NASA/TM—2004-213180

Non-GPS Geolocation for Space and Terrestrial Applications

Daryl C. Robinson
Glenn Research Center, Cleveland, Ohio

December 2004

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2004-213180

Non-GPS Geolocation for Space and Terrestrial Applications

Daryl C. Robinson
Glenn Research Center, Cleveland, Ohio

Prepared for the
International Conference on Computing, Communications and
Control Technologies (CCCT 2004)
cosponsored by The Center for Lifelong Engineering Education of the University of Texas
at Austin and the International Institute of Informatics and Systemics (IIIS)
Austin, Texas, August 14–17, 2004

National Aeronautics and
Space Administration

Glenn Research Center

December 2004

Acknowledgments

I wish to thank my boss, Calvin Ramos, for informing me of MAXIM and originally encouraging me to work on it. I thank him also for allowing me to continue my research in the area of MAXIM Communications, which has proved a very fertile area for spin off applications—for both government and commercial interests. I also wish to thank Dr. W. Dan Williams, my boss's boss, for encouraging the discussion of these ideas in a Brown Bag Seminar, in which other potential applications of this ranging innovation were manifested. Finally, I also thank Dr. Kul Bhasin and David Foltz for funding this research.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Non-GPS Geolocation for Space and Terrestrial Applications

Daryl C. Robinson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135
Phone: 216–433–3553; E-mail: Daryl.C.Robinson@nasa.gov

ABSTRACT

Some near and far term space missions involve formation flying, which requires that the positions of multiple spacecraft be accurately known relative to a hub spacecraft. Many such missions will be located far outside the radius of the GPS constellation. So in such missions it will not be possible to derive position knowledge through the capabilities afforded by the GPS service. Consequently, in such missions, it is necessary to determine relative positions by other means. Depending on how well a position must be known, thus far it has appeared necessary to use means other than RF ranging, due to technical limitations. Once spacecraft have been crudely positioned using RF ranging, other tools such as star trackers, ccd cameras, and laser ranging are to be used for precise and accurate ranging. NASA Glenn is investigating an innovation in RF ranging that could be very useful for extending the capabilities of RF ranging in many circumstances. Currently, this innovation is a technical secret, but this paper will discuss the possibility of using RF triangulation for the purposes stated in its title, without disclosing any proprietary information. This paper includes a simulation that successfully illustrates how this technology could be used to perform vehicle tracking.

INTRODUCTION

While the ranging innovation was inspired by research on formation flying, this paper focuses on other space and terrestrial applications of that innovation. One such space application to be discussed herein has recently emerged from the new Presidential Space Exploration Initiative calling for colonization of the moon [1]. Such a colony would involve a moon base and moon rovers that would transport lunar explorers across the surface of the moon. With such a vision in mind, it is an important requirement that those residing in the base be able to accurately know the location of their colleagues in moon rovers that may have been driven out of the range of line of sight communication. Inasmuch as there are no GPS [2] satellites orbiting the moon and it is impractical to make it so, it is necessary to consider other means by which this remote position-determination requirement may be met. Furthermore, there are also terrestrial applications that can make use of the aforementioned innovation that fall under the broad categories of people, object, and vehicle tracking. An example of people tracking is that of tracking firefighters in a burning building [3]. An example of object tracking is localization or position-determination of a robot's location [4]. Finally, an example of vehicle tracking is non-GPS tracking of automobiles for surveillance or auto-theft recovery purposes.

The simulation and analysis of tracking lunar rovers relative to a moon base is germane to NASA's mission; however, the same analytical techniques can be used to easily generalize the results to other planets or environments navigable by land vehicles, the greatest interest obviously being in terrestrial tracking. With this object in mind, we first consider terrestrial tracking while illustrating how to perform lunar tracking.

Terrestrial Vehicle Tracking Application

There are many reasons one may wish to use terrestrial vehicle tracking. The aim of this paper is not to discuss every one, but to focus on one of timely interest. A particular company has approached us to ascertain whether it is possible to know—at a remote location—the approximate location of a vehicle without using GPS. We address this problem with the same solution we propose for lunar vehicle tracking. We propose establishing a sparse network of towers of potentially modest height. The relative locations of the towers in the network need to be known. We will show that this accomplishment is quite feasible by discussing the required number of towers and their height. To motivate this discussion, we begin with the assumption that if we can communicate with sufficient power then the only barrier that would prevent neighboring towers from communicating is that they are on opposite sides of the horizon. Now we obtain the maximum range between two towers of given height, h, by allowing their line of sight to be tangent to the surface of the earth (fig. 1).

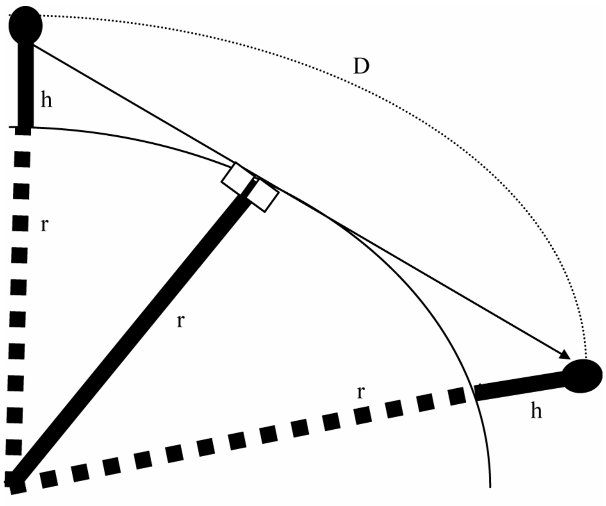

Figure 1.—Auxiliary diagram I for line of sight calculation.

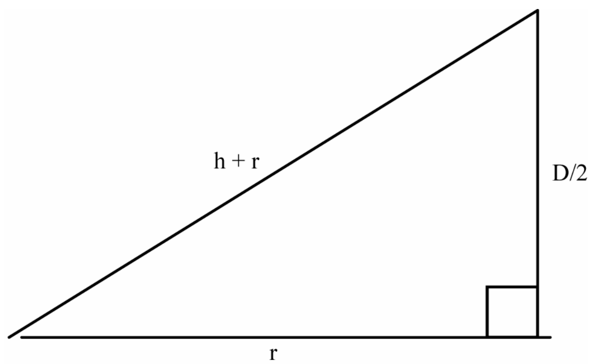

Figure 2.—Auxiliary diagram II for line of sight calculation.

Using auxiliary figure 2, we can obtain the length of the segment, D, joining the transceivers of two such towers:

$$(h + r)^2 = (D/2)^2 + r^2 \qquad (1)$$

We use 6, 356.91 km as the radius of the earth, and 1, 738.09 km as that of the moon. According to Eq. (1), for the earth, D = 71, 313.162 m; for the moon, D = 37, 290 m. To establish the network as a square grid of towers in, say, a metropolitan area, consider figure 3.

So we see that a 3 by 3 grid of 9 towers will cover at least a square area of 62.7 by 62.7 miles. Every point within this square grid is less than a distance D from at least three towers. Such a calculation reveals the installation of such a tower network to be quite feasible. The purpose of each tower is to calculate the range from that tower to the vehicle being tracked. We are at liberty to mention the capability we have developed, but we are not permitted to describe the method of implementation. We have developed ranging technology that will, in the grid described, enable the three nearest towers to determine their ranges to the vehicle being tracked. The range acquisition time chosen for this simulation is 0.0186 s. That is to say, each range is determined in 0.0186 s.

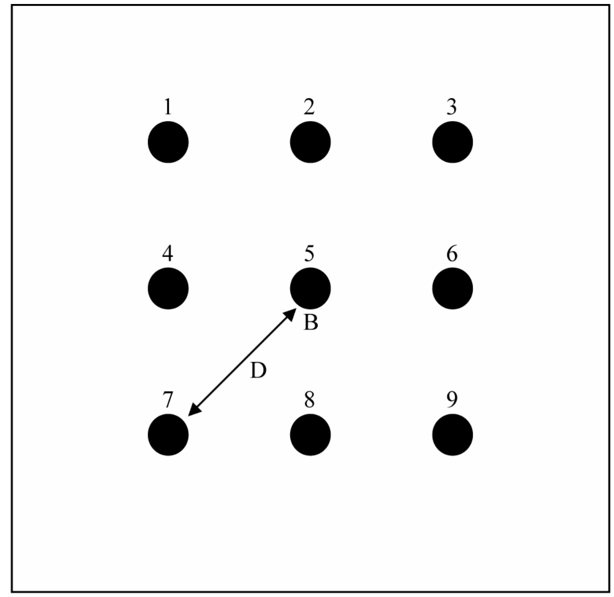

Figure 3.—D_{Earth} = 71 313.162 m. D_{Moon} = 37 290 m. Tower network (s) with dimensions.

Terrestrial Vehicle Tracking Simulation

In the simulations, the tower height h = 100 m. Such a tower height is not unreasonable since the author has personally witnessed a legal Citizen's Band (CB) antenna at a residential address in Cleveland, Ohio that is approximately 150 feet tall. It would not be incredible to envision a tower twice as high (100 m. high) next to, say, a telephone pole. A business could probably pay a residential homeowner a nominal rental fee for the right to erect such a tower in his backyard to serve the business-owner's interests. We establish the altitudes in figure 3 as follows. The planar coordinates of two random points, a and b, in the square are selected. The altitudes of a and b are randomly selected as a uniform random number in the range [0, 10 m.]. For example, in the simulation to be discussed here, a = {–19111.7, –32764.8, 8.25382} and b = {29520.9, 4176.17, 4.02696}. Consequently, the area covered by the towers is on a ramp, which either slopes upward or downward with increasing x. A representative picture of this situation is shown in figure 4. Figure 4 actually depicts a similar scenario later described, but one picture for both scenarios effectively and economically conveys the idea, even if the dimensions in that picture apply only for the latter scenario. The 11 black points embedded in the plane are the 11 positions sampled from the trajectory of the car. With all three coordinates of a and b selected, any point on the line joining a and b can be represented by $p[s] = a + s\,(b - a)$, where s is a free parameter. Given the abscissa or ordinate of any tower, it is possible to determine its corresponding s value. We assume for these simulations that the line joining a and b is not parallel to either the x or y axes. Such an assumption is valid since we choose a and b in order to make it so. Consequently,

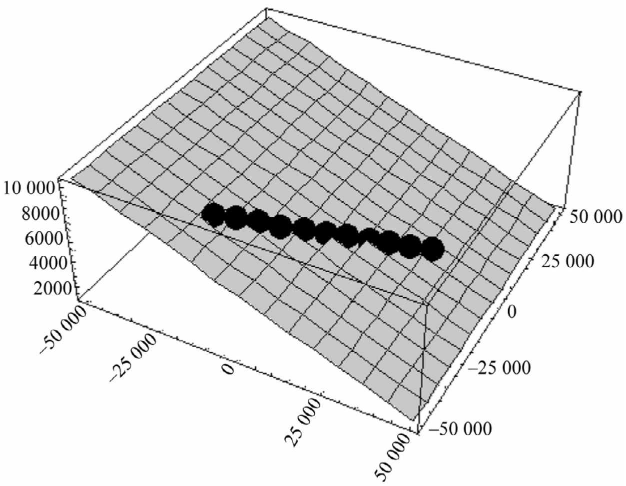

Figure 4.—Simulation scenario with sampled trajectory on inclination.

all towers having the same abscissa also have the same *s* value. Once *a* and *b* are selected, we calculate the *s* value for the central base tower (station) B. The central base station has planar coordinates {0, 0}. Every tower to the left of B has $-d\,\frac{\sqrt{2}}{2}$ as an abscissa. Likewise, every tower to the right of B has $d\,\frac{\sqrt{2}}{2}$ as an abscissa. Every tower above B has $d\,\frac{\sqrt{2}}{2}$ as an ordinate, and every one below B has $-d\,\frac{\sqrt{2}}{2}$ as an ordinate. For a particular simulation, the coordinates of each tower transceiver are given in the following table.

Tower transceiver	Coordinates (m.)
1	{–50426.02027, 50426.02027, 110.9754634}
2	{0, 50426.02027, 106.5927412}
3	{50426.02027, 50426.02027, 102.2100189}
4	{–50426.02027, 0, 110.9754634}
5	{0, 0, 106.593}
6	{50426.02027, 0, 102.2100189}
7	{–50426.02027, –50426.02027, 110.9754634}
8	{0, –50426.02027, 106.5927412}
9	{50426.02027, –50426.02027, 102.2100189}

Suffice it to say that the towers are erected parallel to the radius of the earth extending to the base of the tower (towers are plumb).

In this simulation, the estimated positions at various points of the trajectory found via ranging are juxtaposed with the actual positions of the tracked car in the following table.

Time step	Actual position of tracked vehicle	Tracked position
1	{–19111.73146, –32764.84482, 8.253816322}	{–19292.6, –32579.9, 225.908}
2	{–14248.46881, –29070.74341, 7.831131185}	{–14395.1, –29085.9, 502.434}
3	{–9385.206156, –25376.64199, 7.408446048}	{–9515.18, –25575.3, 107.568}
4	{–4521.943504, –21682.54058, 6.98576091}	{–5071.47, –21831.6, 76.472}
5	{341.3191475, –17988.43916, 6.563075773}	{396.402, –18063.9, 107.205}
6	{5204.581799, –14294.33775, 6.140390636}	{5819.44, –14530.2, 291.259}
7	{10067.84445, –10600.23633, 5.717705499}	{10426.8, –10906.3, –24739.2}
8	{14931.1071, –6906.134916, 5.295020362}	{15253.8, –6937.61, –103283.}
9	{19794.36975, –3212.033501, 4.872335225}	{19753.9, –3220.29, 104.787}
10	{24657.63241, 482.0679141, 4.449650088}	{24621.7, 894.427, 14947.7}
11	{29520.89506, 4176.169329, 4.026964951}	{29533., 4690.04, 142.863}

Note that the altitudes of the tracked positions are badly in error. These poor altitude estimates are primarily due to the unavoidable errors in range measurements; however, by having wide variations in the transceiver altitudes at the tower, they may be mitigated. Both of these statements may be verified by looking at the following simulation data. First we repeat the simulation above under identical conditions, except that we perform the range measurements with no error.

Time step	Actual position of tracked vehicle	Tracked position
1	{–19111.73146, –32764.84482, 8.253816322}	{–19111.7, –32764.8, 8.25382}
2	{–14248.46881, –29070.74341, 7.831131185}	{–14248.5, –29070.7, 7.83113}
3	{–9385.206156, –25376.64199, 7.408446048}	{–9385.21, –25376.6, 7.40845}
4	{–4521.943504, –21682.54058, 6.98576091}	{–4521.94, –21682.5, 6.98576}
5	{341.3191475,	{341.319,

Time step	Actual position of tracked vehicle	Tracked position
	–17988.43916, 6.563075773}	–17988.4, 6.56308}
6	{5204.581799, –14294.33775, 6.140390636}	{5204.58, –14294.3, 6.14039}
7	{10067.84445, –10600.23633, 5.717705499}	{10067.8, –10600.2, 5.71771}
8	{14931.1071, –6906.134916, 5.295020362}	{14931.1, –6906.13, 5.29502}
9	{19794.36975, –3212.033501, 4.872335225}	{19794.4, –3212.03, 4.87234}
10	{24657.63241, 482.0679141, 4.449650088}	{24657.6, 482.068, 4.44965}
11	{29520.89506, 4176.169329, 4.026964951}	{29520.9, 4176.17, 4.02696}

To verify the assertion that by having wide variations in the transceiver altitudes at the tower, errors in tracking positions may be mitigated, we repeat the simulation above with but one change: the altitudes of points a and b are uniformly chosen from the interval [0, 10000 m.] instead of [0, 10 m.]. We obtain the following table for tower transceiver coordinates.

Tower transceiver	Coordinates (m.)
1	{–50426.02027, 50426.02027, 11075.46337}
2	{0, 50426.02027, 6692.741153}
3	{50426.02027, 50426.02027, 2310.018931}
4	{–50426.02027, 0, 11075.46337}
5	{0, 0, 6692.74}
6	{50426.02027, 0, 2310.018931}
7	{–50426.02027, –50426.02027, 11075.46337}
8	{0, -50426.02027, 6692.741153}
9	{50426.02027, –50426.02027, 2310.018931}

The comparison between actual and tracked positions is given as follows:

Time step	Actual position of tracked vehicle	Tracked position
1	{–19111.7, –32764.8, 8253.82}	{–19337, –32579.9, 8373.27}
2	{–14248.5, –29070.7, 7831.13}	{–16863, –29085.9, –19510}
3	{–9385.21, –25376.6, 7408.45}	{–9832.01, –25353.6, 7906.18}
4	{–4521.94, –21682.5, 6985.76}	{–4430.16, –21831.6, 16262.7}
5	{341.319, –17988.4, 6563.08}	{583.033, –18063.9, 6648.69}
6	{5204.58, –14294.3, 6140.39}	{–14051, –14530.2, –215333}
7	{10067.8, –10600.2, 5717.71}	{10168.4, –11065.1, 5865.69}
8	{14931.1, –6906.13, 5295.02}	{15001, –6937.61, 5403.25}
9	{19794.4, –3212.03, 4872.34}	{–978.57, –3280.72, –234734.}
10	{24657.6, 482.068, 4449.65}	{46917.9, 894.427, 261049}
11	{29520.9, 4176.17, 4026.96}	{29514.4, 4690.04, 4288.32}

Clearly, there is some improvement in altitude tracking under this scenario.

Tracking Analysis

It is clear from the data presented thus far that position tracking within the grid is fairly accurate. Unfortunately, it appears that the altitude of the tracked vehicle cannot be accurately calculated through this ranging process. However, for most purposes in terrestrial tracking, the altitude is irrelevant. It is sufficient to know that the tracked vehicle is simply on the ground, where it is expected to be. Two coordinates, longitude and latitude, are sufficient for determining any position on a globe. So in spite of the fact that altitude is apparently not determined here, it appears as though this method is useful for determining planar terrestrial positions. It is important to mention, though, that we could show that the closer (within limits) the vehicle being tracked to the three towers, the more accurate the tracking, with very little dependence on the speed of the vehicle (high tracking accuracies for vehicles with speeds of 350 mph or more); space does not permit such a demonstration in this paper, but such simulations have been performed and this demonstration is in the process of being published. In this case, it does matter that the simulated speed of the vehicle being tracked is 120 mph; though it is very far from the towers, if it were moving very slowly, its tracking accuracy would go inversely with its speed, including that for altitude tracking, assuming wide variations in tower transceiver altitudes.

Space limitations also do not permit a lengthy excursion into the details of lunar tracking. However, calculations of lunar tracking are similar and yield similar results; moreover, the theoretical groundwork for lunar tracking has been laid and foreshadowed during the detailed discussion of terrestrial tracking.

Communications Considerations

In the case of lunar tracking, we do not expect that a lunar base need track many lunar rovers. Probably three rovers, at most, will be simultaneously tracked. So the lunar case will be treated as a subset of the case of terrestrial tracking, in which we expect that the central base tower will track, perhaps, many tens or even hundreds of vehicles within an area serviced by the 3 by 3 grid of towers. We anticipate that fewer than 10 frequencies would be required to implement this system since frequency reuse may be exploited, given that points more than a distance D apart may not communicate. A TDMA system could be used to track the many vehicles. With each vehicle requiring a time slot to be tracked, obviously, the number of position updates would directly depend on the number of vehicles being tracked.

CONCLUSIONS

A draft system for tracking vehicles on a moon or a planet without using GPS has been introduced, simulated, and analyzed. The success of the system depends on undisclosed, proprietary technology under development here at NASA Glenn. In the simulations, it was assumed that the car was traveling at 120 mph—to a significant extent, the slower the tracked vehicle, the more accurate the tracking. Of course, it is an unlikely scenario to be tracking any vehicle moving at speeds around 120 mph, but when the system is successfully tested under the most extreme conditions, it is clear that it would work for less stringent ones as well. It is quite possible that with the right positioning of towers at an airport, this technology and a similar tracking network—involving very little infrastructure—could also enable very accurate non-GPS tracking of aircraft. We are in the process of selecting a company to build a prototype of this ranging innovation.

REFERENCES

[1] http://www.space.com/news/bush_plan_faq_040115.html

[2] http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html

[3] http://www.fcw.com/geb/articles/2003/0818/web-fire-08-22-03.asp

[4] Steps toward triaural perception, H. Peremans, J.V. Campenhout, L. Levrouw, pp. 165–176, http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=5953111

BIOGRAPHY

Daryl C. Robinson received a B.S. in Mathematics from Case Western Reserve University (CWRU) in 1994, an M.S. in Electrical Engineering with a specialty in Computer Engineering from Cleveland State University in 1999, and began working on his doctorate in Computer Engineering at CWRU in 2000. In December 2003, he finished his final doctoral course in wireless communications and began his doctoral research, of which this paper is the second output. Additionally, he became the sole co-investigator for MAXIM communications at the NASA Glenn Research Center. He has expertise in mathematical and computer modeling and simulation, including OPNET, VHDL, and Mathematica.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
December 2004

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Non-GPS Geolocation for Space and Terrestrial Applications

5. FUNDING NUMBERS
WBS–22–302–20–1M

6. AUTHOR(S)
Daryl C. Robinson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135 – 3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E – 14675

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546 – 0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2004-213180

11. SUPPLEMENTARY NOTES
Prepared for the International Conference on Computing, Communications and Control Technologies (CCCT 2004) cosponsored by The Center for Lifelong Engineering Education of the University of Texas at Austin and the International Institute of Informatics and Systemics (IIIS), Austin, Texas, August 14–17, 2004. Responsible person, Daryl C. Robinson, organization code 5610, 216–433–3553.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 32 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Some near and far term space missions involve formation flying, which requires that the positions of multiple spacecraft be accurately known relative to a hub spacecraft. Many such missions will be located far outside the radius of the GPS constellation. So in such missions it will not be possible to derive position knowledge through the capabilities afforded by the GPS service. Consequently, in such missions, it is necessary to determine relative positions by other means. Depending on how well a position must be known, thus far it has appeared necessary to use means other than RF ranging, due to technical limitations. Once spacecraft have been crudely positioned using RF ranging, other tools such as star trackers, ccd cameras, and laser ranging are to be used for precise and accurate ranging. NASA Glenn is investigating an innovation in RF ranging that could be very useful for extending the capabilities of RF ranging in many circumstances. Currently, this innovation is a technical secret, but this paper will discuss the possibility of using RF triangulation for the purposes stated in its title, without disclosing any proprietary information. This paper includes a simulation that successfully illustrates how this technology could be used to perform vehicle tracking.

14. SUBJECT TERMS
Formation flying; Geolocation; Moon; Space exploration; Ranging; Tracking; Surveillance

15. NUMBER OF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	