Defense Navigation Satellite Development Program

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ABSTRACT
The Defense Navigation Satellite Development Program provides for test and evaluation of a new precise positioning technique and user receiver equipment. This equipment with appropriate displays will provide in real time three-dimensional precise position and velocity information. The DNSDP permits test and demonstration of alternative engineering solutions to determine the configuration and characteristics of an operational Defense Navigation Satellite System for the 1980s time period.

A general description of the test system is presented as well as a brief summary of its experimental applications, namely: navigation, military air traffic control (ATC), and military command and control communications.

INTRODUCTION
The Air Force concept for space-based radio navigation affords an opportunity for achieving a global positioning capability with a single passive, all-weather navigation system. Users of the system would make range and range rate measurements from any four of many satellites. The system provides precise and continuous three-dimensional position, velocity, and time determination for a wide range of military and civilian users. These include high performance aircraft, ships at sea, soldiers in the field, missiles, low altitude satellites, and spacecraft.

The system design philosophy has focused on satisfying the need for an accurate common-grid reference system. It is to be of sufficient flexibility to allow the development of individual user equipments based on an assessment of cost versus need.

BACKGROUND
In 1964, the Air Force initiated work directed toward achieving an improved positioning capability for spacecraft and aircraft. Analysis clearly indicated the merits of using satellites to provide highly accurate three-dimensional position and velocity information. Since then, work has progressed through concept formulation studies, various applications studies, laboratory tests and demonstrations, and field tests and demonstrations. A graphic presentation of this work is shown in Figure 1. The specific achievements to date include:

COMPLETED WORK
- Concept Formulation and System Design Studies
- Experimental Receiver Design, Breadboard Fabrication and Laboratory Demonstration Tests
- Various Systems Applications Studies
- Signal Acquisition and Tracking Demonstration Using the NASA ATS-5 Satellite
- Signal Modulation and Reception Technique Studies
- Noncoherent Receiver Techniques Feasibility Demonstrations
- Ionosphere and Propagation Effects Studies
- Preliminary Signal Definition Studies
- Flight Tests with experimental receivers

WORK IN PROGRESS
- User Equipment Definition
- Time-Shared User Equipment Studies

Reports on these activities are available from the Defense Documentation Center (DDC), and most of this work has been covered in various trade magazines and periodicals such as Aviation Week, Electronics News, etc.

DEFENSE NAVIGATION SATELLITE SYSTEM CONCEPT
The Defense Navigation Satellite System (DNSS) is a generic title which applies to the operational system that will satisfy military precise positioning and velocity determination requirements worldwide. A decision to acquire a new, space-based navigation and positioning capability must be based upon the fullest assessment of user requirements, system cost, terminal equipment design, cost and performance tradeoffs, the military value of the new capability, and the impact on existing and programmed facilities and equipment. Before such a decision can be
made, a number of outstanding issues and questions must be resolved. The pertinent issues are:

- Should the United States design and launch satellites and acquire related ground facilities and user equipment for navigation tests, experiments, and system demonstrations?
- What should be the primary objective of the program?
- What should be the schedule and allowable cost of the program?
- What types and levels of performance can be provided by a precise positioning system?
- Relative to other navigation and positioning means, what is the military value of the various types and levels of performance?
- What is a preferred system concept and design?
- What will the positioning system cost?

The Defense Navigation Satellite Development Program (DNSDP) was conceived by the Air Force to address these questions, as well as to demonstrate (qualitatively and quantitatively) that radio signals originating from satellites can be used to determine precise three-dimensional position and velocity. Further, the DNSDP permits demonstration that the trend toward more complex, expensive, heavier user equipment and avionics can be reversed. Cost data obtained in the demonstration can show a favorable comparison between a satellite-based system and other position determining systems. The demonstration program will provide training and the development of tactics to permit an orderly transition to a space-based operational positioning system. First satellite will be launched in 1977.

DEFENSE NAVIGATION SATELLITE DEVELOPMENT PROGRAM

The DNSDP is designed to provide flexibility to accommodate a wide selection of test and experiments. Its basic elements are the space segment, the ground command and control segment, and user equipment segment. The DNSDP test system will use four nonprocessing repeater satellites which transpond positioning signals generated by the ground segment facilities. This combination of equipment provides for a ground/aircraft-to-satellite uplink, a satellite-to-aircraft/ground downlink, and an accurate ephemeris determination system. Radio link crosstrapping capability in the satellite can accommodate the uplink/downlink interconnection needs of a variety of experiments (Figure 2).

Configuration of the space segment has been tentatively selected as a "rotating Y" constellation using repeater satellites. The driving considerations favoring this selection are: the constellation is stationary over the United States providing full time access for test and command and control purposes and, flexibility for testing a wide spectrum of signal characteristics and operational modes of use. In this configuration, three satellites are inclined in 24-hour elliptical orbits, i.e., apogee and perigee are 25,500 NM and 13,100 NM, respectively. The fourth satellite is in a synchronous equatorial orbit. Looking down on the earth's surface, the inclined satellites trace a circular ground pattern. Their projection is like the letter "Y" with one satellite at the end of each leg of the "Y" and one in the center, moving in a clockwise direction (see Figure 3).

The synchronous equatorial satellite appears geostationary in the center of the circle. It is proposed that the center of the constellation be located at 100° west longitude. The satellite configuration will include sufficient propulsion energy to displace the constellation about the earth, and be returned to a position over the United States. This capability provides the opportunity for test and demonstration in areas other than the United States.

The ground segment of the DNSDP consists of a master ground station at Vandenberg AFB and three monitor stations located throughout the United States. The master station uses four 12-foot antennas, each dedicated to a designated satellite in the constellation. Location of the monitor stations will be precisely known and serve as calibration sources to provide updating information for ephemerides data to be included in the content of signals originating in the master station and transponded through the repeater satellites to the users. The user must know the position of the satellites to accurately determine his own position.

The system radio links are labeled with subscripts in Figure 2. The navigation links are located in the 1 to 2 GHz region and satellite tracking links in the 5 to 6 GHz region. Table 1 presents the various satellite links.

The satellite transponder is an integrated package involving several uplink and downlink frequencies and cross-strap modes. All of the transponder channels are nonprocessing and designed to operate linearly at the required power levels. The spacecraft antenna is 5 feet in diameter and illuminates most of the four satellite visibility area (see Figure 3). The antenna is double-gimbaled, providing the flexibility to steer the antenna toward any desired area of operation within the four-satellite coverage area.

The user equipment segment will represent a broad spectrum of applications. These range from configurations suitable for use in the latest aeronautical systems such as the F-111 to man-packs that might be employed by ground forces in advanced tactical situations. A variety of hybrid interface relationships with current in-service positioning systems will be evaluated. The principle objective in the user equipment area is to utilize pre-production qualified avionics equipment to
provide meaningful cost prediction data to be used in estimating life cycle costs. It is expected that a limited number of operational force aircraft will be modified with DNSDP receiver equipment to fully evaluate the operational value of the capability.

**TECHNICAL DISCUSSION OF DNSDP**

The DNSDP will experimentally address a variety of technical issues. Among those issues are system accuracy, signal structuring and attenuation, user avionics configuration, and other pertinent performance characteristics which need to be validated and substantiated. Referring to Figure 2, links \( L_1; L_2; C_1; C_2; \) and \( C_3 \) are used in the test and evaluation program.

Among the experiments, various techniques for signal acquisition and multipath rejection will be tested. The basic ranging signal will be evaluated and optimized in terms of data format, and techniques for generation and reception of the signals. Different types of receivers will be tested. The value of this demonstration is that, from the user's point of view, operations with the DNSDP are essentially identical to operations with an actual operational system. The relationship between the user and satellite is identical regardless of where the signal is originated.

There are five major technical areas to consider in the DNSDP test and evaluation program. They are:

1. Satellite tracking and ephemeris determination
2. System calibration
3. Signal generation and data transmission
4. User position and velocity determination
5. Prototype engineering of user equipment

The satellite ephemerides are determined and updated in near real time. The results are put into a format suitable for transmission to a user for his positioning calculations. Errors in satellite ephemerides have a direct impact on positioning error, and thus it is necessary to track the satellite to a greater accuracy than is presently achieved by existing tracking techniques. A two-way ranging technique is employed using a pseudorandom noise biphase modulated ranging signal up via \( C_1 \) and down via \( C_2 \). The modulation on the signal \( L_1 \) is the same as that on \( C_1 \). The 24-hour orbit has the advantage that the outer satellites are constrained to move through basically the same portion of the earth's gravitational field each revolution. So, the requirement for detailed knowledge of the earth gravity model is reduced.

Once the state of the satellites has been estimated and projected forward in time for several hours, a nominal ephemeris can be formed and the system calibration process to reduce user position and velocity errors can begin. Each monitor station simultaneously receives both the signal \( L_1 \) and the downlink of the two-way ranging signal \( C_2 \). Receiving both signals simultaneously provides an opportunity to measure the propagation delays through the ionosphere. Ionospheric attenuation is viewed as a major source of error for the system. These data are relayed back to the master station to be added to the system data, which are transmitted to the users. Using the positioning signal \( L_1 \), the monitor station takes measurements and computes his position as any other user would. The monitor station compares his measured position to his known surveyed position and any differences between the two are relayed back to the master station. These position difference data are treated as an additional data source for satellite ephemeris determinations and the ephemerides are adjusted accordingly. To the extent that the propagation delay data are accurate, the monitor station measured position will tend to approach the surveyed position as ephemeris adjustments are made.

The propagation delay data, the ephemeris adjustments, and other pertinent system parameters comprise the system data which is broadcast to the users for their computational needs. The system data are directed toward providing the user the information necessary to achieve maximum accuracy. Depending on the strength of his computational software and his accuracy requirements, the user can take advantage of as much or as little of the system data as he desires.

An equally important aspect of the system is the generation and transmission of the positioning signals. These signals are pseudorandom noise (PRN) sequences, biphase modulated onto a carrier. They are generated at the master station, sent up to the satellites via uplink \( C_1 \) (and/or \( C_2 \)) and transponded to the users via \( L_1 \) (and/or \( L_2 \)). The \( L_1 \) is termed the primary navigation signal and \( L_2 \) is termed the secondary positioning signal. The primary signal has system data, propagation delay data, system time and other pertinent system information. Many techniques for modulation, message formatting, and signal acquisition will be tested. However, based on previous analyses, the starting point for the signal design and tests will be biphase modulated PRN sequence. By using transponder satellites and originating the navigation signal on the ground, we have the experimental flexibility to refine the signal design as the program progresses. Each satellite will transpond a unique PRN sequence (or Code) orthogonal to the other codes for code division multiple access (CDMA) operation. The individual codes will be synchronized relative to one another.

During the DNSDP primary attention will be focused on the users equipment and development of a family of avionics configurations to satisfy military requirements. The majority of costs to be incurred when converting to an operational DNSS will be that required to equip
the user population. Relative minor design perturbations in user equipment could have major cost implications for a national population. Furthermore, the DNSDP is designed to evaluate the precise positioning capabilities and the prospective user will desire that the evaluation be conducted with representative prototype equipment, both from a cost as well as performance standpoint.

To determine position and velocity, the user equipment correlates an internally generated replica of the PRN biphase modulated code with the coded signal received from the satellites. The receiver measures the relative phase or equivalent time displacement between the generated code and the incoming code, thus measuring the relative range. Since the user oscillator (clock) is generally not synchronized to the oscillator at the master ground station, the four range measurements are not equivalent to the geometrical ranges. They are actually "pseudoranges" which are offset from the geometrical range by the relative phase bias between the user oscillator and the system's master oscillator. Along with range measurements to each satellite, the corresponding frequency doppler is measured based on the carrier frequency doppler of each signal and the corresponding motion of the particular satellite as described by the ephemeris data. As before, the master oscillator and the user oscillator are not perfectly synchronized (after satellite motion doppler has been accounted for) and thus pseudorange rates are derived. The pseudorange rates are offset from geometrical range rate by the relative frequency bias between the master and user oscillators. The user software solves two groups of four equations in four unknowns \((x, y, z, t)\) and \((x, y, z, t)\). Given the satellites' ephemerides (satellite position and velocity with respect to time) and the system time of day, this information is sufficient to calculate user position and velocity (see Figure 4).

**EXPERIMENTAL RESULTS**

Results of laboratory and flight test experiments, and studies conducted confirm that the DNSDP concept is feasible. The Air Force has just completed a nine month flight test program on the White Sands Missile Range which dramatically demonstrated that very high degrees of accuracy in three-dimensional positioning are possible.

The Air Force positioned transmitters on the ground at White Sands with approximately the geometry that a surface or airborne receiver would see when viewing a constellation of satellites in 24-hour orbit (Figure 5). Four separate signals were generated in a master station and radiated through individual antennas located on radials of approximately 4 miles from the center antenna. The antenna configuration is approximately that of the rotating-Y constellation described earlier for the DNSDP.

An NC-135 test bed aircraft was equipped with two receivers of different electronic designs which provided comparative test results. It was found during data reduction that these two receivers tracked each other within one foot in each of the three dimensions. The flight test program was divided into two phases, i.e., area navigation where the test aircraft flew over the transmitters at 30,000 feet, and low altitude tests duplicating an aircraft completing a final approach for landing. During the latter phase, one transmitter was placed on a balloon at about 2000 feet above the ground to provide favorable geometry to the aircraft antenna during the final approach (Figure 6).

Test results confirmed that the position of a dynamic fast moving user operating in three-dimensions could be determined within tens of feet.

**APPLICATIONS OF THE PRECISE POSITIONING CAPABILITY**

The space-based positioning system is characterized as being a three-dimensional, all-purpose system with aircraft navigation being only one system application. Some representative applications are now enumerated.

1. En Route Area Navigation
2. Terminal Area Navigational and Instrument Landing
3. Surveying and Photomapping
4. Shipboard Navigation
5. Ground Vehicle Navigation
6. Manned Backpack Navigation
7. Test Range Instrumentation
8. General Weapons Delivery

Many of these applications will be configured experimentally and tested in the DNSDP. The underlying, fundamental characteristics in each of these applications is that position and velocity of the user can be determined in three dimensions and in real time. Specific considerations for utilizing this positional and velocity knowledge in a myriad of potential applications is left to the imagination or, interests of the reader. However, as matters of example the following specific applications are discussed.

**AIR TRAFFIC CONTROL**

Cooperative aircraft surveillance experiments can be carried out where the three-dimensional position and velocity of properly equipped aircraft can be observed within a given airspace. The air traffic control (ATC) experiment is made up of separate but integral parts. In this experiment, everything is centered around a cooperative aircraft surveillance scheme. The aircraft position derived from the surveillance data forms the basis for the spatial address communications system. Given both the surveillance and communications capability, the experiment can be extended to a collision avoidance experiment.
COOPERATIVE AIRCRAFT SURVEILLANCE

The cooperative aircraft surveillance scheme has the user aircraft carrying a simple transmitter (or ATC beacon) which emits a unique ranging signal in a free running, autonomous manner. The ranging signals achieve their uniqueness by employing various combinations of carrier frequency, coded phase shift keying, pulse position modulation, or pulse repetition rate.

Consider a single aircraft for the moment. The ranging signal is transmitted to all four satellites via uplink L, where it is transponded to the master ground station via the four C, links. Relative time-of-arrival measurements are made between all of the four incoming signals and three sets of range differences are defined. Given the satellite ephemerides, and the ground station-to-satellite ranges, the position of the aircraft transmitter can be determined. The incoming signals are first separated according to carrier frequency. Then, a matched filter arrangement in conjunction with digital tracking loops can be employed to further sort out and track the signals according to phase shift code, pulse repetition rate, and pulse position. With each unique signal sorted and tracked by the signal processing equipment the relative time-of-arrival data are properly formatted and sent to the computer for position determination.

Peripheral to the master ground station, signal processing equipment, digital computers, surveillance data display and readout equipment, and necessary interface devices are required in the surveillance experiment (see Figure 2). The resultant surveillance data can be displayed or outputted in any form to satisfy the particular purpose.

SPATIAL ADDRESS COMMUNICATIONS

Air traffic control can be exercised through digital communications with spatially addressed messages. The typical messages are routine digital messages such as "climb", "dive", "your position is——", "turn left" and so forth. With proper time multiplexing of the message among four satellites, the system can adequately handle ATC messages, back-up navigation data, and collision avoidance messages. The key to this technique of air traffic control is knowing the position of the message recipient with respect to prospective conflicting traffic.

In the digital communications scheme, the surveillance data could be used to spatially address routine digital messages to any cooperative aircraft in the surveillance system. First, the user requires a simple receiver on board the aircraft which can accept digital messages over downlink. The particular user is notified that a message is forthcoming when he receives a particular pulse pattern at his receiver, four pulses equally spaced in succession, for example. This pulse pattern is achieved by the ground station properly time-sequencing the pulse transmissions through each satellite such that the particular pulse pattern can only be received in the proper sequence at a particular position in the airspace. This position corresponds to the aircraft's position as determined from the surveillance information. Once the user is notified, the message can be sent in whole through a single satellite or the message can be divided up into two segments and transmitted in a spatially addressed manner.

Performing the cooperative surveillance and spatial address experiments together essentially would constitute an ATC system experiment. One can envision monitoring airspace surveillance data and then issuing routing ATC or collision avoidance messages (digital) as necessary to control and route each individual aircraft. Within such an ATC experiment, there are some interesting collision avoidance and navigation schemes that could be implemented. One example is a back-up navigation system where each individual aircraft's surveillance data are sent back to that aircraft as a message. Another example is a collision avoidance system where the surveillance data are compared at a ground center, potential collision situations are identified, corrective actions for the aircraft involved are synthesized, and collision avoidance messages are sent out to the aircraft.

COLLISION AVOIDANCE

To have a complete air traffic control experiment, a collision avoidance scheme could be implemented which would determine potential collisions and synthesize corrective maneuvers for the aircraft involved. The heart of the collision avoidance scheme is a three-stage serial collision situation filter set up in a computer with the appropriate peripheral equipment. The input to the system is the surveillance data and the output device is the communications system. The first stage of the serial filter divides the airspace into controlled volumes to limit the number of aircraft under consideration. The second stage solves for the approach geometry (assuming constant velocity) for the aircraft in the control volume. Data on aircraft on a potential collision course are sent to the third stage where worst case dynamics are assumed and a corrective maneuver is synthesized for each aircraft involved. The prescribed corrective maneuver is sent to each aircraft by way of digital message.

TEST AND EVALUATION OF THE PRECISE POSITIONING CAPABILITY

The end point or result of the DNSDP will be the information required to formulate a decision to acquire the precise positioning capability. Therefore, a comprehensive test and evaluation in representative operational environs is necessary to provide an adequate data base. An essential requisite for the data base is that the cost data must be developed on representative pre-production configured user/avionics equipment.
Minor perturbations in the cost base assumptions can have far-reaching implications in estimates to equip the potentially large user population. Objectives of the test and evaluation program will be to:

1. Demonstrate the operational effectiveness and suitability of the precise positioning capability and equipment;
2. Demonstrate reliability, maintainability and logistic supportability;
3. Develop and demonstrate new military applications and tactics made possible by the unique capabilities of the precise positioning concept;
4. Identify navigational facilities which currently exist or are programmed that could be replaced by the DNSDP positioning capability.

The Air Force is presently examining the composition and equipage of a test force to evaluate the effectiveness and suitability of the precise positioning capability. This test force could include F-111s, RF-4s, WC-130s, B-52s, Remote Piloted Vehicles, and space boosters. It is envisioned that the Initial Operational Test and Evaluation (IOT&E) program would be conducted separately from development testing. A major operational/supporting command will be designated as the lead command to direct the IOT&E. These commands in conjunction with the Air Force Systems Command will prepare a Master Test Plan to be approved by Headquarters, USAF.

The following factors have been identified for the test and evaluation program:

1. System Performance: Area and terminal navigation, blind bombing, tactical and strategic reconnaissance, weather reconnaissance, airlift, aerial delivery, ground command and control, air refueling rendezvous, search and rescue, air combat maneuvering, strategic strike, ocean surveillance, terrain following/avoidance, climatic and other environmental extremes, countermeasures, survivability, vulnerability, superseded navigational equipment/systems, and new tactics/applications.
2. System Operability: Reliability, maintainability, supportability, transportability, human factors, and safety.
3. System Support: Maintenance concept, aerospace ground equipment, logistic support, transportation and handling, technical data and support facilities.
4. System Training: Trained personnel requirements, training standards course material, training equipment and facilities, technical publications and training courses.

Both airborne and ground testing will be conducted utilizing production prototype terminal equipment previously qualified in development flight tests. The majority of testing will be conducted at one location to simplify logistic support. However, temporary support at other locations will be provided to meet specific test requirements such as climatic, terrain, or other environmental conditions. Sufficient support flexibility will be provided to insure that other Government Agency requirements are accommodated. Testing will be conducted in as realistic an operational environment as possible. Particular emphasis will be placed upon demonstrating reliable system performance under severe environmental conditions. User receiver/avionics will be maintained by operational personnel with contractor technical support.

Applications of the precise positioning capability falls into many categories and mission modes of military operations. The inherent precision in three dimensional positioning and velocity determination will have profound influence on those operations which today are cumbersome or dangerous because of dependence on ground based signal sources. Since the operational capability would eventually encompass the earth, it is ideal for providing a common grid for users and employers of the capability. Applications which are enhanced or made possible by the precise positioning capability are: Enroute/terminal navigation; weapons delivery; photomapping and targeting; air sea rescue; initialization of air launched missiles; retargeting of strategic force; missile and space guidance and tracking, air traffic surveillance/control, and integrated command control and control of surface forces.

A decision to acquire the space based precise positioning capability will be predicated on a disposition of present day navigational facilities and cost of ownership to equip the operational force. For example, a decision must be made whether inertial platforms will be retained in present systems with updating from the satellite based system. This decision will be determined principally by considerations on survivability of the weapon system.

CONCLUSIONS

Facilities for enroute and terminal area control represents a major investment which could eventually be outdated by the precise positioning capability. Equipping the civilian and military user population will prove to be a major national investment. However, there will be corresponding reductions in investments by selecting the precise positioning capability. Results from the DNSDP will permit evaluation of the capability, estimation of equipage costs, and define cost savings that can be accrued by phasing out outdated equipments and facilities.

ACKNOWLEDGEMENT

The electronic principles described for the DNSDP were developed under the direction of the Space and Missile Systems Organization of the Air Force Systems Command.
Table 1. Satellite Transponder Channels

| TRANSPONDER CHANNELS | RECEIVED SIGNALS | | | TRANSMITTER CHANNEL |
|----------------------|------------------|------------------|------------------|
| CHANNEL              | NOM. FREQ./ | ORIGIN. | PURPOSE | CHANNEL |
|                      | BANDWIDTH  |          |          |          |
| C₁                   | 5 GHz/20 MHz | Mstr. Sta. | Passive Nav Primary Signal and Satellite Tracking | L₁ |
| C₂                   | 5 GHz/20 MHz | Mstr. Sta. | Secondary Nav Signal or Comm. to ATC or C₂ Experiments Aircraft | C₃ |
| L₃                   | 1600 MHz/20 MHz | C₂ or ATC Aircraft | Surveillance or Comm | L₂ |

TRANSMITTED SIGNALS

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</tr>
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<td>5 GHz/20 MHz</td>
<td>L₃</td>
<td>1.5 watts</td>
<td>1 ft</td>
</tr>
</tbody>
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CFP/TDP DEVELOPMENT PLAN

SAMSO / AEROSPACE / INDUSTRY

SAMSO / AEROSPACE / INDUSTRY

SAMSO / AEROSPACE

NEW DEVELOPMENT PLAN

1 TRW 2 HAC

2 TRW 3 MRL

3 GAC 4 BOEING

KEY
1 MISSION ANALYSIS
2 CONCEPT FORMULATION & SYSTEM DESIGN STUDIES
3 RECEIVER DESIGN, BREADBOARD FABRICATION & LABORATORY DEMONSTRATION TESTS
4 VARIOUS SYSTEM APPLICATION STUDIES
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PHILCO 10
TRW 11

CALENDAR YEAR
Figure 1. Historical Background

Figure 2. DNSDP System Operations
Figure 3. Regions of Continuous Four Satellite Visibility for Pacific Theater and Conus Deployments

Figure 4. Pseudo Range/Range Rate Concept

- PSEUDO-RANGE = \( t_j \cdot c = \sqrt{(x-x_j)^2 + (y-y_j)^2 + (z-z_j)^2} - t_B \cdot c \)

- PSEUDO-RANGE RATE = \( \frac{(x-x_j) \dot{x}_j + (y-y_j) \dot{y}_j + (z-z_j) \dot{z}_j}{\sqrt{(x-x_j)^2 + (y-y_j)^2 + (z-z_j)^2}} - \frac{t_B \cdot c}{t_j} \)

- SINCE \( x_j, y_j, z_j, \dot{x}_j, \dot{y}_j, \dot{z}_j \) ARE KNOWN, 4 \( t_j \)'s AND 4 \( \dot{t}_j \)'s ALLOW SOLUTION FOR USER POSITION \( (x, y, z) \), AND VELOCITY \( (\dot{x}, \dot{y}, \dot{z}) \), AND TIME BIAS \( t_B \)
Figure 5. Area Navigation Demonstration

Figure 6. Final Approach to Landing Demonstration