Pseudolite Augmented Navigation for GEO Communication Satellite Collocation [1]

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ABSTRACT

This paper presents some of the technical and economic incentives for developing satellite communication systems based on clusters of spacecraft located in a single GEO orbit slot. Collocating multiple satellites in the same slot will require improved techniques for relative vehicle sensing of both position and velocity. Current ground based tracking of satellite positions requires a high level of ground operations support to provide this information, a burden which will become unmanageable as the number of GEO satellites increases in the future. As a result, autonomous navigation of GEO orbiting satellites has become highly desirable, and GPS ranging measurements are a key enabling technology for achieving this goal.

However, the visibility of the NAVSTAR constellation from GEO is limited, due to the earth pointing transmit antennas of the GPS constellation [3]. There is sporadic visibility to the GPS satellites due to the beamwidth of the GPS transmitter being slightly larger than the limb of the Earth, but these signals are only briefly visible, and are degraded due to the low grazing angle through the Earth's atmosphere. For these reasons, an augmentation of the visible NAVSTAR signals with additional ranging signals is required. Two different methods for augmenting the GPS constellation with additional ranging measurements are examined in this paper. One method is based on placing ground-based pseudolite transmitters at widely separated locations on the Earth to provide constantly visible ranging signals to the GEO satellite. The second method uses pseudolite transmitters onboard each satellite in the GEO cluster to directly measure the relative spacecraft range and range rate.

Results from a simulation study of the relative position and velocity determination performance of these two methods are compared with the performance using measurements from the unaugmented NAVSTAR satellites. Also, the benefits and drawbacks of these two methods, in terms of cost and potential for interference, are briefly addressed.

1 INTRODUCTION

GEO satellite-based communications represents a significant portion of the space-based telecommunications market. A satellite nominally drifting over a single region of the globe is attractive because a single platform can remain in view of a target market region 24 hours a day providing narrowband and wideband services over regions as large as the Americas. Multiple LEO or MEO platforms would be required to provide a similar concentration on a specific region of high commerce. However, there are many challenges for a GEO communications satellite system. Large distances from the Earth (22,000 nm) mean larger antenna apertures are required compared to LEO or MEO. A 250 msec one-way delay is present for a GEO system, which is unattractive for telephony and broadband data applications. And there is a high acquisition cost, associated primarily with launch into geosynchronous transfer orbit (GTO), but also with a 15-17 year mean mission duration of the satellite. However, technology is available to deal with these issues and GEO remains a very attractive growth area for telecommunications. Forecast market demand, parameterized in terms of DC payload power, follows a Moore's Law growth curve similar to that observed in the semiconductor industry [14].

To meet this future demand, spacecraft designers are faced with the dilemma of providing more capability (payload broadcast power) in a volume confined by launch vehicle faring and lift capability. The end results are formidable technology barriers in terms of spacecraft thermal management, materials and structure, and propulsion systems. A rational look at alternatives to address these issues is warranted. Formation flying of multiple platforms operating in the same orbital slot offers one attractive alternative. This collocation concept was demonstrated in 1984 with the deployment of the ASTRA satellites [13], where a GEO cluster was deployed as a way to share an

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[1] ID#195, Presented at IEEE Aerospace Conference, Big Sky, MT, March 18, 2000, ©2000 IEEE

orbital slot among several European countries (SES Luxemburg).

The future need for clusters at GEO is driven strongly by technology and also by the need to maximize the usefulness of individual GEO slots, particularly those preferential to regions of high market demand. GEO satellites typically occupy station keeping boxes of 0.10° × 0.10° in latitude and longitude, which is approximately 40 nm ×40 nm. The ASTRA cluster is 5 satellites in this box controlled by several different ground stations. Spacing on the order of 10 nm is therefore achievable. With the advent of GPS and other augmentation sensors to provide relative position among clustered satellites, a higher population of satellites per GEO slot is anticipated.

This paper presents two different methods for solving the relative position and velocity sensing problem for GEO communications satellites. These methods are derived from and build on current GPS sensing technologies. In particular, the advent of commercially available local L1 GPS pseudolite transmitters [7] has provided spacecraft designers with a new sensor opportunity that complements the current NAVSTAR constellation. The results of the analysis and simulation of two configurations using L1 GPS pseudolite transmitters to augment the position and velocity sensing capabilities of the NAVSTAR constellation are shown here.

The first augmentation method examined is placing ground based pseudolite transmitters [7] at widely separated locations on the earth to increase the average number of visible transmitters for a satellite in GEO. The navigation performance of such an enhancement system is examined, as well as the interference issues of placing a high powered upward looking ground based L1 transmitter on the earth. Pulsing schemes and directional antennas are addressed.

The second augmentation method described in this paper places GPS pseudolite transmitters onboard the GEO communications cluster satellites, to form a 'self-constellation'. The separation visibility requirements for effective code and carrier phase ranging are examined, as well as issues involving self-jamming of a GPS L1 pseudolite transceiver.

The paper also includes a more detailed description of the GEO communications cluster mission and the cost and technical incentives for developing satellite clusters collocated in a single GEO slot, presented in Section 2. The previous research involving the use of GPS pseudolite transmitters for augmenting the NAVSTAR signals is summarized in Section 3. The results of a simulation study providing a comparative analysis of the two different relative position and velocity sensing augmentation concepts is presented in Sections 4. These studies also examine the trade-offs associated with developing each GPS sensing augmentation strategy in terms of cost.

2 GEO COMM MISSION DESCRIPTION

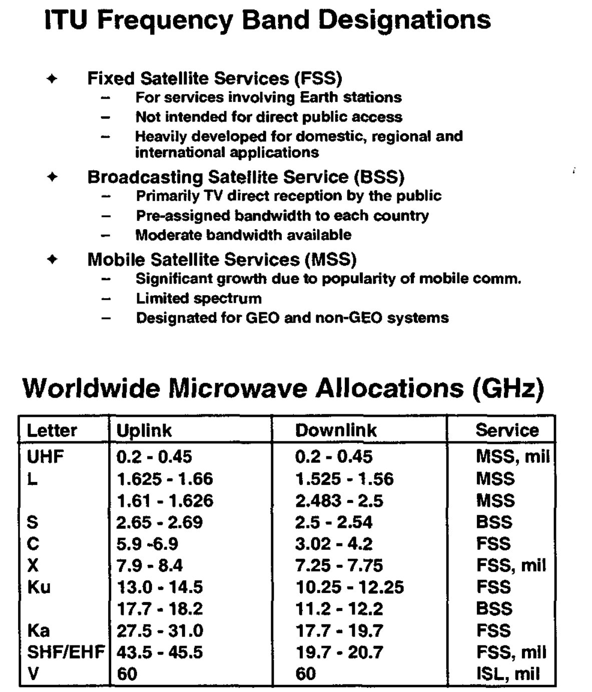
To examine geostationary communications as a segment of the global communications business, the influence of market demand, economics, and technology on defining affordable systems architectures must be explored.

Table 1 lists four basic architectures for space-based communications.

Table 1: Basic space-based communication system architectures.

Architecture	Advantage	Disadvantage
Low Altitude, Single Satellite, Store and Forward	• Low-cost launch • Low-cost satellite • Polar coverage	• Long message access time and transmission delay of up to several hours.
Geostationary	• No switching between satellites • Ground station tracking often not required	• High-cost launch • High-cost satellite • Need for stationkeeping • Propagation delay ~250 msec • No polar coverage
Geostationary w/ crosslink	• Greater coverage • Reduced propagating delay • No foreign ground station • better security • less cost	• Higher satellite complexity & cost • Cost of relay satellite & launch
Molniya	• Low-cost launch per satellite • Polar coverage	• Several satellites for coverage • Need antenna tracking and satellite handover • Need stationkeeping • Network control is complex
LEO Multiple Satellites w/Crosslinks	• Highly survivable • Limited Earth view; limited jamming • Polar coverage • Low-cost launch per satellite • Reduced transmitter power	• Complex & dynamic network control • Complex end-to-end link acquisition • Many satellites required to support minimum link margin

The International Telecommunications Union (ITU) establishes a constraint envelope in which service providers must operate. For example, Figure 1 shows the ITU designated frequency bands and the allocation of type of service within those bands. Other restrictions also apply concerning radio interference and radiated power. This brings us to the next important topic; how to describe or rank different services. There are two basic classes, broadcast (10's of channels at 10's of MHz) or bulk-transfer (10's of thousands of telephone circuits). The common denominator that is typically used as a figure of merit is power, in particular kilowatts of payload power. In the past 15 years there has been a steady growth in the amount of radiated power that is provided by a communications satellite [14]. This "Moore's Law" type of growth is illustrated in Figure 2, where an exponential curve was fit to payload capability dating back to 1984. This curve is then extrapolated to the future to illustrate the type of demand that could be anticipated should this trend continue. This growth in demand for radiated power from the communications satellite is what the service providers of the communications industry believe is a reasonable expectation of future growth. Commercial satellite manufacturers such as Lockheed Martin, Space Systems LO-



ITU Frequency Band Designations

- **Fixed Satellite Services (FSS)**
  - For services involving Earth stations
  - Not intended for direct public access
  - Heavily developed for domestic, regional and international applications
- **Broadcasting Satellite Service (BSS)**
  - Primarily TV direct reception by the public
  - Pre-assigned bandwidth to each country
  - Moderate bandwidth available
- **Mobile Satellite Services (MSS)**
  - Significant growth due to popularity of mobile comm.
  - Limited spectrum
  - Designated for GEO and non-GEO systems

Worldwide Microwave Allocations (GHz)

Letter	Uplink	Downlink	Service
UHF	0.2 - 0.45	0.2 - 0.45	MSS, mil
L	1.625 - 1.66	1.525 - 1.56	MSS
	1.61 - 1.626	2.483 - 2.5	MSS
S	2.65 - 2.69	2.5 - 2.54	BSS
C	5.9 -6.9	3.02 - 4.2	FSS
X	7.9 - 8.4	7.25 - 7.75	FSS, mil
Ku	13.0 - 14.5	10.25 - 12.25	FSS
	17.7 - 18.2	11.2 - 12.2	BSS
Ka	27.5 - 31.0	17.7 - 19.7	FSS
SHF/EHF	43.5 - 45.5	19.7 - 20.7	FSS, mil
V	60	60	ISL, mil

Fig. 1: ITU frequency band designations and allocations.

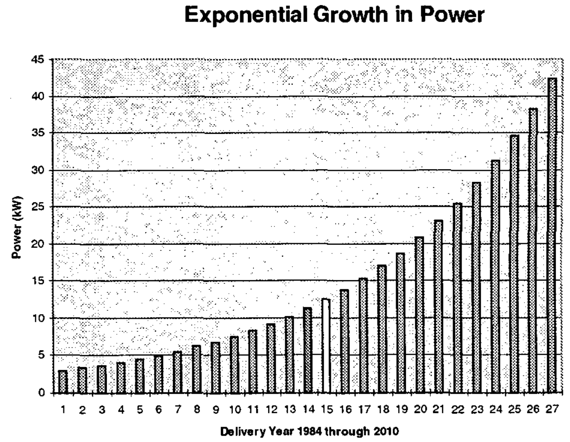


Fig. 2: Market demand for satellite payload power versus time. Data fit for years 1984 to 1999, and extrapolated to the year 2010.

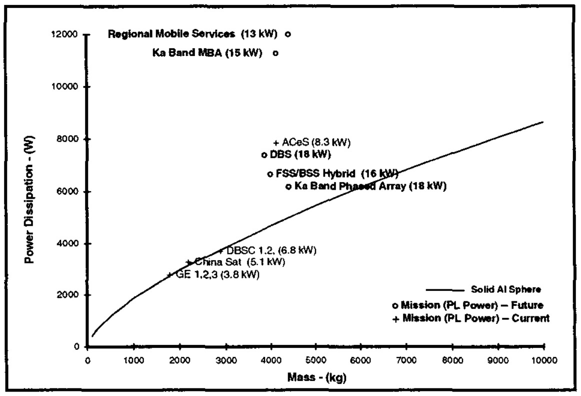


Fig. 3: Payload power dissipation versus satellite mass for several GEO spacecraft examples, compared with 850° C Aluminum sphere (solid line).

RAL, and Hughes, as well as European satellite manufacturers, are competing to provide the highest available payload power. One approach to achieving this goal is to build bigger satellites capable of generating higher powers, but this is not the only possible answer.

One key problem with this predicted growth is that radiated power demand will significantly outpace the ability of spacecraft to support the kinds of high powered payloads that will be required. To meet this challenge, hardware providers are pushing technology to the limit. Power generation, at least for the near term, is not as critical an issue as dealing with the consequential heat load on the spacecraft. Figure 3 is an illustration of the problem. As the payload power grows to meet the market demand, the dissipation within the body of the spacecraft increases.

The increase in heat actually helps the dissipation problem because the power the spacecraft radiates into free space goes as σT^4, where T is spacecraft temperature and σ is Boltzmann's constant. Some temperature rise is beneficial in that it increases the amount of radiant heat dissipation. However component lifetimes suffer with increased spacecraft temperature, as mean time to failure becomes shorter and active electronics still need to run at junction temperatures below 1250° C. As a result, designers try to keep the maximum temperature rise to 850° C. Figure 3 also plots a simple solid Al sphere (6061), a typical material used to build structure and enclosures. The sphere represents the ideal packaging density for electronics. The sphere is extrapolated to the spacecraft mass equivalent to illustrate a point. The spacecraft below $\approx$3,500 kg seem to track along the curve pretty well. These are probably very efficient designs. In other words, the spacecraft is passively cooled; there are no extreme measures taken to dissipate the wasted heat, the spacecraft structure does an adequate job. As the payload power increases, the body dissipation increases and it becomes necessary to add extra mass just to deal with the extra heat. As a result the spacecraft gets heavier because of a larger power demand and higher power dissipation. The design is not optimized for payload mass any longer. Since the mass is growing, the volume is also growing, which also raises concerns about available launch capabilities for placing these large, high power satellites in a GEO orbit. Table 2 lists some GEO launch options that are, or soon will be, available and their respective payload mass capabilities.

Table 2: Current launch payload mass capability.

Launcher	Init. Mass (Kg)	LEO	GTO	GEO
ΔV km/sec	-	7.7	10.1	11.9
Ariane-4	200,000	-	4000	2400
Ariane-5	-	-	-	-
Atlas Centaur	150,000	-	3000	1500
Atlas IIAR	-	-	4500	-
LongMarch	-	-	4000	-
Delta	-	-	2000	1000
Japan, H-II	-	-	-	1500
USSR-Proton	-	-	4600	200
STS-Centaur	2,000,000	30,000	-	4000
Titan, 34D-IUS	500,000	15,000	5000	1500

It is desired to launch these large communication satellites all the way to GEO. An analysis of the rightmost column in Table 2 shows that 4,000 kg is the current capability limit, neglecting substantial increases in launch vehicle cost in the trade space. This optimum spacecraft mass is corroborated by the shift in the radiated power versus mass curve shown for actual spacecraft missions in Figure 3.

If we look at 'Satellite Cost-Effectiveness' (as defined by J. A. Vandenkerchkove [11] of the European Space Agency) as:

$$\frac{\text{Satellite Cost}}{\text{Satellite Usefulness}} \tag{1}$$

where 'usefulness' is related to the service actually rendered over life plus any residual value, the analysis supports an optimum spacecraft mass of $\approx$4000 kg. Figure 4 shows the results of Vandenkerchkove's evaluation of satellite designs for the period 1990 to 1998. The lower the curve, the more cost effective the satellite. The result indicates that up to about 4,000 kg the satellite efficiency increases with size. However, as launch mass increases, the usefulness of the satellite decreases and cost-effectiveness gets worse. At $\approx$4,000 kg, the satellite appears to be optimized for the launch vehicles available.

All of these factors in conjunction (the technical demands of building large, high operating temperature satellites, the launch system costs and capabilities associated with large GEO satellites, and the optimum cost-effectiveness for a communications satellite) are driving GEO communications system architectures towards the use of multiple satellite clusters. In this configuration, each satellite can be optimally sized for cost and technical considerations, while the demand for increased radiated power can be satisfied by increasing the number of satellites in the cluster. The technical challenge addressed in this paper is the increased accuracy requirements on relative vehicle position and velocity sensing associated with increasing the number of satellites in the GEO cluster.

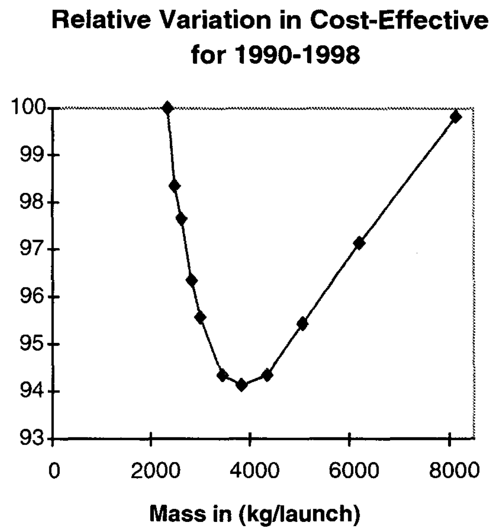


Fig. 4: Satellite cost effectiveness versus satellite mass data, as compiled by J. A. Vandenkerchkove of ESA [11].

3 PREVIOUS AUGMENTATION WORK

The use of additional transmitters to augment GPS position estimation accuracy has been previously examined, both for terrestrial [2] [4] and space-based applications [5] [8] [10].

In the work by Rupp [10], Earth-fixed pseudolite transmitters were proposed for augmenting the orbit and attitude determination accuracy for LEO spacecraft that may rotate such that their receive antennas are in view of only a portion of the NAVSTAR constellation.

Altmayer looked at using pseudolites onboard vehicles in GEO stationary orbit as a method of improving both orbit and attitude determination [8]. And Corazzini [5] has looked at augmenting the NAVSTAR constellation with signals from onboard pseudolites for the relative vehicle position sensing problem applied to spacecraft formation flying and self-constellations.

This work provides an extension to the previous work in several key areas. First, the idea of using ground based pseudolites for augmentation is extended to satellites in GEO to supplement the sporadic visibility of the NAVSTAR satellites due to Earth occlusion rather than vehicle attitude motion as examined in Rupp [10]. The focus of this work is *relative* vehicle sensing problem as it pertains to the satellite cluster mission. For formation flying, in many cases the knowledge of relative vehicle velocity is equally, if not more, important than the accuracy of relative vehicle position knowledge. In this work, we present some simulation results for the velocity estimation accuracy of two different methods of augmentation.

4 SIMULATION STUDIES

A simulation study was performed to validate the relative vehicle position and velocity estimation performance for three different cases: the unaugmented NAVSTAR constellation; the NAVSTAR constellation augmented by ground-based pseudolite transmitters; and NAVSTAR augmented with pseudolite transmitters onboard the vehicles. The relative range and range rate estimation performance is examined here for a pair of spacecraft flying in formation in a single GEO orbit slot, with one spacecraft trailing the second intrack by 1 km. The measurements were modeled in the earth-based augmentation simulation study as code phase pseudorange with 30 m RMS error. The measurements modeled in the onboard augmentation simulation study were carrier phase based pseudorange with 0.3 cm RMS ranging error. For the relative velocity estimates, we used carrier phase Doppler measurements with a normal random error of 0.5 mm/sec.

4.1 NAVSTAR With No Augmentation

As a reference point, relative position and velocity estimation simulations were performed using signals from the NAVSTAR constellation alone. As is shown in Figure 5, the total number of unaugmented transmitters visible is frequently zero, and never more than 4. The STD of the position determination error, as shown for three axes in Figure 6, shows a corresponding rise and fall as satellites come in and out of view. A similar pattern can be seen in the relative vehicle velocity estimate STD shown in Figure 7.

4.2 NAVSTAR With Earth Based Augmentation

The second set of simulations augmented the NAVSTAR constellation with 4 transmitters located on the ground. The locations of the ground based transmitters, as shown in Figure 8, were chosen to be widely spaced, with close to 150° separation in longitude and 120° separation in latitude, for improved positioning dilution of precision (DOP). The use of powerful ground based transmitters raises issues of interference with terrestrial GPS users. While some mitigation of these concerns can be achieved through the use of directional antennas pointed at particular GEO orbit locations, it will be required for this type of augmentation system that the transmitted signal not be located at the GPS L1 frequency.

The results in Figure 9 show that using these Earth fixed transmitters, the minimum number of visible transmitters over the orbit is now never less than 4. The STD of the resulting relative vehicle position error is plotted in Figure 10 for comparison to that for the unaugmented case. This result shows that the error in position determination can be significantly decreased through augmentation. A similar result for relative velocity determination is shown in Figure 11. The relative vehicle position dilution of precision is plotted in Figure 12 for the earth augmented case. For the unaugmented case, the DOP diverges when the number of measurements decreases to less than 4, so the augmented case is a significant improvement.

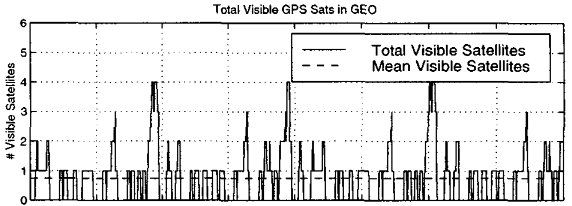


Fig. 5: Typical NAVSTAR constellation visibility from GEO orbit. The total number of satellites visible is zero for much of the orbit, and never more than 4.

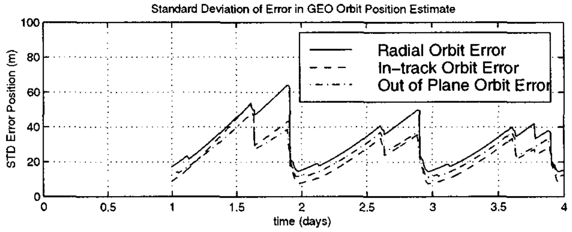


Fig. 6: Standard deviation of three axes of relative position error covariance with no GPS augmentation.

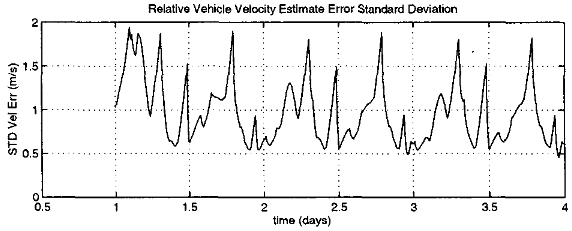


Fig. 7: Standard deviation of relative range rate error with no GPS augmentation.

4.3 NAVSTAR With Onboard Augmentation

An alternative augmentation concept is to place GPS transceivers onboard each satellite in the GEO communications cluster. A GPS transceiver consists of a GPS signal generator, GPS receiver, and a communication link between vehicles. These components can either be integrated into a single device, or remain as separate components. By employing transceivers on each vehicle, local GPS signal coverage is provided to the entire formation. These local signals enable *relative* positioning between all vehicles. In contrast with other augmentation concepts, absolute position information is not provided by the transceivers, since the transmitters are not located in known positions. Instead, the onboard transceivers provide continuous signal coverage for resolving relative position and attitude to a lead vehicle. In order to incorporate NAVSTAR satellites, absolute position and attitude information must still be obtained for one vehicle in the formation. This can be derived from standard GPS positioning techniques with the NAVSTAR constellation if a sufficient

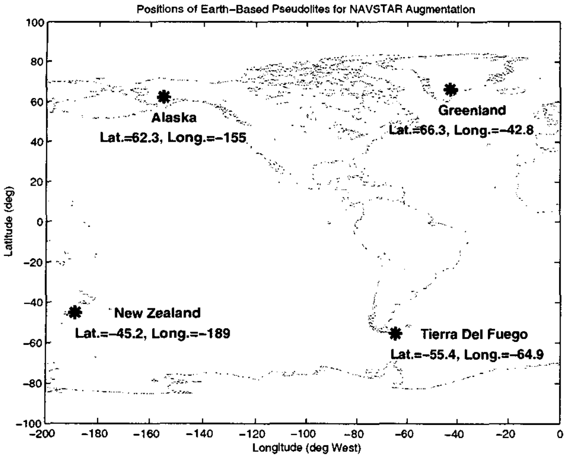


Fig. 8: Positions of ground-based pseudolite transmitters for NAVSTAR augmentation used in simulation.

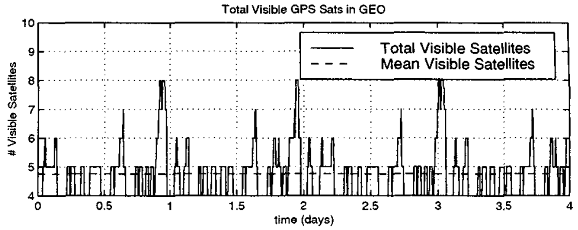


Fig. 9: Augmented NAVSTAR constellation visibility from GEO orbit. Four Earth-based pseudolite transmitters are continuously visible from GEO orbit.

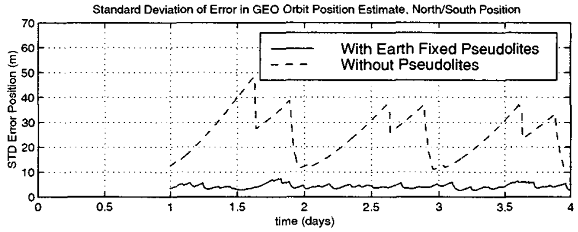


Fig. 10: Standard deviation of relative position error covariance with Earth-based pseudolite transmitter augmentation compared to the no augmentation case, for radial position component.

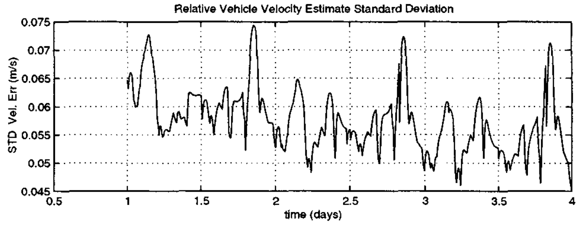


Fig. 11: Standard deviation of relative velocity error with Earth-based pseudolite transmitter augmentation compared to no augmentation case.

number of satellites are in view, or a combination of other techniques such as star trackers and ground radar ranging.

Position estimation with onboard transceivers differs from positioning with the NAVSTAR constellation in several key ways. For one, the absolute positions of the transmitters are dependent on the relative position states between vehicles. In addition, the size of the formation will determine what parameters can be estimated. With only two vehicles and no visibility to the NAVSTAR constellation, the range between vehicles and relative bearing angles can be resolved, but a full three-dimensional positioning solution cannot be carried out due to the lack of sufficient available signals. As the formation size increases beyond two vehicles, three-dimensional relative positioning can be achieved. Several changes also exist as a result of the hardware differences between the onboard transmitters and the NAVSTAR satellites. Primarily these arise from the close proximity of the transmitter to the receiver, as well as the lack of precise clocks in the onboard transmitters.

For a pseudolite to be tracked, the received signal must be greater than -130 dBm [15]. Thus, for example, if the separation between vehicles is to be 1 km, the transmitted power must be at least -70 dBm. The receiver that is collocated with the transmitter must not only be able to receive signals at -130 dBm from other vehicles and from the NAVSTAR constellation, but must also be able to handle the local transmitter at *e.g.* -70dBm. This extreme range of signal power leads to what is known as a near/far problem. If the local transmitters broadcast continuously, the receivers will be unable to track the other satellites. However, this near/far problem can be alleviated by pulsing the transmitted signal [7]. By only broadcasting the local signals for a fraction of each code epoch, the receivers in close proximity to the transmitter will not be jammed, and the much weaker NAVSTAR satellite signals can still be received. For small formations (*e.g.* ≤ 3 vehicles) a random pulsing scheme will provide sufficient information to the receivers for tracking the signals. However, as the formation size increases, coordination among vehicles may be desirable to avoid overlapped broadcasting.

Pulsing alone will not eradicate all problems associated with onboard transmitters. The desired size of the formation will impact the choice of an effective transmitting architecture. There is an upper limit on the formation size, based on the ability to receive satellite signals. A certain percentage of the GPS satellite signals can be blocked before the receivers are no longer able to track the signals. For the NAVSTAR satellite signals at -130 dBm, that percentage is approximately 20% [7]. With a single pulsed transmitter operating at approximately a 7% duty cycle, this would allow at most three onboard transmitters to be tracked before the NAVSTAR constellation would no

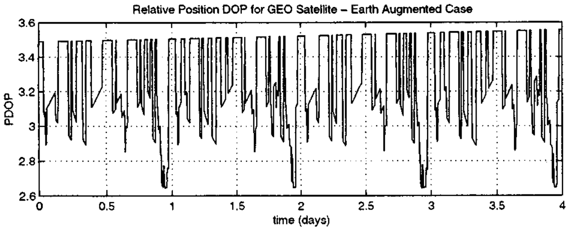


Fig. 12: Relative position dilution of precision (DOP) for NAVSTAR constellation augmented with four Earth-based pseudolite transmitters, for radial position component.

longer be able to be tracked by the receiver. This situation can be mitigated by the use of the pulse blanking technique recommended by Cobb [7]. If the satellite tracking channel correlators are disabled during the pulsing of the local transmitters, the interference is significantly reduced. The percent of the GPS satellite signal that could be blocked while employing pulse blanking is increased to greater than 60%. Thus, for example, with a 7% duty cycle on the onboard transmitters, at least eight pseudolites could be used. However, this illustrates the hard limit on the number of onboard transmitters. For larger formations of spacecraft, one alternative is to break the formation into clusters, such that any individual vehicle is not receiving more than eight onboard transmitters. This can be achieved through careful antenna placement and beam-shaping. Breaking the estimation problem for large formations into smaller clusters of spacecraft is a desirable estimation architecture, thus this is not necessarily a severe limitation.

An important consideration for onboard augmentation is a consistent source of timing. For differencing of measurements between vehicles, the measurements must be taken at the same time. For most GPS applications, this is based on GPS time. However, when the NAVSTAR constellation is not in view, inter-vehicle differences with the onboard pseudolites must still be taken at the same time, and this timing can no longer be based on GPS time. One solution is to designate the transmitter on one vehicle the "master pseudolite" [16]. All synchronization is then carried out with respect to this master pseudolite. To simplify the amount of logic needed, the master pseudolite can continue to be the source of timing, even when the NAVSTAR constellation satellites are in view. Synchronization is achieved through interpolation and a 50 bit per second data message on the master pseudolite. The receivers are synched to the 1 ms level by the 50 bps message [16], and further alignment is carried out by interpolation. Each phase measurement can be corrected using the linear equation,

$$\phi_{tt} = \dot{\phi}(t_{tt} - t_{lt}) + \phi_{lt} \tag{2}$$

$$y = m(x - x_1) + y_1 \tag{3}$$

where ϕ_{tt} is the phase measured at the "true time" (defined by the master pseudolite), and ϕ_{lt} is the phase measured at the "local time". The time difference between true time and local time, $(t_{tt} - t_{lt})$ is simply the code phase measurement from the master pseudolite, corrected by the time of flight between the master pseudolite and the receivers. For closely spaced vehicles, the time of flight can be omitted entirely. However, as the inter-vehicle spacing is increased such that the error approaches 1 μs, an approximate range measurement should be used to include the time of flight. The range measurement can be found with sufficient accuracy through code ranging between vehicles. This approach has been sucessfully used for several ground vehicle testbeds.

4.3.1 Simulation Results: In these simulations, the accuracy of relative range and range rate estimation for a formation of vehicles is examined. Only one receive antenna per vehicle is considered in the problem formulation. In practice, multiple antennas could be placed on each vehicle in order to solve not only relative range, but also relative bearing (see [6] for a description of resolving relative bearing angles for a two vehicle self-constellation with an RF sensor system). For the simulations and experimental results presented in the following sections, a formation of two vehicles is considered. For a two vehicle formation, when no NAVSTAR satellites are available, only the magnitude of the range vector can be resolved. More measurements would be needed to resolve three components of the position vector. Therefore all equations have been framed in terms of two states: a relative range between the vehicles, and a relative clock offset between the two receivers. The resulting measurement equation is,

$$\begin{bmatrix} \Delta_1\phi_{12} \\ \Delta_2\phi_{12} \\ \Delta\phi_{12}^1 \\ \vdots \\ \Delta\phi_{12}^n \end{bmatrix} = \begin{bmatrix} 1 & -c \\ -1 & -c \\ \cos(\theta_1)\cos(\psi_1) & -c \\ \vdots & \vdots \\ \cos(\theta_n)\cos(\psi_n) & -c \end{bmatrix} \begin{bmatrix} \rho_{12} \\ \delta_{12} \end{bmatrix} + \lambda N + \nu \tag{4}$$

The notation used in Equation 4 is depicted graphically in Figure 13. ρ_{12} is the relative range from vehicle 1 to vehicle 2, δ_{12} is the relative clock error between the two receivers, n is the number of NAVSTAR satellites in view, N is the column vector of integer ambiguities associated with carrier phase measurements, ν is the noise on the measurements, c is the speed of light, $\Delta_1\phi_{12}$ is the single difference measurement from the transmitter on vehicle 1 to the receivers on vehicles 1 and 2, and $\Delta\phi_{12}^1$ is the single difference measurement from the first available NAVSTAR satellite to the receivers on vehicles 1 and 2. Thus, the first two rows of Equation 4 are the self-constellation equations that are available independently of the NAVSTAR satellites. The subsequent rows are only available when NAVSTAR satellites are in view. Two angles are associated with the measurements with the NAVSTAR constellation. These angles define the relative bearing of the two vehicles with respect to the line-of-sight (LOS) to the NAVSTAR satellite. Note that the LOS is assumed to be the same for both vehicles and both the LOS and the bearing angles are assumed to be known. These assumptions are consistent with the initial problem statement that the onboard transceivers provide relative position information only: the absolute position of the lead vehicle is assumed to be known, therefore the LOS to the satellite is available. The angles could be resolved by using multiple antennas on each vehicle and completing an attitude estimation problem.

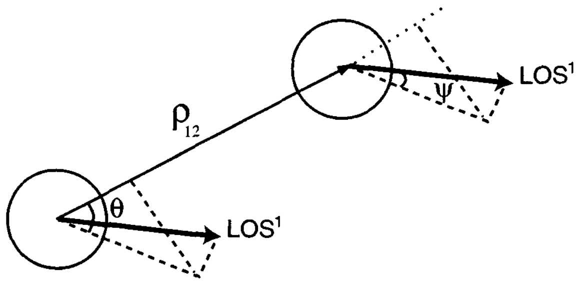


Fig. 13: Notation for Formation Estimation Problem

With these assumptions, simulations were run to quantify the range resolution accuracy and the DOP on the range measurements, for comparison with other augmentation methods. An equatorial orbit was chosen, and for a single orbit, the DOP on the range is plotted in Figure 14. These DOP values relate the single difference measurement noise to the resulting range error. When all satellites drop out of lock, the onboard pseudolites provide measurements yielding a DOP of 0.5. When satellites are available, the DOP is decreased further.

As an example of the ranging accuracy expected with such a system, a simulation was run for the same orbit, and at each timestep range and relative clock error were resolved without adding additional knowledge from the orbital dynamics. Zero mean, 0.37 cm^2 variance noise was added to the measurements. The integer ambiguities were assumed known for simplicity. Optimal methods for integer resolution for the measurements involving the onboard transmitters are still under investigation. For more detail on how to resolve the relative positioning integers with the NAVSTAR satellites, see [9]. The resulting position error covariance is depicted in Figure 15.

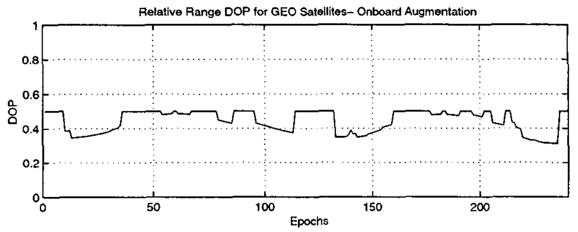


Fig. 14: DOP on relative range for two vehicles in GEO orbit, using onboard augmentation.

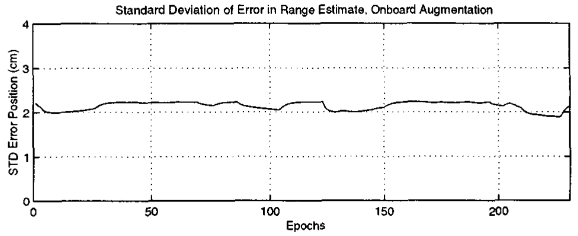


Fig. 15: Error in range for two vehicles in GEO orbit, using onboard augmentation.

Simulation results for relative velocity sensing using onboard pseudolite transmitters indicate that using Doppler measurements relative range rate estimates with accuracies on the order of 2.5 mm/sec are possible.

4.3.2 Experimental Results: An indoor testbed was used to validate the ranging sensor and to provide data for determining the measurement noise characteristics used in the simulations of onboard augmentation. The testbed consists of two autonomous vehicles, each equipped with a GPS transmitter, and GPS receiver. The transmitted signal is produced by an Integrinautics IN200c signal generator, and transmitted through a quadrifilar helix antenna. The signal is pulsed with a 10% duty cycle. (A slightly larger duty cycle than discussed previously was chosen due to the receiver used in these tests: the TANS Quadrex receiver multiplexes between four antennas, thus requires a slightly larger duty cycle than other receivers). The two receivers collect the GPS data, and all information is sent to the one lead vehicle, which processes the data. The only measurements used in the ranging solution are the two single differences from each of the onboard transmitters.

Initialization of the integers was ignored for this demonstration, thus the resulting ranging accuracy is plotted in Figure 16 with the constant bias offset subtracted out. The variance in the ranging solution is 0.13 cm^2 which is consistent with the value predicted by the measurement noise and the dilution of precision. In the indoor environment, and with the receivers used in this experimental demonstration, the variance on the single difference measurements was approximately 0.37 cm^2 (see Figure 17).

5 SUMMARY OF SIMULATION RESULTS

The simulation results from the previous section are summarized in Table 3. This table compares the

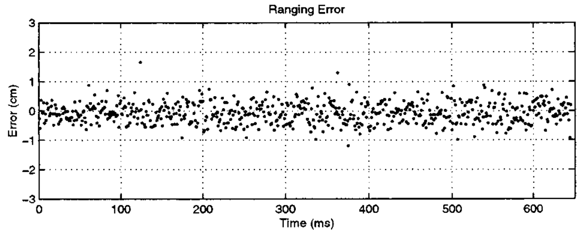


Fig. 16: Experimental error in range for two vehicles, onboard augmentation.

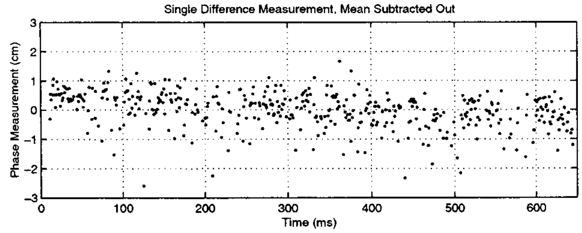


Fig. 17: Measurement noise for single difference, indoor testbed.

Table 3: Relative performance and cost for GEO relative ranging augmentation.

Augmentation Method	No Aug.	Earth-based Aug.	Onboard Aug.
Mean Relative Position DOP	—	3.26	0.44
Mean Relative Position STD(m) (Radial Component)	25.34	4.31	0.022
Mean Relative Range Rate STD(m/s)	0.97	0.058	0.003
Relative Cost	Low	Med	High
Interference Potential	—	High	Low

three transmitter configurations; no pseudolite augmentation, ground-based pseudolite augmentation, and onboard pseudolite augmentation for relative position and velocity estimation performance, relative costs of the different methods, and potential for RF interference with the existing GPS signals.

6 CONCLUSIONS

This research has demonstrated in simulation the usefulness of augmentation of the NAVSTAR constellation with additional ranging signals for relative spacecraft position and velocity determination in GEO.

Relative position determination accuracy is greatly improved through augmentation in particular for the onboard augmentation method. Relative position accuracies on the order of centimeters are possible after the carrier phase measurement biases have been resolved, which is far below the required positioning accuracy for the GEO cluster mission. Earth-based augmentation accuracies are adequate for position determination performance.

However, the simulations of relative velocity determination indicate that augmentation is crucial for achieving required accuracies for relative velocity knowledge in the spacecraft cluster. This is driven by the desire to minimize thruster firings and conserve fuel. The simulation results presented here indicate that to achieve desired relative velocity determination accuracies on the order of mm/sec, the onboard pseudolite augmentation method is required.

And finally, while earth-based pseudolite augmentation avoids the costs associated with space-rating the transmitter electronics for a long duration GEO mission, this augmentation method has the liability of having a high potential for interfering with terrestrial GPS users.

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