewed in accelerated time. For instance, one could delete all satellites but one. Since manual time (including accelerated time) is offered to the computer four* times a second, one could secure six positions per orbit. But this minor improvement is secured at the expense of viewing only one satellite at a time, whereas it may be important to study future trends involving many satellites.

For viewing up to 11 satellites at once, it was possible to provide 15 points per 90-min orbit by operating the time control at nearly 360X. However, there was then no advantage to offering time to the computer four times each second, as it would take the computer 1.1 sec to update the positions of the selected satellites.

If search time is a critical item, this time can be reduced somewhat through use of a more sophisticated computer program and still further through selection of a faster computer.

Map Overlay

While an edge-lighted optical overlay depicting geographic detail such as continental outlines was planned, this overlay was not made due to lack of time. Its use would have led to parallax error due to the thick faceplate glass of the 19-in. cathode-ray tube, with maximum error occurring at the periphery of the faceplate.

Parallax error could have been reduced by use of either optical port projection of a film frame to the rear surface of the phosphor or generation of electronic map signals by a flying-spot scanner.

*This arbitrary number is readily altered by a simple change in circuit design.

No geographic detail was planned for the expanded display, since the need was not established, and since this feature would have led to practical difficulties in design of a suitable film-strip projector containing the several hundred frames needed for the expanded display with adequate speed in frame selection.

Display Appearance

The following statements regarding appearance of the SPAD geographic display represent opinions of engineers who designed the equipment and demonstrated it to Department of Defense personnel. This limited experience led to the following conclusions, which appear to have merit.

1. Electronically generated map grid lines, satellite position dots, and identifying alphanumerics were satisfactory in appearance. The latter were more legible than one can infer from the photograph (Fig. 3). Any ambiguities due to information overlap could readily be resolved by means of video inhibit buttons.

2. The tail-dot velocity vector was not satisfactory in appearance and was particularly prone to erroneous interpretation, even though it was generated for only one satellite. The tail dot, representing satellite position one minute prior to the head-dot position, should be replaced by a solid line generated by the stroke-writing technique. While this random-scan method of presenting information was rejected in order to eliminate hysteresis errors in deflection, recent technical improvements in display hardware and other considerations render more attractive the random-scan approach with stroke writing of lines.

3. The orbit, painted as 128 or fewer dots approximating a smooth curve, was not satisfactory. As is apparent in Fig. 3, the 4° quantization error in position of each dot led to a portion of an orbit* being represented as two parallel lines of dots. This compromise permitted circuit economy in generating orbit video for the TV raster. However, use of a random-scan display would lead to a simplified orbit store and permit stroke-writing of lines joining precisely located orbit points.

4. The area-of-view circle in the polar region (Fig. 5) was suitably approximated by an octagon, although some dots were spaced rather far apart. Simpe circuit modifications (14, 15) would permit generation of a polygon of 12, 16, etc., sides. However, such an improvement is not warranted in view of the objectionable discontinuities in the longitudinal direction seen in Fig. 4. These discontinuities are a feature of the imperfect correction for convergence of meridians which takes place as the circle approaches either pole.

Tabular Printout

The page printer would print the fine-grain position and other data (line two of the tabular printout) in seven seconds. In order to limit the waiting time to this value, the label line

Tabular Printout

SPTR	CATEGORY	MO	DA	HR	MN	SC	LATIT	LONGIT	HEIGHT	AREA	AZ	EL	TN
1234	USA NAV	12	20	16	30	05	32.5N	158.3W	12,355	1503	255	47	10

*The figure-eight shaped orbit represents a synthetic synchronous satellite having a large inclination angle.

for the following tabular printout was immediately written in a succeeding seven-second interval, with the computer interleaving character printing and position predicting. This label-line interval could have been omitted by use of an optical overlay.

It is obvious that a tabular readout device can be made to present any information (expressible as an alphanumeric) which the computer can either compute or store. Thus, the format of the tabular printout is intended to illustrate the versatility of SPAD. The Spacetrack number* would certainly be needed, and one can imagine a need to "freeze" time and values of fine-grain position for further use, while the geographic display proceeds to make subsequent predictions. The antenna pointing angles labeled AZimuth and ELevation were printed merely to show that the computer can generate this information; in practice the data would probably be used to slew the antenna automatically until lock-on occurs, should this slewing feature be needed.

The teleprinter used to provide the tabular printout has the advantages of low cost, ready availability, and being remotely locatable. The need for hard-copy output remains to be established. The teleprinter has the disadvantages of being noisy, bulky, and slow.

Updating Orbital Elements

SPAD predictions are based on values of orbital elements and related variables placed in computer memory at suitable intervals. As certain orbits decay, these values will vary somewhat with time and hence will need to be refreshed at intervals of perhaps a week. This interval is tentative; further study is needed to determine doctrine for the various decaying satellites. Problems involved in the preparation of orbital elements in the SPAD format for shipboard predictions are discussed in two NRL memoranda for file (26, 27), as well as in Appendix A of Ref. 9.

In the absence of the updating message, prediction and display can continue but with degraded accuracy for decaying orbits. However, accurate predictions far in the past (or future) are possible provided orbital elements are available for the time of interest.

Position Prediction Error

While preliminary performance data are given in Ref. 7, a more complete discussion is found in Appendix C of Ref. 9. There the importance of taking $\dot{a}$ into account is emphasized. Now $\dot{a}$ is the temporal rate of change of the semi-major axis and may be expressed in earth radii per day (er/d). For SPADAT satellite No. 632 with $\dot{a} = -10^{-3}$ er/d (a value corresponding to a decaying satellite), the maximum error in latitude and longitude at a prediction time of nine days from epoch was 1.1° and 1.9°, respectively. In this nine-day interval the average position error was 0.4° and 0.5°, respectively.

The design objective proposed in Ref. 1 provided for a maximum combined prediction and display error of 1°, with updating of the orbital elements at weekly intervals. At a prediction time of six days after epoch, the same decaying satellite had maximum prediction errors of 0.7° and 1.1° in latitude and longitude, respectively. These errors were found by comparing the tabular readout with the ephemeris prepared by the U.S. Naval Space Surveillance System (SPASUR).

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*The Spacetrack number is a number permanently assigned to identify an individual orbiting object. This has been superseded by the five-digit SPADATS number of the Space Detection and Tracking System of the North American Defense Command (NORAD).

IMPROVED VERSION OF SPAD

In the absence of a formal requirement for a dynamic satellite display similar to SPAD, it is difficult to offer firm opinions as to what a second-generation version of this satellite display should be like. The following discussion is based on the assumption that, in general, the "black box" capabilities of SPAD as previously described are to be retained. Thus, attention is directed toward how various design approaches will affect equipment complexity, display accuracy, and computer time-sharing.

Three possible design approaches will be considered here. These are:

a. Repackage SPAD, retaining display formatter (not recommended)

b. A random-scan general purpose display driven by a general-purpose digital computer

c. A random-scan display using NTDS display and time-shared computer.

Repackaged SPAD

As SPAD was being designed, constructed, debugged, and operated, certain ideas for improvement were placed in a loose-leaf notebook entitled "SPAD: 20-20 Hindsight." These ideas involved minor changes in function and extensive packaging changes which would lead to major improvements in size, weight, and power while retaining the concept of a buffer store between computer and display which would generate a TV display raster.

Further study indicated that many circuits in the display formatter could be eliminated if the raster scan used in painting positions was deleted, and if the random-scan feature used for painting symbol groups was augmented to paint all information. It appeared that state-of-the-art improvements in deflection yokes and amplifiers would make it feasible to delete the raster scan and use only random scan in the display, as there would now be negligible hysteresis effect in magnetic deflection.

Since the original SPAD had a display frame rate of about 30 frames per second, with a random-scan duty cycle of about 20 percent for painting all symbol groups, it is evident that significant time economies are possible with an all-random-scan display. Conversely, this would permit a slow-speed deflection system, with resultant economies in cost and power. In either case, map information would likely be provided by means of an optical overlay rather than by electronic mixing. This conclusion suggests that the computer could drive the display directly with no intervening formatter.

Repackaging of SPAD is not recommended.

Random-Scan Display

Factors relevant to driving a random-scan satellite display directly from the prediction computer are discussed in Ref. 11. Such a computer could be the AN/UYK-3 general-purpose digital computer with the BR-141 input/output controller. Since the programming of the AN/UYK-1 (used with SPAD) is compatible with the AN/UYK-3, much of the original SPAD program could be used with this higher speed computer. Equipped with the optional 32,768-word memory, this computer could predict satellite positions on a time-shared basis.

A suitable commercial display console is the model M10000 Dualflec display manufactured by Information Displays, Inc. A special computer control panel would have to

be added to this console. While its logical complexity would be roughly equal to that for the SPAD counterpart (subject to any change in operational capability), modern construction techniques would permit a striking reduction in power and size.

Other combinations of commercially available computers and displays are doubtless possible. A conventional cathode-ray tube can be used, as there are many schemes for generating characters which do not use the shaped-beam method that happened to be used in SPAD. In any case, a tabular printout device would be needed.

NTDS Adapted for SPAD

A preliminary feasibility study (13) reveals that with suitable computer programming a Naval Tactical Data System (NTDS) display and computer can be used to implement the SPAD function. If the computer is already worked to capacity, it may be necessary to bump a low-priority unit of the total program so that the computer can predict satellite positions for the minutes or hours that such information may be required. While the computer is also performing tasks on a time-shared basis, an NTDS console switched to the SPAD mode will display satellite information received directly from the computer.

Two advantages of the NTDS version of SPAD are: (a) the satellite display feature can be added to an existing system without adding new hardware, providing an NTDS display console can be time-shared; (b) a separate tabular printout device is not needed, as this feature is part of the NTDS display console. (No hard copy is available, however.)

A disadvantage of the NTDS version of SPAD is that some modifications to the display console are desirable to make the display more acceptable from the human-engineering viewpoint. However, the equipment can be used essentially "as is" to demonstrate the SPAD concept.

The NTDS approach would seem to be a convenient and inexpensive way to further study the SPAD concept, since the equipment problem then becomes essentially a software problem.

"Ideal" Version of SPAD

While it would be reasonably convenient to produce any of the above improved versions of SPAD, each has some characteristic which renders it somewhat less than ideal. While a complete description will not be attempted, an ideal satellite display, unhampered by fiscal consideration, would likely include the following features:

a. Operational features essentially as described above

b. Display console, computer control panel, and tabular printout designed just for the task

c. Satellites to be identified by the permanent SPADATS number, rather than by the present arbitrary two-digit track number

d. World map geographic detail (including poles) to be provided by optical overlay, e.g., via rear projection port in a crt

e. Geographic display to employ random scan, with circles, vectors, and orbits appearing as broken line segments

f. Accelerated time predictions to be made with a cycle rate of about four per second, with time varied forward and backward up to perhaps 3600 times normal.

DESIGN DECISIONS

It will be evident from the foregoing discussion of SPAD and other possible configurations for a dynamic satellite display that there are a number of design decisions which will greatly influence the cost, complexity, and capability of the display. These design decisions and their implications will now be reviewed.

Is a Dynamic Display Worth the Cost?

While some satellite displays are available at comparatively low cost, their speed and versatility are likewise low. On the other hand, a device such as SPAD provides a notable improvement in performance but at such a price that one must ask, "Is a dynamic display worth the cost?" This can be answered only in terms of a formal display requirement, and further discussion is beyond the scope of this report.

Where Should Positions be Computed?

In spite of the duplication of computer facilities, there are advantages to predicting satellite positions as required at the user site, using orbital elements and related information. With this approach, SPAD is able to remain in operation (but with degraded accuracy) even though the orbital elements are not updated at regular intervals. Furthermore, temporal variations in values of these elements can be compensated for from orbit to orbit.

Prior to SPAD, predicted satellite positions were computed by one central sophisticated computer. The predicted-position message included representative points which the user would (either mechanically or electronically) plot to form an orbit template. This template would then be displaced in longitude according to a selected equator crossing taken from the data message. The position at the desired time was found by interpolation, using the time elapsed since crossing for the several points on the template. This procedure provided reasonable accuracy for well-behaved satellites but led to serious position errors when the orbital elements varied with time during the week between updating messages.

It is concluded that positions should be computed at the user site, using orbital elements and related information. The orbital element message used in such computation should be prepared in the SPAD format (see Refs. 9, 26, and 27) prior to transmission to the user. This preparation would require a change in doctrine at the SPASUR station.

Satellite Repertoire

If one includes the space debris (e.g., expended booster stages), there are now many hundreds of orbiting objects. The number having immediate significance may be more than the 100 suggested for the SPAD user. The repertoire is readily altered at any time by feeding a new data tape into the prediction computer. At the procurement level, the repertoire can be augmented by selecting a computer having adequate speed and memory capacity.

Questions involving satellite repertoire can be answered only after a firm operational requirement is established.

Selecting Satellites for Display

While the decision to present no more than 11 satellites at once on the SPAD geographic display was quite arbitrary, it could readily be changed by design. When time

was varied at an accelerated rate, it proved to be difficult to watch so many rapidly moving targets at once. However, the category selection and individual satellite selection and deletion switches made it convenient to reduce or otherwise alter the selection. It is recommended that these features be retained.

A subject worthy of further study, however, is the matter of how to categorize satellites. The SPAD category matrix was selected to demonstrate the versatility of SPAD. Design of this matrix should be reexamined when firm display requirements have been formed.

The question of how to select satellites for display should have little practical effect, however, on equipment complexity and computer programming.

Display Scan Technique and Display Formatter

Use of a TV raster for SPAD led to the need for a display formatter which accepted and stored all computer output data as it was generated each 1.1 sec (approximately). The formatter then presented this information to the display at about 30 frames per second (to avoid flicker in a conventional display). As has been discussed, the formatter could have been greatly simplified had the TV raster been eliminated and an all-random scan scheme used. With random scan, only those areas are scanned where information is to appear. Thus, periodic sweep waveforms are eliminated, and the display is successively connected to each store containing position, vector, and symbol information, etc. Since a computer-driven display is designed for such service, these stores which comprise what is left of the formatter can be conveniently located in the computer. Thus, the computer has the additional duty of presenting the contents of these stores to the display once each scan interval, while updating the stores at less frequent intervals.

It is recommended that a modern, random-scan, computer-driven display be used, since with modern deflection circuits the errors in deflection are acceptably small.

Prediction Rate, Display Rate, and Fast Time

For real-time prediction and display, each position need be computed only every five seconds or so to avoid excessive updating error in position. Thus, it would seem adequate to provide a storage-tube type display which would need to be refreshed only at the prediction cycle rate. (This assumes a constant prediction cycle rate under all conditions of use.)

The preceding "slow" approach is not compatible with the need for fast computer cycling and display frame rate when the computer is predicting in accelerated time. Until the question is decided by experiment, a fast-time prediction rate of perhaps 4 cps is suggested. A storage-tube type display could still be used, providing the erasure could be adjusted to avoid symbol smear and providing the resolution was acceptable (Ref. 3, Table 1). However, for reasons too involved to be considered here, the practicability of using a storage tube to save on computer time requires further study.

Orbits, Velocity Vectors, and View Areas

As has been stated, display appearance would be improved by use of solid lines to represent orbits, velocity vectors, and periphery of the view areas. Such solid lines cannot be satisfactorily approximated by means of the conventional display raster, whereas the modern computer-driven display is designed to generate these features by stroke-writing. Thus, the use of the random-scan technique leads to a display of improved appearance.

Tabular Readout Display and Hard Copy

While experience with SPAD has established the feasibility of providing a tabular readout of ancillary information regarding a selected satellite, an operational requirement must specify content, format, and need for hard copy. While the state of the art will permit design of a fast, quiet device with hard copy available only on demand, the cost will be much higher than that of the standard but large, slow, and noisy page printer used in SPAD. Thus, the cost of the preferred device must be weighed in terms of its need.

Computer Time Sharing

The question of time sharing the prediction computer among SPAD and other required functions would seem to be a matter of logistics. Technically, the time sharing is feasible. Probably it will be considered desirable as a relatively inexpensive and convenient way to provide the satellite prediction function.

CONCLUSIONS

Experience with a research version of SPAD has shown that it is technically feasible to construct a dynamic satellite position prediction and display equipment exhibiting great flexibility in presenting information on selected satellites at arbitrary times. The performance of SPAD has substantially met the requirements which were tentatively suggested for such a satellite display. However, the cost and complexity of a dynamic satellite display are such that these two factors must be considered carefully when a formal operational requirement is established.

The following detailed conclusions are necessarily tentative and are subject to the assumption that an operational satellite display should perform substantially as did SPAD. The conclusions are based on experience with SPAD and on study of other possible approaches.

1. Predicted satellite positions should be computed at the user's location, using orbital elements so that prediction can continue even with stale data.

2. Such computation is best done by digital techniques, rather than by the hybrid computer originally proposed for SPAD.

3. Adequate accuracy in predicting positions is achieved when calculations take into account orbital decay, as was done for SPAD predictions.

4. While an operational evaluation was not conducted, it seemed to be satisfactory to show predicted positions on a geographic display as subsatellite points on the earth's surface, together with such reference information as map grid lines and some geographic details such as continental outlines.

5. The viewer should have a choice of a world map or an expanded display. The size of the expanded display for SPAD was satisfactory.

6. Although time did not permit addition of a map overlay, the most satisfactory choice for the world map display appears to be a modified cylindrical equal-spaced projection which includes the poles as straight lines of finite length. While a map overlay for the expanded display would be desirable, it is concluded that this is technically not now feasible.

7. Use of two dots to represent head and tail of the ground-speed vector was not satisfactory; a solid line is preferred.

8. Use of a series of dots to represent an orbit was not satisfactory; a solid line is preferred.

9. The area of view circle was not satisfactory where abrupt longitudinal discontinuities were used to compensate for convergence of the meridians near the poles. In general, the use of a raster to paint lines is not desirable and use of stroke generator techniques is aesthetically more pleasing.

10. It was satisfactory to identify satellite positions on the geographic display by means of alpha numerics depicting height, category, and SPADATS number. Any of several conventional techniques for generating alpha numerics would be suitable.

11. The satellite track number (an arbitrary number assigned automatically as the satellite is placed in computer memory) proved to be a somewhat confusing way to designate an individual satellite. It should be replaced by the permanent SPADATS number.

12. It appeared to be desirable to have the adjacent tabular readout display to provide additional information for a given satellite. While the time delay and noise of the mechanical printer used for SPAD were just tolerable, use of a faster and quieter machine would be desirable.

13. The procedure used for designating satellites both individually and by category was satisfactory, with the computer and display providing prompt response.

14. The procedure for designating and varying prediction time was generally satisfactory. However, for the great majority of satellites (excepting those in synchronous orbit), there was no need for varying accelerated time as fast as 3600X.

15. The capability for varying time forward and backward at an accelerated rate proved to be valuable in answering such questions as when any communication satellite will be above the radio horizon for a given ship location.

16. The video inhibit buttons were useful in resolving such ambiguities as those caused by overlap of symbol groups, juxtaposition of two velocity vectors, etc.

17. The formatter, which acted as a buffer between computer and display, can be greatly simplified if the display employs random scan rather than raster scan.

18. The SPAD concept can be implemented using the NTDS computer and display on a time-shared basis. While this can be done with no major equipment alterations, such a configuration involves some compromise from the human-engineering viewpoint.

19. A more desirable equipment configuration would involve a display and computer control panel designed or adapted just for the SPAD function.

20. Should it be important to minimize the time the time-shared computer spends on the SPAD function, a buffer store and display formatter should be included between the computer and the display, as was done at NRL. The computer would then be needed only once in perhaps five seconds to update the satellite positions in real time. For operation with accelerated time, the updating rate should be perhaps four new predictions per satellite per second. The formatter would refresh the display at, say, 30 frames per second.

21. While use of a direct-view storage tube could permit reduction of the display frame rate to equal the data updating rate, with consequent circuit or time economies, it is

concluded that the resultant display smear due to symbol overlap could easily result in an untidy display.

RECOMMENDATIONS

The following recommendations for a dynamic satellite position prediction and display equipment similar to SPAD may need to be re-evaluated when a formal operational requirement is established. Thus, the recommendations as well as the preceding conclusions must be regarded as tentative.

1. A satellite display should be based on predictions made at the user's site, using orbital elements and related information so that operation can continue in the event periodic updating information is not received.

2. The SPAD prediction equations should be used, since they are relatively simple and provide reasonably accurate predictions by using the $\dot{a}$ term (rate of change of semimajor axis of orbit) to compensate for orbital decay.

3. The geographic display should provide for both a world map display and an expanded display, with either mode being presented as required.

4. The world map display should provide geographic information in the form of a modified cylindrical equal-spaced projection by some means that eliminates parallax error. (Thus, the edge-lighted optical overlay planned for SPAD should not be used.)

5. Design of the geographic display should permit the viewer to inhibit video so that one can resolve such ambiguities as that caused by overlap of symbol groups, etc.

6. A random scan display is recommended over one employing raster scan in order to simplify the formatter.

7. For overall efficiency in system planning, satellite predictions should be made by means of a general-purpose digital computer which is electronically time-shared among several shipboard functions. (Thus, the hybrid, special-purpose computer originally proposed for SPAD should not be used.)

8. There should be provision for manually varying the prediction time both forwards and backwards at a variable accelerated rate up to perhaps 360 times faster than real time.

9. To eliminate operator error, circuit design and computer programming should provide for automatic counting of months and years as time varies.

10. Most of the features of the SPAD computer control panel should be retained to provide display flexibility. Features of limited value which can be deleted involve the PRECISION SELECT and DELAY CATEGORY INTERRUPT buttons described in Ref. 7. Individual satellites should be designated by means of the permanent SPADATS number rather than the randomly assigned track number of SPAD.

11. A tabular readout display adjacent to the geographic display should provide precisely computed positions and other information as may be specified by the operational requirement yet to be produced.

12. When an operational requirement is prepared, consideration should be given to the following questions:

- How many satellites can an operator watch in a meaningful way, and how fast can this group be moving across the display?
- What information should be presented by the tabular readout device, and in what format?
- What is the optimum fast-time prediction rate?
- Is hard-copy readout required?
- Should predicted data be used automatically, say to slew an antenna for acquisition of a communication or navigation satellite?
- How often is it necessary to update values of the orbital elements for decaying satellites?

13. Doctrine at the SPASUR station should be changed to permit the satellite updating message to be prepared in the SPAD format prior to transmission to the user.

14. The questions raised in recommendation 12 should be studied in an operational environment. For this purpose, it is recommended that the SPAD concept be implemented using the NTDS computer and display on a time-shared basis with no major equipment alterations (13). This approach will save time and money, but involves some compromise from the human-engineering viewpoint.

15. For a service version of SPAD, use of a modern computer-driven display is recommended, with display and computer control panels being designed or adapted just for the SPAD function.

16. It is further recommended that a buffer store and display formatter be included between the time-shared computer and the SPAD display, so that the computer need be utilized only once in five seconds to update the satellite positions in real time. For operation with accelerated time, the updating rate should be perhaps four new predictions per satellite per second. The formatter should then be used to refresh the display at, say, 30 frames per second, thus freeing the computer for other tasks.

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13. ABSTRACT

A satellite position prediction and display device (SPAD) has been conceived, constructed, and operated at the Naval Research Laboratory. Experience with the research equipment has shown that it is technically feasible to implement the SPAD concept in several ways, using a digital computer for prediction and using both a geographic display and a tabular readout to present predicted positions of selected satellites at arbitrary times.

Other conclusions include the following. Predicted satellite positions should be computed at the user's location, using orbital elements and orbit decay information so that prediction can continue even with stale data. The general features of the SPAD computer control panel should be retained, since they provided a great deal of flexibility in presenting predicted positions at arbitrary times for a number of satellites selected either individually or according to category, as fast as such information was requested of the AN/UYK-1 computer.

Such flexibility and speed was achieved at the expense of equipment complexity. It is difficult to assess the merit of achieving this performance in view of the attendant expense, since there is no known operational requirement for a shipboard prediction and display device similar to SPAD.

This discussion leads to the following tentative recommendations. For further system studies, the SPAD concept should be implemented on an NTDS-equipped ship, using the Naval Tactical Data System computer and display console on a time-shared basis. Thus, with some sacrifice in operator convenience, SPAD design becomes essentially the software problem of programming the NTDS computer and reassigning functions to the controls and indicator lamps on the NTDS display console. This modest investment using available hardware will facilitate further studies to provide answers to such questions as how satellites should be categorized, how many can be viewed at once, how fast should accelerated time be varied, the need for hard-copy readout, and what information and format is needed for the tabular readout display.

For a service version of SPAD, use of a modern computer-driven display is recommended. For system efficiency, the computer should be time-shared among several functions. Doctrine at the SPASUR station should be changed to permit the satellite updating message to be prepared in the SPAD format prior to transmission to the user.

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