
NON-GPS Methods of Geolocation

Study Leader
J. Cornwall

Contributors Include:

K. Case
C. Callan
A. Despain
F. Dyson
J. Goodman
R. Jeanloz

W. Nierenberg

C. Stubbs
P. Weinberger

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JASON
The MITRE Corporation
7515 Colshire Drive
McLean, Virginia 22102-7508
(703) 883-6997

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13. ABSTRACT (Maximum 200 words) JASON was asked to conduct a brainstorming session on the problem of precision (that is, at GPS-like accuracy) geolocation of ground elements by means other than use of GPS satellite transmissions in the usual way. This is important because GPS transmissions are weak and easily jammed, so it may be possible for enemy forces to deny conventional GPS use. We had no briefings on this subject, and (aside from the conventional idea of pseudolites) we are not aware of other work going on in this area. Our work was also limited by the very short time available for this project in the Winter Study, and so we furnish a rather brief report. Our general conclusion is that there are several perfectly practicable schemes for non-GPS geolocation, although more detailed investigation is needed to sort out the various advantages and disadvantages. If DARPA is interested, further studies on the best schemes could be carried out in the Summer Study.				
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1 INTRODUCTION

JASON was asked to conduct a brainstorming session on the problem of precision (that is, at GPS-like accuracy) geolocation of ground elements by means other than use of GPS satellite transmissions in the usual way. This is important because GPS transmissions are weak and easily jammed, so it may be possible for enemy forces to deny conventional GPS use. We had no briefings on this subject, and (aside from the conventional idea of pseudolites) we are not aware of other work going on in this area. Our work was also limited by the very short time available for this project in the Winter Study, and so we furnish a rather brief report.

We considered several possibilities, in some cases concluding that the proposed GPS substitute is infeasible. The schemes we looked at are:

1. **Public-service SAR**
2. **Variants on LORAN**
3. **Satellite methods (other than conventional GPS)**
4. **Inertial navigation systems (INS)**
5. **Celestial navigation**
6. **Other methods, including orienteering, precision navigation from celestial radio objects, and gravimetry**

We did not explicitly consider conventional pseudolites, or high-power close-in substitutes such as aircraft or UAVs in place of GPS satellites, far less

susceptible to jamming than GPS satellites themselves. These pseudolites derive their own positions from GPS or other means and broadcast high-power signals equivalent to GPS signals for use by ground or air elements. Nor did we consider the prospects for overcoming GPS jamming by directional antennas (the location of the GPS satellites is very well known) with adaptive nulling, or what should be done with future GPS fleets to make them less susceptible to jamming. It will be seen that several of our schemes amount to using pseudolites of opportunity, emitting signals which were not designed as GPS substitutes. And we suggest a way of using non-GPS communication satellites as pseudolites. In fact, pseudolites, whether conventional or unconventional, as some of ours are, are an attractive alternative to GPS.

Our general conclusion is that there are several perfectly practicable schemes for non-GPS geolocation, although more detailed investigation is needed to sort out the various advantages and disadvantages. If DARPA is interested, further studies on the best schemes could be carried out in the Summer Study.

2 PUBLIC-SERVICE SAR

The idea behind public-service SAR has been put forth in several other JASON reports [1, 2]. A public-service SAR is one which provides functions to ground-based elements such as broad-band communications and geolocation as well as conventional SAR imaging. Typical public-service SARs might be theater-based UAV/SARs or fleets such as were proposed for Discoverer II. In brief summary, geolocation services are provided to ground elements equipped with antennas capable of communicating to the SAR. These antennas may simply be modulatable corner cubes, in which case transmissions from the ground element are essentially covert. The SAR localizes the transmission from a ground element requesting geolocation and simply transmits that geolocation to the ground element. Note that the SAR does not need to know its position with very high accuracy, since it is in the business of making images of ground which has previously (we assume) been accurately mapped; the SAR simply reports to users their positions relative to the mapped scene. Each ground element supplies an identification with its request for service, which restricts responses to friendly forces and allows the determination of which requesting element on the ground is which. References [1, 2] cover some technical questions, in particular the problem that sending a coded message in slow time creates a smeared target in the azimuth direction. This can be overcome by using different parts of the overall SAR frequency band and of the total coherent integration time to divide the functions of communication, identification of a ground requester, and geolocation of requesters. A question needing more detailed study is how much latency such SAR geolocation generates. This depends on the number of ground elements requesting geolocation at a given time.

3 VARIANTS ON LORAN

Variants of LORAN or other hyperbolic navigation systems involve active transmission from ground elements desiring geolocation. In one variant, only two transmitters are required, instead of three or more as in conventional LORAN. When a ground element receives navigation pulses from the master transmitters, it (immediately or with a precisely-known delay) transmits its own pulse followed by an identification message (on a different band). The master stations then know how far away the ground element is, and transmit that information (on a different band from its main signals). Now the ground element has enough information to locate itself, up to a twofold ambiguity which is usually easily resolved, since the ambiguous locations are widely-separated. Disadvantages are the need for active transmission from the ground elements, as well as the requirements of good lines of sight. Steps can be taken to minimize the disadvantages of active transmission, including coding, frequency hopping, and so forth. Advantages are that hostile forces cannot use the variant LORAN for its own geolocation, since all it can get from two stations is a position along a hyperbola.

Some other methods discussed below are only practical for the geolocation of relatively large and immobile devices such as radars; once these are geolocated by some other scheme, they can be used as variant-LORAN transmitters.

It is not necessarily the case that all geolocation users need be in line-of-sight with the two transmitters. A number of users can be networked and transmit appropriate time signals, TDOA information, and the like to one another, as long as a line of sight "percolates" throughout the system

of users. Users in direct line of sight with the two master transmitters can locate themselves, then others in line-of-sight with the first users, and so on.

Other variants include the use of transmitters of opportunity, such as TV stations.

4 SATELLITE METHODS (OTHER THAN CONVENTIONAL GPS)

Natural and manmade celestial objects provide opportunities for geolocation. Astronomical sources of electromagnetic radiation provide an absolute coordinate system which has long been used for navigational purposes (see, *e.g.*, our section on celestial navigation).

The scheme presented below is perhaps not very practical for the soldier in the field. Even though only a small portable telescope is needed (see below), this telescope must be pointed very accurately, to about 20 arc seconds, a demanding job better suited for a base station or at least a vehicle which can stop in one position for 15 or 20 minutes. One must then wait for at least four satellites of accurately known ephemerides to transit. Nor can the method be used in cloudy weather. Still, it might be used to establish accurately the location of a base station to be used in some other geolocation technique, such as the variants on Loran described elsewhere in this report.

For an astronomical object directly overhead, the positional uncertainty Δr on the surface of the earth is given by $\Delta r = R_e \Delta \theta$, where R_e is the radius of the earth and $\Delta \theta$ is the angular uncertainty of the satellite position. Attaining Δr of 30 meters requires angular position accuracy of about a second of arc ($5 \mu\text{rad}$), consistent with a small telescope of a few inches aperture and normal seeing conditions. By comparison, for a LEO satellite R_e is replaced by the orbital altitude, perhaps one-tenth of R_e . Given this numerical advantage, plus the strength of emission of many LEO satellites, including an increasing number of them in the multi-GHz range, it makes sense to exploit these satellites. Of course, this requires good knowledge of

their ephemerides. These might be known from a source such as NORAD. Satellites need not be actively transmitting in order to be used for geolocation; below we consider the case of satellites equipped with corner cubes for geolocation purposes. Following that, we discuss geolocation by triangulation on LEO satellites emitting at GHz frequencies.

Using a laser might become a simple and straightforward exercise for a single soldier if corner cubes were to be made available on selected satellite fleets. A certain amount of equipment aside from the laser would be needed: A small telescope tripod which must be accurately oriented (level and pointing north) on which the laser is mounted, plus a computer-controlled drive to point the laser at the (assumed known) satellite positions. One does TDOA on four or more satellites to determine one's distance from them, just as in conventional GPS. Small telescope mounts with computer-controlled drives are available commercially for the amateur market at quite a reasonable cost; they weigh perhaps twenty pounds and are easily portable in vehicles.

We calculate roughly the performance required of the laser and the detector.

The number of received photons in one measurement of range is

$$N = f L, f = (\epsilon S A / \pi^2 R^4 \theta^2 \phi^2). \quad (4-1)$$

The symbols have the following meanings, with reasonable numerical values for each of them:

$$L = \text{number of emitted photons} \sim 10^{16} \quad (4-2)$$

$$\epsilon = \text{combined efficiency of reflection, detection} \quad (4-3)$$

and extinction ~ 0.5

$$S = \text{area of corner-cubes} \sim 10^{-2} \text{m}^2 \quad (4-4)$$

$$A = \text{area of photon collector} \sim 10^{-2}\text{m}^2. \quad (4-5)$$

$$R = \text{distance of satellite} \sim 10^3\text{Km}. \quad (4-6)$$

$$\theta = \text{half-angle of emitted beam} \sim 10^{-4}\text{radians}. \quad (4-7)$$

$$\phi = \text{half-angle of reflected beam} \sim 10^{-4}\text{radians}. \quad (4-8)$$

The angles (7) and (8) are wide enough so that the motion of the satellite during the photon travel-time is negligible. The photon number (2) requires about a milli-Joule of energy. With these numbers, (1) gives

$$f = 5 \cdot 10^{-14}, \quad N = 500. \quad (4-9)$$

We suppose that the photons are emitted during an interval of time T , using a modulation-template switching the beam on or off with a pseudo-random pattern. Let the template have duty-cycle δ and resolution gT . Reasonable numerical values are

$$T \sim 1 \text{ second}, \quad (4-10)$$

$$g \sim 10^{-8}, \quad (4-11)$$

$$\delta \sim 0.5. \quad (4-12)$$

We need then to use a laser with peak-power

$$P = (L h\nu / \delta T) \sim 2\text{mW}, \quad (4-13)$$

and the round-trip photon travel-time is measured to an accuracy of 10 nanoseconds.

The computer must calculate the correlation between the emitted template and the received photons with all possible delay-times, including a calculated correction for the motion of the satellite during the measurement.

The number of possible time-channels will be of order

$$n = (R/cgT) \sim 3 \cdot 10^5. \quad (4-14)$$

The signal in the correct time-channel will be N photons, while the signal in each of the incorrect channels will be δN photons. Assuming that photon statistics are the dominant source of noise, the signal-to-noise ratio of the difference between counts in correct and incorrect channels is

$$(S/N) = (1 - \delta) \left(\frac{N}{1 + \delta} \right)^{1/2} = 0.4N^{1/2} \sim 9. \quad (4-15)$$

There is a negligible chance that this signal-to-noise ratio would be accidentally exceeded in any of the $3 \cdot 10^5$ incorrect channels. A fast and efficient algorithm for identifying the correct time channel is described in Ref. [3].

This sketch of a possible substitute GPS system is grossly over-simplified. It needs to be further analyzed in detail before any judgment can be made of its feasibility.

A notional scheme for finding ground positions from satellites which radiate uses a triangular array of antennas, each feeding a fast digitizing signal chain. By performing a cross-correlation between the resulting bit streams, the angle between the plane of the receivers and that of the source can be determined. Given the ephemerides of satellites or positions of stars, this angular information can be used to determine location. The same system could be used with ground emitters of known location, to UAV or aircraft signals such as those from pseudolites. Rough calculations suggest that a system with three antennas separated by only one meter might achieve positional accuracy of tens of meters in a few seconds, for satellites emitting in K-band. The small separations needed for the antennas suggests that this could lead to an eminently field-portable system of non-GPS geolocation.

Another possibility for communications satellite fleets without accurate clocks is that these satellites reradiate accurate time signals from a ground station of accurately-known location. Given the ephemerides of the fleet satellites, one corrects the bent-pipe time signal for the upleg travel time, and in effect turns all the communications satellites into GPS satellites. This is an example of using in-place satellites as pseudolites.

It is far from trivial to use radars to geolocate by making TDOA measurements on four or more satellites of a fleet. Consider the obvious example of the fleet whose ephemerides are best-known, generally, which is GPS itself; the GPS constellation is simply too far away for active interrogation by a ground radar of reasonable power. We estimate tens of GW would be needed to receive returns from the GPS fleet. A LEO fleet must be used such as a communications fleet like Iridium. It is then a question of how often must the ephemerides for the LEO fleet be updated so that ground elements can make reliable use of them. In any case, a severe disadvantage is that only large and relatively immobile ground radars can geolocate themselves this way. However, it could be that two or more such radars could be used in some variant of hyperbolic geolocation, as discussed above. Once the radars locate themselves accurately by methods of this section, they can be used to locate others by a hyperbolic navigation scheme.

Finally we mention the Transit system, a US Navy navigational system whose first successful launch was in 1962; the system was retired in 1996.

Given the computer and satellite technology of the time, it was a tremendous achievement. One-time navigation fixes were good to about one half a mile, not too much better than Loran but global coverage was uniform and free from propagation errors. It was much used during the Vietnam war and back pack units were built to enable differential navigation of great preci-

sion. The principle of operation was the ground measurement of Doppler shifts from the Transit satellite signals; the more measurements, the more accurate the geolocation fix.

With today's technology transit technology could be employed to yield the same precision as that obtained with the GPS. Any of several LEO satellites could be used as part of a system, provided that they emit stable frequencies and that the ephemerides are known to the requisite precision. If ephemerides are not supplied as part of the satellites' normal operation they could be established by conventional tracking methods or by using the basic techniques of the Transit system in conjunction with established geodetic points.

Johns Hopkins University, developers of the Transit system, maintain a web site with further information [4].

5 INERTIAL NAVIGATION SYSTEMS

In the brief time we could allot to this project in the Winter Study we did not gather the necessary information on state-of-the-art INS technology which would allow quantitative precision in our discussion. In general, man-portable INS systems cannot maintain GPS-like accuracy over a period of more than some minutes, which means that they cannot be used as a stand-alone GPS substitute. This does not mean that INS systems can play no role; on the contrary, they might be vital adjuncts. One use of an INS is to maintain precision location between updates from any of the other schemes we propose, some of which might have considerable latency, and others of which might use fairly large equipment such as radars, which cannot directly be used by troops or aircraft. But timing signals and other location reference signals could be transmitted by this large and immobile equipment to nearby INS users, who could then update their INS periodically.

6 CELESTIAL NAVIGATION

Celestial navigation is not a full-time fix to the geolocation problem, since it needs essentially cloud-free viewing at night, although this latter problem might be overcome with reasonably accurate positioning of a telescope.

First we recall (see Section 4) that celestial navigation by stars produces a considerably larger error for a given star position than by LEO satellites. However, star positions are known very accurately which makes them potentially useful for geolocation. One needs an accurate time fix, perhaps from a remote master station. It should be straightforward to automate the operation of the telescope to make many sightings and to reduce the data automatically by a computer. Accurate leveling of the telescope is essential.

The Naval Observatory's web site [5] for the Astronomical Applications Department contains a reference to high-precision celestial navigation. This site speaks of obtaining positions to one arc second, corresponding to about 30 meters on the surface of the earth. Classical celestial navigation involves finding the angle of celestial bodies above the horizon, which leads to lines of possible positions on the surface of the earth. Conventionally the technique is applied to a ship sailing on a rhumb line (a straight line on a Mercator map) at constant velocity, but by taking many measurements one reduces the statistical errors to get a more precise position estimate than one gets by making only a few measurements, as in ship navigation practice.

The USNO has implemented this method and made it available to the Navy (but not to civilian visitors to their web site). Clearly, the details would be available to DARPA.

High-precision observations and an accurate clock are necessary. But the clock need not be nearly as good as a GPS time signal. The earth rotates 1.3×10^6 arc seconds per day, or one arc second in 66 msec. If a tenth of the position uncertainty comes from clock error, then one needs a clock of millisecond accuracy. This sort of accuracy, although not available from conventional wristwatches, is not hard to come by; a field-deployed time-signal transmitter slaved to a time standard will give this level of accuracy over theater dimensions of 100 km or so with no corrections made for distance from the transmitter (although a first-order estimate of these is trivially made).

7 OTHER METHODS

We briefly considered the possibilities of orienteering, precision navigation by celestial objects emitting radio waves, and high-precision gravimetry. By orienteering we mean that the element needing geolocation is equipped with a (digital) camera which can take a panoramic picture of its surroundings, which is then compared to a (remote) database capable of constructing views of what would be seen from any given position and comparing to the digital camera view presented to the computer at the database. Precision navigation by celestial objects would mean the precise location of objects such as pulsars which emit radio signals; known celestial locations of these objects could be compared with received signals for geolocation. And gravimetric instruments which could be carried in a vehicle (not by man-pack) can measure the local acceleration of gravity at an accuracy corresponding to about 10-15 m of positional accuracy (at least at mid-latitude).

Some simple qualitative analysis shows that precision geolocation by celestial objects does not work; to receive the signals would require unduly large antennas. Orienteering might work, but it depends on a very comprehensive 3D data base. Similarly, gravimetry depends not only on a highly-accurate database of gravity variations, but also corrections for tides and other confounding effects.

8 CONCLUSIONS

1. If SARs in UAVs or in LEO fleets are available for near-continuous coverage of a theater, they can furnish precise and timely geolocation to theater ground elements, but not air elements, which move too fast to be located by the SARs.
2. Inertial navigation systems are probably necessary adjuncts to several schemes for non-GPS geolocation, to overcome possible latency problems. By themselves they do not maintain position accuracy over long enough intervals to solve the geolocation problem.
3. There are several possible methods for recruiting satellites, especially LEO satellites, to be used essentially as pseudolites, either by passive signal reception and correlation in the theater, or by active interrogation. These are worthy of further study, since it is not clear from our preliminary work which of them are really practical.
4. Such prosaic methods as celestial navigation may be much more accurate than when they were first used, given the present availability of accurate time transfer technology and automated telescopes. Further investigation is warranted.
5. A theater-scale variant on LORAN or other hyperbolic navigation systems is practical with today's technology at much greater accuracy than originally promised by these systems.

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Dr. Jane Alexander
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3701 N. Fairfax Drive
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DARPA
STO
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Dr. Darrell W. Collier
Chief Scientist
U S Army Strategic Defense Command
PO Box 15280
Arlington, VA 22215-0280

Dr. James F. Decker
Principal Deputy Director
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U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dr. Martin C. Faga
President and Chief Exec Officer
The MITRE Corporation
N640
7515 Colshire Drive
McLean, VA 22102

Mr. Dan Flynn [5]
Program Manager
DI/OTI/SAG
5S49 OHB
Washington, DC 20505

Ms. Nancy Forbes
Senior Analyst
DI/OTI/SAG
5S49 OHB
Washington, DC 20505

Dr. Paris Genalis
Deputy Director
OUSD(A&T)/S&TS/NW
The Pentagon, Room 3D1048
Washington, DC 20301

Dr. Lawrence K. Gershwin
NIC/NIO/S&T
2E42, OHB
Washington, DC 20505

General Thomas F. Gioconda [10]
Principal Deputy for Military Application
Defense Programs, DP-12
National Nuclear Security Administration
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

General John Gordon
Under Secretary for Nuclear Security
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Mr. Lee Hammarstrom
National Reconnaissance Office
14675 Lee Road
Chantilly, VA 20151

Dr. Theodore Hardebeck
STRATCOM/J5B
Offutt AFB, NE68113

Mr. David Havlik
Manager
Weapons Prg Coordination Office
MS 9003
Sandia National Laboratories
PO Box 969
Livermore, CA 94551-0969

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Dr. Robert G. Henderson
Director
JASON Program Office
The MITRE Corporation
W553
7515 Colshire Drive
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Mr. O' Dean P. Judd
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Dr. Yeongji Kim
IC JASON Program Coordinator
Intelligence Technology Innovation Center
3N21 Plaza A
Gate 5, Colonial Farm Road
McLean, VA 22101

Dr. George Mayer
Scientific Director
Army Research Office
4015 Wilson Blvd
Tower 3, Suite 216
Arlington, VA 22203-21939

Dr. Maureen I. Mc Carthy
US DOE
NNSA
1000 Independence Ave, SW
DP-10, Room 7B-252
Washington, DC 20585

Dr. Thomas Meyer
DARPA/DIRO
3701 N. Fairfax Drive
Arlington, VA 22203

Dr. Julian C. Nall
Institute for Defense Analyses
1801 North Beauregard Street
Alexandria, VA 22311

Major General John S. Parker
U.S. Army Medical Research and Material
Command
504 Scott Street
Ft Detrick, MD 21702-5012

Dr. Ari Patrinos [5]
Associate Director
Biological and Environmental Research
SC-70
US Department of Energy
19901 Germantown Road
Germantown, MD 20874-1290

Dr. John R. Phillips
Chief Scientist, DST/CS
3N21 Plaza A
Gate 5, Colonial Farm Road
McLean, VA 22101

Mr. John Rausch [2]
Division Head 06 Department
NAVOPINTCEN
4301 Suitland Road
Washington, DC 20390

Records Resource
The MITRE Corporation
Mail Stop W115
7515 Colshire Drive
McLean, VA 22102

Dr. Dan Schuresko
Acting Director
National Security Space Architect
Po Box 222310
Chantilly, VA 20153-2310

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3450 Massachusetts Ave, NW
Building 1
Washington, DC 20392-5421

Dr. Anthony J. Tether
DIRO
DARPA
3701 N. Fairfax Drive
Arlington, VA 22203-1714

Dr. George W. Ullrich [3]
ODUSD(S&T)
Director for Weapons Systems
3080 Defense Pentagon
Washington, DC 20301-3080

Dr. Bruce J. West
FAPS
Senior Research Scientist
Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

Dr. Linda Zall
Central Intelligence Agency
DS&T/OTS
3Q14, NHB
Washington, DC 20505