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By

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USE OF ARTIFICIAL EARTH SATELLITES FOR TERRESTRIAL NAVIGATION

by

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Navigation can be defined as "the process of directing the movement of a craft from one point to another, or of determining the position and heading of a craft at any time." The term is derived from the latin words "navis" meaning "ship" and "agere" meaning "to move" or "to direct". In modern usage the term applies to any type craft, whether its natural habitat is land, water (either surface or subsurface), air, or space. Navigation normally involves position, direction, and distance (or speed and time).

Position is maintained by advancing a previous position for assumed values of direction of motion and distance traveled (usually by means of the velocity vector and time, where no acceleration is involved). The position so determined is corrected from time to time by an independent determination utilizing aids external to the craft. Such an independently-determined position is called a <u>fix</u>.

Direction measurement involves determination of a reference direction (generally true north or magnetic north), and the angular difference between this direction and the desired direction, usually the heading of the craft or the direction of its motion.

Distance may be measured directly, or indirectly by means of speed and time.

It is convenient to classify all methods of navigation as one of the following:

<u>Dead reckoning</u>, involving the extrapolation forward of the anticipated movement of the craft.

<u>Piloting</u>, involving the use of objects, identifiable points, or geophysical patterns external to the craft, position being determined relative to the features used.

<u>Celestial navigation</u>, utilizing celestial bodies to mark points on an imaginary celestial sphere at an infinite distance from the craft. Position on the earth is determined relative to those terrestrial positions directly beneath these points; that is, those places on earth at which the celestial bodies are in the zenith.

A number of methods and techniques of navigation have evolved over the centuries, reflecting varying requirements and capabilities. No one method meets all requirements of all types of craft. Specifically, the deficiencies of conventional methods include the following:

Dead reckoning in any form, including the most modern, sophisticated Doppler and inertial, degrades with elapsed time or distance traveled, or both.

Optical piloting is limited by visibility and availability of landmarks or aids to navigation, as well as a need for a prior survey.

Radio piloting is limited by large variations in accuracy due to land configuration, diplomatic considerations, siting problems, vagaries of propagation through the atmosphere, divergence of position lines, and logistic problems. A multiplicity of systems throughout the world increases the requirements for user equipment and training, and complicates the traffic control problem. Ground stations are expensive to construct, expensive to operate, subject to damage by storm or enemy action, and vulnerable to countermeasures and sabotage.

Geophysical pattern matching, utilizing the topographic features or the pattern of geophysical data such as geomagnetism or gravity, is not presently available except in a crude form and will require such an extensive survey effort as to be prohibitive except in special applications in certain priority areas.

Optical celestial navigation is limited by weather and horizontal refraction (dip) problems. This is true, also, of celestial-monitored inertial navigation.

Radio astronomy utilizing radio stars requires antennas too large to be practical aboard ship or in the air.

Studies made by responsible groups during the last two decades indicate increasing requirements for accuracy and a speed of obtaining a navigational fix.

The International Meeting on Marine Radio Aids to Navigation (IMMRAN), meeting in 1947, stated that an error of 1% of the distance from the nearest danger, for distances greater than 50 miles, would be acceptable, and that such a fix should be obtained within 15 minutes from the time of measurement of data.

Ten years later, in July 1957, Special Committee 30 of the Radio Technical Commission for Marine Services (RTCM) considered five miles an acceptable error at sea, and five minutes an acceptable time for obtaining such a position.

In December of the same year, the RTCM Special Committee 35 stated an immediate requirement for one to two mile accuracy for most purposes of navigation, with one to ten minutes being reasonable under different conditions. It also stated an "ultimate" requirement (after 1975) for 0.1 mile accuracy, or better, available continuously.

The long-distance accuracy requirements for air navigation decreased even more spectacularly during the same period. In 1945, an accuracy of 15 to 20 miles was considered normal, with larger errors being encountered frequently.

On May 8, 1956, the Radio Technical Commission for Aeronautics (RTCA) issued its paper 92-56/EC-288, which stated an enroute accuracy requirement of 1,000 feet for helicopters. In 1957, the Air Coordinating Committee (ACC) document 58/9.1 stated a general requirement of three miles for 95% of the readings, and an "ultimate" objective of providing "exact" position fixing under any conditions.

These various studies, plus recent statements by responsible government agencies, indicate the need for a universal all-weather navigation system of higher accuracy, with less time lag in obtaining a fix, than is now available with global coverage.

The system should preferably serve both air and marine requirements, as well as those of land vehicles operating in remote areas such as deserts or polar regions. For wide acceptance by commercial users, the system must be reliable, moderate in cost of user equipment, and of sufficient permanence and stability to encourage the expenditure of funds needed for acquisition of suitable user equipment.

Improved navigation can reasonably be expected to increase efficiency of operation of all types of ships and aircraft by saving time now required to correct navigational errors and to allow greater margins of safety in passing obstructions. In addition to the savings by faster passages, merchant ship operations would benefit from better maintenance of schedules and avoidance of overtime and idle paid time of stevedores. Better navigation is particularly needed when a vessel approaches landfall after several days at sea.

Commercial fishing vessels can improve their economic situation if they can return expeditiously to favorable fishing areas, often of small extent.

The practicability of extensive commercial ship operations in the arctic depends, in part, upon the availability of better navigation in an area where aids to navigation are few in number and difficult to maintain, shore-based electronic systems are somewhat less reliable than elsewhere, celestial navigation is unavailable or uncertain for extended periods of time, and both magnetic and gyro compasses are of reduced reliability.

Oceanographic and hydrographic survey vessels need more reliable, all-weather, accurate navigation if they are to meet the requirements now being imposed upon them.

Cable-laying vessels, ocean weather stations, ice patrol craft, offshore drilling rigs, and radiation waste disposal vessels all require accurate navigation for efficient performance of their assigned tasks.

Of considerable significance is the possible increase in safety by a reduction in the danger of collisions and groundings and by an improvement in the efficiency of search and rescue operations. In 1961, 32 vessels of 500 gross tons and upward were a total loss due to stranding, and 922 were damaged. During the same year, seven ships of 500 gross tons and upward were lost due to collisions, and 1621 were damaged. Strandings accounted for 42.0% and collisions for 12.6% of all total losses during the five-year period ending in 1961. Better navigation could be expected to materially improve the situation.

The present air traffic separation requirements over the North Atlantic are 120 miles laterally, half an hour along the track, and 2,000 feet vertically (above 29,000 feet). Because of the popularity of some arrival and departure times, insufficient air space is available to accommodate all traffic that desires to use the space. With increased navigation accuracy this condition could be improved significantly.

A recent comprehensive study conducted for the Maritime Administration indicates the need for better navigation if automatic or semiautomatic ship operation is to be achieved.

Land vehicles operating in remote areas have a problem in determining position where stable, identifiable, charted landmarks are not available.

If previous experience in other new ventures is a valid guide, additional benefits that cannot be identified at this time can reasonably be expected to follow any significant improvement in navigational accuracy.

The use of artificial earth satellites for navigation is justified to the extent to which this will significantly improve the situation at a cost that is economically practical. The probability of meeting these requirements now appears reasonable.

Desirable characteristics of a navigation satellite system will include the following:

1. Global coverage by one system.

2. All-weather capability.

3. Minimum interval between fixes, or continuous fixing capability.

4. Maximum accuracy, considering all sources of error.

5. Uniformity of accuracy, independent of position with respect to geography or the path of the subsatellite point.

6. Minimum time lag between the time of the fix and availability of the information.

7. Employment of a technique familiar to the typical user, or easily understood by him.

8. Computational requirements of minimum complexity met easily by the navigator or an inexpensive computer.

9. Maximum simplicity of antenna requirements.

10. Minimum maintenance requirements of user equipment, permitting operation over long periods of time with little or no maintenance.

11. Minimum cost of user equipment.

12. Minimum obsolescence of user equipment.

13. Maximum stability of technical characteristics with minimum vulnerability to changes.

14. Freedom from saturation of system by a large number of users.

15. Maximum user acceptance.

16. Maximum alternate capability, permitting useful information to be obtained, for example from the sun, if navigational satellites are unavailable for any reason, such as failure or malfunction of components. With alternate capability, fewer satellites may be needed.

17. Minimum succeptibility to electronic interference.

18. Versatility of user equipment specifications, permitting use of the same satellites by a variety of user equipment to meet different requirements.

19. Suitability for use by all mobile units.

20. Minimum dependence on ground installations such as injection station, computer centers, and tracking stations, with ability to provide useful information over a maximum period during which some or all ground facilities may be unavailable.

21. Minimum tracking requirements, as to station numbers, dispersal, and complexity.

22. Maximum stability of orbit, permitting prediction of future positions of the satellites over a long period of time and simplifying the distribution of orbital or ephemeridal information to users.

23. Maximum useful satellite life, which depends upon the number, complexity, and reliability of satellite components.

24. Minimum number of satellites required, based upon coverage per satellite per unit time (hour).

25. Minimum development costs.

26. Minimum operating cost of system, including cost of replacing satellites and maintaining and operating fixed ground installations.

27. Freedom from adverse affects of user craft velocity.

28. Freedom from adverse affects of antenna motion due to roll, pitch, yaw, etc.

29. Bonus features such as time signals and measurement or indication of true north, roll, pitch, and position between fixes.

30. Potential additional applications, as for geodesy and surveying.

31. Maximum economy of spectrum utilization.

Ten separate techniques and a comparable number of major variations have been investigated. Many of these are considered impractical or having disadvantages clearly outweighing advantages. The following techniques are considered of more than academic interest:

Elevation angle. The elevation angle technique involves measurement of the altitude (elevation angle) of the satellite above the horizontal, using a modified radio sextant. The satellite serves the same purpose that a natural celestial body does in ordinary celestial navigation, except that radio signals in the gigacycle region are used instead of optical frequencies. Each measurement provides a small circle line of position. Orbits at any height can be used. A line of position could be obtained at any time that the satellite is above the horizon, and a fix after a suitable change in azimuth of the satellite, or by observation of two or more satellites. Computations can be performed by celestial sight reduction tables commonly used by navigators, or by a simple computer. A fix might also be obtained by simultaneous observation of altitude and its first time derivative. A simple computation would produce two orthogonal lines of position. However, advanced integrating techniques would be required, and the time needed to establish rate of change of altitude with sufficient accuracy may be comparable to that needed for a simple running fix if the satellite were not more than a few thousand miles from the surface of the earth. An advantage would be that the effect of a constant error in the reference level would be nullified. The essential satellite components for the elevation angle technique are a CW transmitter, a power source, and an antenna. Orbital or ephemeridal data could probably be disseminated by printed almanac months in advance. Radio sextants designed for use with the sun could be used with satellites after minor modification. The technique would probably be applicable in aircraft if some reduction in accuracy were acceptable. However, radiometric or other advanced techniques for determining the horizontal in flight may reduce the error in the aircraft application.

Advantages of the elevation angle technique include the following:

1. All-weather, global coverage can be provided with essentially uniform accuracy everywhere and at any time.

2. The technique is familiar to the navigator, enhancing his acceptance and utilizing his ability to interpret results.

3. User equipment can be provided with capability for using both the sun and satellites, increasing the usefulness of such a system and decreasing its vulnerability to malfunction.

4. The technique is capable of providing accurate directional (north) reference.

5. Coverage per unit time per satellite can be relatively extensive.

6. Stable orbits can be used, minimizing dependence on ground installations and reducing the complexity of satellite components.

7. Computational requirements are modest.

Disadvantages of this technique include the following:

1. A stabilized directional antenna of the order of one meter in diameter would be needed by the user for high accuracy.

2. Because of the distance of the satellites in optimum orbits, of the order of 5,000 miles, satellite power requirements would be relatively large.

3. An accurate time standard is required.

Horizontal angle. The horizontal angle technique involves the measurement of azimuth (horizontal angle) of the satellite at various times during a pass. Each such measurement provides a great circle line of position. Two such measurements separated by enough time to permit sufficient change of azimuth to provide a wide crossing angle of the two lines of position would provide a fix. A third measurement would provide a check on results. Adjustment would be needed, of course, for any motion of the observer between observations. A fix could also be obtained by observation of two satellites, by simultaneous observation of altitude and azimuth, or by simultaneous observation of azimuth and its first time derivative. The line of position resulting from the rate of change of azimuth measurement would not always be orthogonal to the azimuth line. For high accuracy, a stable platform would be needed, but its accuracy could be somewhat less than with the elevation angle technique. An error in the reference azimuth (north) would be reflected in the position. With several observations, the error could be removed by adjustment of all azimuth lines to make them cross at a point, if allowance were made for motion of the observer between observations. Orbits at any height might be used.

Advantages of the horizontal angle technique include the following:

1. All-weather global coverage can be provided with essentially uniform accuracy everywhere and at any time.

2. The technique is familiar to the navigator.

3. Satellites at virtually any height might be used.

4. Coverage per unit time per satellite can be relatively extensive.

5. Computational requirements are modest.

Disadvantages include:

1. A stabilized directional antenna would be needed.

2. A reference (north) direction indicator with high short-term stability would be required.

3. An accurate time standard is required.

Range. The range technique involves the measurement of distance between the observer and the satellite. Each measurement produces a small circle line of position. Two such measurements separated by a sufficient change in azimuth to provide a wide angle of intersection of the lines of position are sufficient for a fix but with ambiguous positions on opposite sides of the track of the satellite. A third measurement would provide a check and remove ambiguity if a high-inclination orbit were used. Several measurements could be used to eliminate a constant error in the range measurements.

Several methods of measuring range might be employed. For example, a transponder in the satellite might be interrogated by the user, the elapsed time from transmission of the interrogating signal to reception of the return signal from the transponder being an indication of distance. Reflected signals without a transponder could be used if enough power were available, or synchronized clocks could be maintained in the satellite and the user craft; the time of reception of a signal transmitted at a predetermined time at the satellite would be a direct indication of distance. A variation would be to make the comparison by phase difference instead of direct measurement of time of travel of the signal. The maintenance of adequate synchronization of the clocks or phase relationship would be a problem of considerable magnitude. It might be accomplished by setting the clock or frequency standard of the user to agree with that in the satellite when the distance between the satellite and user was known accurately. An error of one microsecond in time interval measurement would introduce an error in distance (range) measurement of about 300 yards.

An interesting variation of the range technique is to use a number of cooperating ground stations located throughout the world. These would relieve the mobile stations of the requirement of carrying any but the simplest equipment, and of computing the fix following observations. The ground stations would have available the latest information on the position of the satellite, either through direct tracking, or by communication from tracking stations, and would determine by direct measurement the distance of the mobile station from the satellite. By a method of sequential interrogation, difficulties relating to multiple response problems might be minimized. Such a technique could provide suitable shore installations with current or recent positions and velocity vectors of all suitably equipped ships and aircraft, as an aid to search and rescue operations in the event of an emergency. It might even be used to provide home offices of steamship companies and airlines with information on the locations of all their craft throughout the world.

<u>Advantages</u> of the range technique include the following:

1. Global, all-weather coverage is possible.

2. The technique is particularly promising for use by aircraft.

3. The basic technique is simple and familiar to navigators.

4. Coverage per unit time per satellite for the optimum orbit of the order of 1,000 miles is good.

5. A relatively simple receiving antenna is adequate.

<u>Disadvantages</u> include the following:

1. With the transponder method, the technique is subject to saturation and multiple response problems, unless cooperating ground stations are used.

2. The technique has relatively poor spectrum economy.

3. An accurate time standard is required.

<u>Range rate</u>. The range rate technique involves measurements of the rate of change of distance (range) between the observer and the satellite during a pass. This might be accomplished directly by any method of measuring

range, or indirectly by utilizing the Doppler effect resulting from the motion of the satellite relative to the observer. For maximum accuracy measurements should be continued throughout an entire pass of the satellite. With some reduction in accuracy, position might be established by a relatively small number of points of the curve of received frequency versus time. A computation of some complexity would be needed for any method of using the range rate technique. With four satellites in circular, polar orbits at a height of about 600 miles, a fix should usually be available at approximately 110-minute intervals; oftener in high latitudes. However, passes near the zenith and at low altitudes would provide some positional information but not satisfactory fixes.

Errors would be introduced by uncertainties in satellite position, frequency standard errors (in the Doppler or phase comparison method), propagation effects, and uncompensated motions of the receiving antenna. Because of the low orbit required for high accuracy with this technique, a new orbit determination would be required once or twice daily. The orbital parameters might be transmitted from ground stations to the satellites, which would store the information and transmit new orbital parameters at frequent intervals. Refraction errors could be minimized by the use of two frequencies, preferably harmonically related, thus increasing the accuracy of the positional fixing.

Advantages of the range rate technique include the following:

1. The technique is capable of providing all-weather global coverage.

2. Reduced-accuracy single-frequency user equipment could probably be produced at moderate cost.

3. A simple omnidirectional receiving antenna is adequate.

Disadvantages include the following:

1. The relatively low orbits required with this technique produce problems in orbit prediction, ground coverage, ground support systems, and dissemination of satellite positional information.

2. The technique is generally unfamiliar to navigators.

3. Either an accurate time standard or accurate knowledge of the satellite's position at the time of observation is required.

Orbits. Orbits near the earth provide relatively small coverage area at any one time, but the relatively high speed of the satellites in these orbits increases the dynamic coverage. As the height increases, the instantaneous coverage increases but at a decreasing rate. The speed of the satellite decreases. The percentage of the earth's surface illuminated per hour per satellite is approximately as follows (neglecting the rotation of the earth):

Ht. in miles	Earth coverage in % per hour
500	33
1,000	41
3,000	47
5,000	46
10,000	45

The effective coverage is somewhat less, the amount depending upon the technique used.

The height of the orbit also affects the interval at which orbital data must be updated. At optimum angle measurement height the interval is probably semi-annual, or annual; at range height it is per week; and at range-rate it is once or twice per day for high accuracy.

For low orbits, the problem of predicting future satellite positions is severe because of:

1. Unpredictable perturbations due to variable drag.

2. Uncertainties in the figure of the earth.

3. Lack of knowledge of the effects of the earth's gravity field.

4. Uncertain changes in proton density, reaching a maximum at 1900 miles and a minimum at 5,000 miles, at unpredictable intervals following solar flares.

5. Perturbations caused by other celestial bodies of the solar system.

6. The effect of solar pressure.

The solar pressure and drag effects can be minimized by making the navigation satellite spherical and as dense as possible.

Stationary orbits provide one outstanding advantage over all others. If the satellite can be maintained truly stationary with respect to positions on the earth, the lines of position from any technique usable at this height would also be stationary and could be overprinted on charts, as is commonly done with hyperbolic and azimuthal systems. Disadvantages of stationary orbits include the following:

1. A larger number of satellites would be needed because of lack of apparent motion of the satellites, requiring two or more to be visible to obtain a fix.

2. Coverage would not extend to polar regions.

3. Any imperfection in establishing a truly stationary orbit would cancel out the one advantage.

4. Periodic use of small amounts of thrust to counteract a tendency of the satellite to drift from the stationary position would require the use of fuel, limiting the useful life of the satellites.

The disadvantages appear to outweigh the one possible advantage.

The selection of orbit depends upon the technique to be used. The following considerations apply:

1. Elevation angle. This technique, being a form of celestial navigation, is applicable at any satellite height. Considerations of orbit stability, coverage per hour, time needed for change in azimuth for a satisfactory fix, launch costs, and power requirements suggest 4,000 to 6,000 miles as a desirable range, with 5,000 miles being optimum. Circular, polar orbits would probably prove most satisfactory from a coverage standpoint.

2. Horizontal angle. The same considerations apply as with elevation angle, with the same conclusions.

3. Range. Being a piloting technique, range measurement involves position determination relative to the satellites. As the distance to the satellite increases, the measurement becomes more critical, reducing the effective area for accurate position determination on earth. The optimum orbit for this technique appears to be about 800 to 1200 miles, with 1,000 miles being most satisfactory. Circular polar orbits would be desirable.

4. Range rate. This, too, is a piloting technique with the added restrictions that range rate measurement is more difficult than range measurement to achieve an equivalent accuracy. The optimum orbit is probably circular, polar at a height of 500 to 700 miles with optimum at about 600 miles.

Stabilization of the satellites would permit use of directional, higher gain antennas but might not be needed if adequate power were available at the satellites.

Frequency. The optimum frequency for a particular navigation satellite system depends upon the technique to be employed. The same signals used for providing navigation data from the satellite can be used for tracking. Optical tracking may also be employed. Telemetering may be accommodated within the same frequency channel used for transmitting navigational data. Telecommand would require a separate frequency channel.

1. Elevation angle. Medium to short centimetric waves are desirable to minimize ionospheric refraction effects. If the frequency is too high, however, the attenuation effect in the atmosphere results in high power requirements. If the radio sextant is to be used, both in the narrow band phase lock mode with satellites and in the broad band radiometric mode, three frequency areas produce good results. At approximately 8 Gc, relatively low power is needed with minor refraction problems. The radio center

of the sun is variable, but prediction of the effect may be possible. At about 35 Gc the radio center is stable, but the absorption during rainfall is severe. The third frequency area, at about 16 Gc, appears to be a good compromise between the other two. If the sun is not to be tracked, any frequency from about 8 Gc to 20 Gc should produce good results.

2. Horizontal angle. The frequency is not critical; any value high enough to have good directivity with modest size antennas and low enough to avoid absorption problems are satisfactory, with 8 Gc to 20 Gc being considered suitable.

3. Range. The optimum frequency is dependent somewhat upon the method of determining range. For a transponder, the frequency is not critical, the approximate region 300 Mc to 700 Mc probably being satisfactory. If phase comparison is used, the ambiguity in distance determination is related to frequency. If an ambiguity of 60 miles is acceptable, the required frequency is 2,700 cycles per second. This would be a modulation frequency superimposed on a carrier frequency of any convenient value. It may be necessary to use more than one modulation frequency, a higher one to provide a fine reading for accuracy and a lower one to provide a coarse reading to eliminate ambiguity.

4. Range rate. If measurement is by any of the range techniques, the frequency considerations are the same as indicated above. If Doppler is used, two frequencies, preferably harmonically related, are desirable to minimize ionospheric refraction errors. With present equipment and techniques, including antenna considerations and practical powers, frequencies in the VHF and UHF range up to about 1000 Mc are considered suitable.

Telemetering of conditions inside the satellite is considered desirable.

Although a number of techniques have been suggested, as indicated above, the only navigation satellite system under active development utilizes the Doppler range-rate technique. This system, known as TRANSIT, is scheduled to become operational, but probably not with full capability, by the end of 1962. The TRANSIT system was designed to meet a military requirement established by the Chief of Naval Operations "to provide accurate, all-weather, world-wide navigation for naval surface ships, aircraft, and submarines". It is understood that the effort has since been restricted to meeting the needs of submarines and a limited number of special-purpose naval surface vessels.

The range-rate technique used in the TRANSIT system is based upon the transmission by each satellite of signals on two frequencies. The second frequency permits reduction of errors due to ionospheric refraction. The curve of received frequency versus time is unique for each position on the surface of the earth, if the rotational effect of the earth and motion of the receiving antennas during observation are considered. Lack of orbit stability at the optimum height of 600 miles requires a new orbit determination at 12-hour intervals. The orbital parameters will be transmitted by ground "injection stations" to the satellites, which will store the information and transmit new orbital parameters at precise two-minute intervals. After completion of a pass of the satellite, a fix for the approximate time of nearest approach of the satellite can be calculated. An electronic computer of some complexity will probably be needed for this purpose. With four satellites in polar orbits, a fix should usually be available at approximately 110-minute intervals; oftener in high latitudes. However, passes near the zenith and at low altitudes will not provide satisfactory fixes.

Operational feasibility of the TRANSIT system has yet to be demonstrated. It appears doubtful that the system will meet all military requirements. Whether it proves satisfactory for nonmilitary use depends upon satisfactory answers to such questions as the following:

1. Will the operational accuracy of the system meet somewhat diverse nonmilitary requirements with equipment that can be made available at a cost that can be justified economically?

2. Will the lag between nearest approach of the satellite and determination of the fix be acceptable to the nonmilitary user?

3. Will the fact that the technique is generally unfamiliar to navigators adversely affect acceptance of the system by nonmilitary users?

4. Will the user equipment be sufficiently reliable and of sufficiently simple operation to meet the requirements of merchant ships and aircraft operating with a minimum of personnel?

5. Can suitable airborne equipment be developed to provide acceptable accuracy within size, weight, cost, and power limitations?

6. Can the interval between fixes be reduced sufficiently to be acceptable in air navigation?

7. Can the military convince the potential nonmilitary user that the technical characteristics and the availability of the system will be sufficiently stable to prevent their equipment from becoming obsolete within a reasonable amortization period?

Because answers to these questions are not yet available, because military requirements differ in several important respects from nonmilitary requirements, and because significant state-of-the-art advances have taken place since development of the TRANSIT system began in 1958, any program to meet the needs of nonmilitary users, as well as those of military requirements which may not be met by the TRANSIT system, should logically include a careful consideration of other promising techniques.

Any such program would appear to include the following steps, a decision being made at the end of each step after the third, to determine desirability of continuing on with succeeding steps:

1. Establish firm sets of requirements and desirable additional features for each class of users.

2. Determine to what extent requirements are or can be met by means of existing or contemplated systems.

3. Study the probability of meeting remaining requirements by means of satellites.

4. Invite proposals from industry for meeting requirements.

5. Conduct design studies of the most promising approaches.

6. Select the approach to be pursued.

7. Develop an operational system.

8. Set up an operating organization.

9. Continue to monitor changing requirements and state-of-the-art advances to improve or eventually replace the system.

Limited military navigation capability by means of artificial earth satellites is promised for the near future. A considerable effort appears to be needed before navigation by satellite becomes general. The probability of this occurring at some time in the future appears reasonably good.