A Novel Self-localization Protocol for Spacecraft Clusters

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Introduction

There is a need for multipoint in-situ measurements to address many scientific problems related to Geospace. In this paper, we outline an efficient and innovative algorithm that allows multiple spacecraft (s/c) to self localize their position within a cluster. The new technique is based on measurements of the time-of-arrival of transmitted calibration signals that each s/c broadcasts. Among the features of our self-localization protocol, we emphasize:

(a) distributed processing - all computations are performed over the entire cluster network, which provides great stability to the algorithm in case of failure or malfunction of some s/c in the cluster;

(b) relative localization of spacecrafts' position allows for local computation of physical quantities of interest (such as the electric field, the magnetic field etc), which reduce the communication time with Earth-based computational centers; and

(c) an algorithm that is robust vs. statistical noise which is inevitably present, and can be kept under control by increasing the number of spacecrafts in the cluster.

Such an algorithm minimizes both communication and computation costs, and therefore is expected to be energy efficient. Determination of iteration cycles in the self-localization process in critical in order to achieve an acceptable level of accuracy.

Multidimensional Scaling

1) Given the distance matrix D, compute the auxiliary matrix: $B_{ij} = \frac{1}{2}(D_{i1}^2 + D_{j1}^2 - D_{ij}^2)$

2) Compute the centered matrix:

$$B_c = JBJ, \quad \text{where} \quad J = -\frac{1}{N}\begin{pmatrix} 1-N & 1 & 1 & 1 & \\ 1 & 1-N & 1 & 1 & \\ 1 & 1 & 1-N & 1 & \cdots \\ 1 & 1 & 1 & 1-N & \\ & & \cdots & & \end{pmatrix}$$

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Multimensional Scaling

3) Find the eigenvalues and eigenvectors of Bc

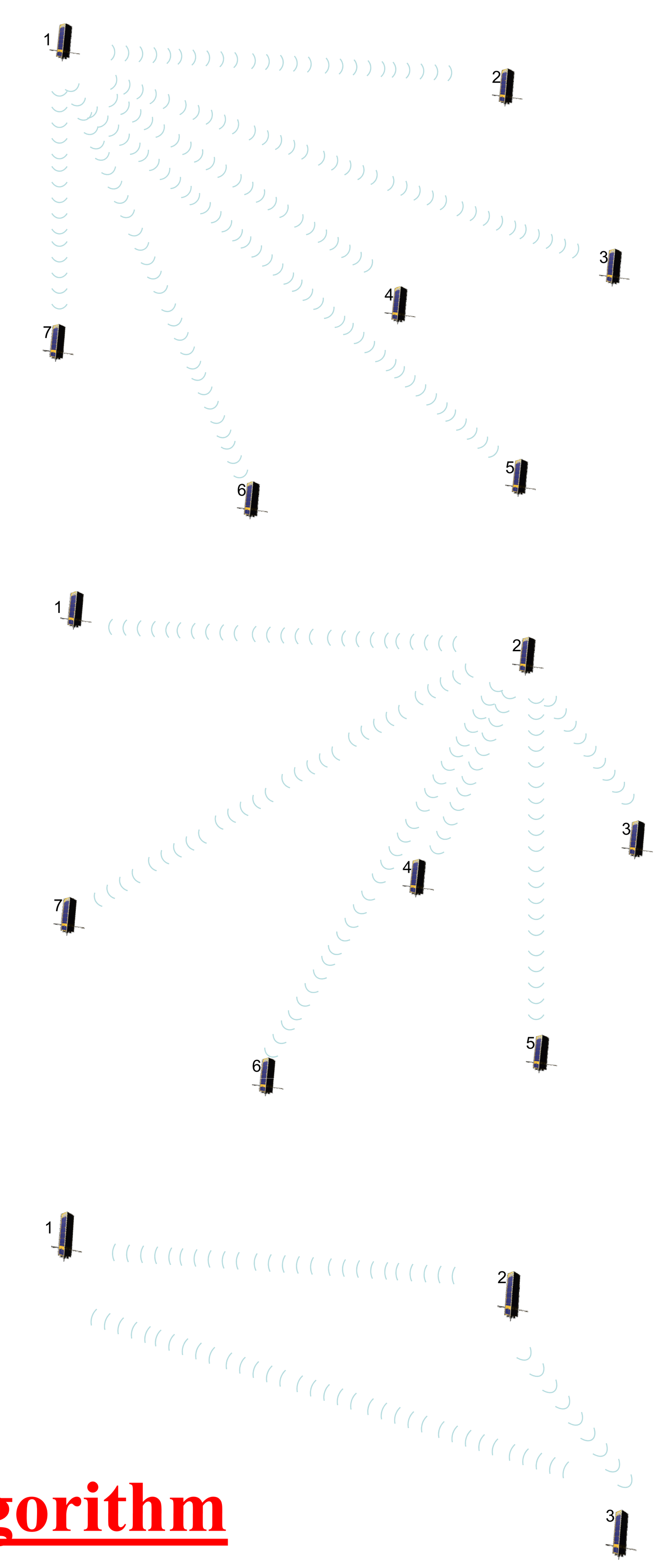
$$B_c = O^T \Lambda O$$

4) The 3D positions of all the satellites are finally given by the first three non-zero columns of the matrix

$$P = O\sqrt{\Lambda}$$

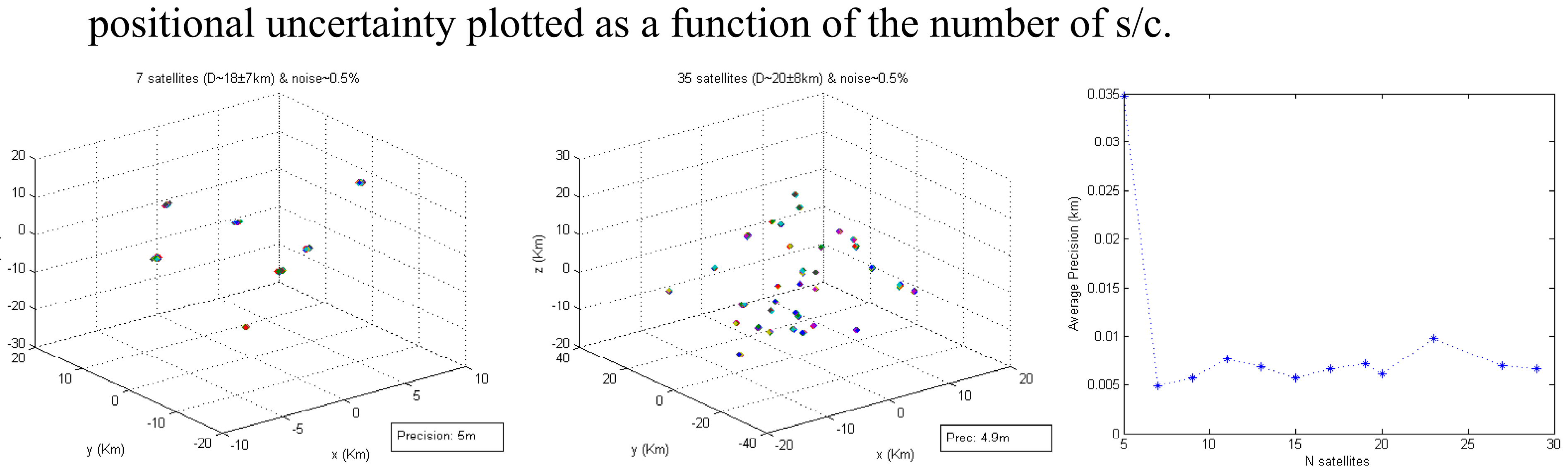
The Algorithm

1) Satellite number 1 broadcasts the time t1 of its internal clock.
2) All other satellites record the time t1 and the arrival time τ_{1x} of the broadcast.
   - The difference $\Delta_{1x} = c(\tau_{1x} - t_1)$ gives the distance of the x-satellite from satellite 1.
3) Satellite number 2 broadcasts the time t2 at which it receives the broadcast from satellite 1.
4) All other satellites record the time t2 and the arrival time τ_{2x} of the broadcast.
   - The difference $\Delta_{2x} = c(\tau_{2x} - t_2)$ gives the distance of the x-satellite from satellite 2.
5) At this point all satellites can also compute the distance between satellites 1 and 2: $\Delta_{12} = c(t_2 - t_1)$
6) Steps 3), 4), 5) are repeated for all remaining satellites, in turns.
7) At this point in time, a second iteration of broadcasts begin in which each s/c broadcasts the distance between itself and every other s/c in the cloud.
8) From the distance matrix D each satellite can reconstruct the three-dimensional positions of all satellites in the cluster, by using multidimensional scaling.



Advantages of the Algorithm

- It guarantees the exact determination of all positions of satellites, efficiently and in only two iterations.
- It is stable against noise (uncertainties) in the arrival times. This figure show the result of 1000 simulated noisy cycles for systems of 7 and 35 s/c along with the positional uncertainty plotted as a function of the number of s/c.

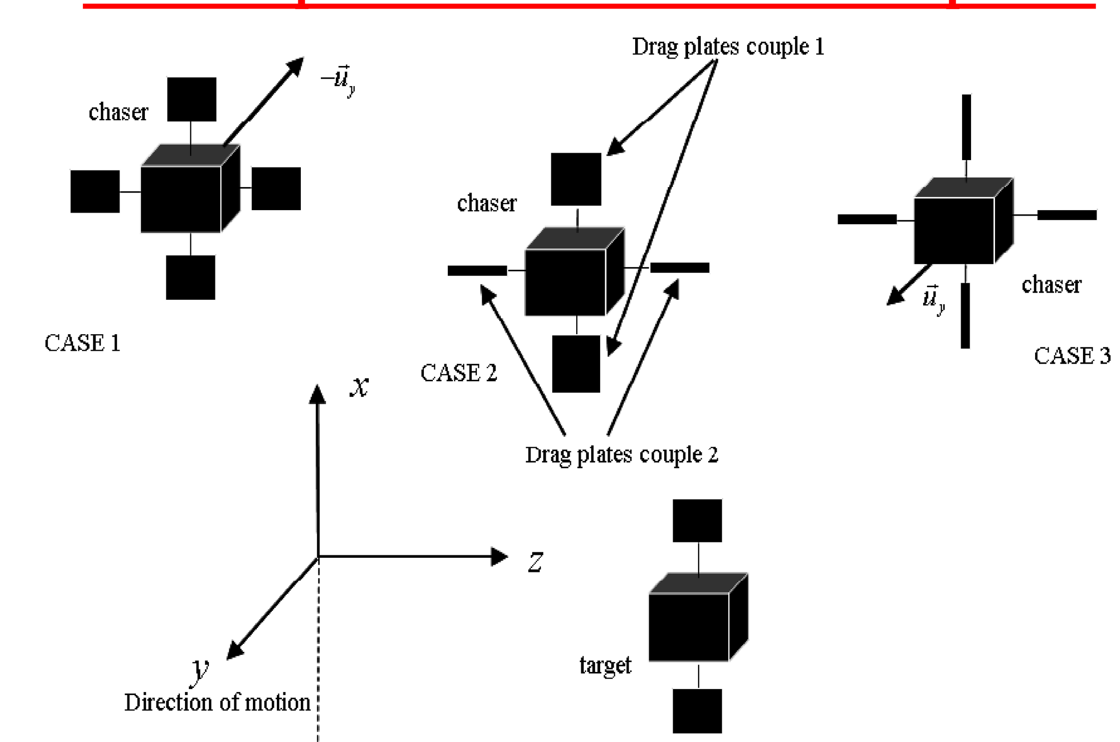


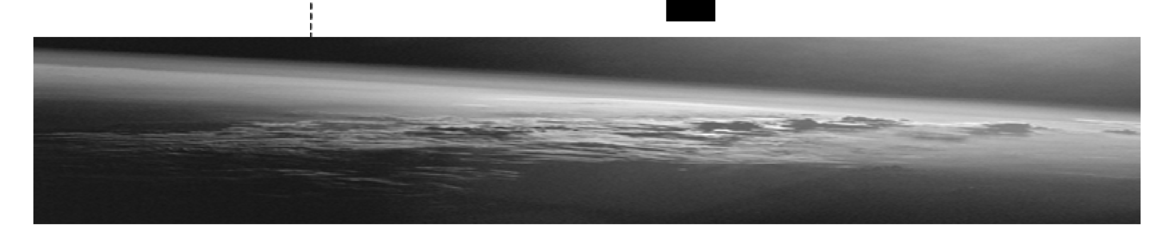
Atmospheric Differential Drag

Spacecraft positioning within the cloud can be addressed, for example, within the context of atmospheric differential drag techniques. This technology enables reactionless formation control, guaranteeing that the entire system will have line of site communications with every other spacecraft in the cluster. The overarching cluster architecture goal is such that a single spacecraft will aggregate all data and be the source of all communications to the ground. Thus, from a ground operational perspective, communications with the system can be achieved using approximately the same resources normally allocated to communicating with individual spacecraft.

See http://www.riccardobevilacqua.com/

Atmospheric Differential Drag
Control Spacecraft Formations w/o Propellant





Advanced Autonomous Multiple Spacecraft (ADAMUS) laboratory: 6DOF spacecraft simulator for GNC validation & spacecraft on-the-ground testing