AN OPTIMAL SEARCH ALGORITHM FOR SATELLITE ACQUISITION

Pasquale Di Stasio*
Glauco Di Genova
Telespazio S.p.A.
* E-Mail: cratos@tin.it

Abstract

The Cooperative Search Algorithm (CSA) is an algorithm developed in the framework of an IRIDIUM™ task; the purpose was to provide a procedure for directing ground antennas in satellites searching; a software package for the Ground Segment was implemented together with a software testbed for the performance evaluation of the search algorithm. The subject of this paper is the description of the CSA in terms of algorithm philosophy as well as the description of the results obtained by using the CSA and the testbed software in the simulations of the nominal acquisition scenario.

Key words: Algorithm, Search, Antenna, Acquisition, testbed.

Introduction

The software package Cooperative Search Algorithm (CSA) is the implementation of an algorithm to be used to direct ground antennas in satellites searching. It was developed in the framework of an IRIDIUM task to provide a procedure both for satellites acquisition after their launcher release and for satellites re-acquisition in mission orbit after contact failure, by means of one or more ground antennas. Moreover a software testbed for the performance evaluation of the search algorithms was developed.

The IRIDIUM™ constellation

The IRIDIUM™ constellation consists of 66 satellites in circular, nearly polar orbits (with an inclination of 86.1º) of 780 kilometers altitude. The satellites are placed in six planes (11 satellites per plane) equally spaced over 180º of longitude providing worldwide coverage. Initially, the satellites (in groups of five or more satellites) have been placed in a parking orbit of approximately 460 kilometers, released by different launchers (DELTA, Proton, Long March). From there they have performed orbit raising maneuvers to either their storage orbit of approximately 650 kilometers or their mission orbit.

The Ground Segment is in contact with the constellation of satellites through a network of four Telemetry, Tracking & Command (TT&C) facilities: two ground antennas are located in northern Canada, one in Haway, and one in Egil (Island).

The algorithm was applied to a typical configuration (nominal scenario) during the simulations: two ground antennas for the acquisition of five satellites released by the launcher DELTA. As input parameters were assumed as known the initial (at the launcher separation) state vectors, the initial covariance matrix, and the antenna characteristics, that is Field Of View (FOV), maximum rate, maximum acceleration, and elevation cut-off. In addition to this scenario different cases were also considered, with a single tracking antenna, with the TT&C network in full configuration (four ground stations), and with different elevation cutoffs.

The CSA task

The task execution was based on several activities:

- modeling of the satellite dynamics after launcher separation and in mission orbit;
- covariance analysis and ground tracks determination for different launchers;
- dynamical modeling of antenna pointing mechanism to the extent needed to take into account slewing rates, accelerations, and pointing constraints;
- implementation of two algorithms (multi antenna - one satellite and multi antenna - multi satellite) and evaluation of their performance.

The successful outcome of the work was strongly dependent on the possibility to reduce as much as possible, through accurate modeling the portion of sky in which to search for the satellites: the acquisition of the satellites after their launcher separation is actually a problem more complicated than the loss of the contact with the satellite in mission orbit. Apart from the information about the satellite dynamics during the first revolutions after the separation (position, velocity, sequence of maneuvers planned, attitude data, etc.), the critical data were represented by the satellites release dispersion data.

A software tool was developed and used to simulate the satellite dynamics and the link acquisition process, acting as a software testbed for the performance evaluation of the search algorithm: although this work was performed specifically to simulate the IRIDIUM™ satellites acquisition by using the CSA, the software tools developed are generic enough to be used for the simulation of a number of scenarios relevant to a generic satellite mission analysis.

CSA description

CSA functional description

The CSA program generates both a binary file containing the tracking data (azimuth and elevation angles) for each single antenna in order to search the satellites released by launcher, and a text file containing the same information along with some auxiliary quantities (at least range and range rate).

The algorithm was applied to a configuration based on two antennas which followed the satellite trajectory. The adopted search strategy used the two antennas to track a point on a reference orbit moving respectively faster and slower than an actual satellite on that orbit, that is an antenna operated in *fast-scanning* mode and the other one in a *slow-scanning* mode.

The initial covariance matrix was assumed to be the same for all the satellites released. The initial sigmas (1σ values) were 1600 meters, 600 meters, and 4400 meters in Height, Cross-track, Along-track (HCL) components. The velocity dispersions were 2 m/s in all the HCL components. These sigmas were inferred from the 99^{th} percentile levels of the injection parameters, without relying on any particular hypothesis about the details of their statistical distribution (i.e. they were <u>not</u> assumed to follow a Gaussian distribution). From dispersion analysis data it resulted that the main satellite trajectory dispersions developed along the in-track direction with a rate approximately constant in time, while the cross-track and radial dispersion oscillated between bounds which were approximately constant over a few hours time span; thus the main search direction has been selected to be the along-track one.

Without relying on any particular hypothesis on the trajectory distribution apart from the obvious one that the most probable trajectories were the closest to the nominal one, the search started somewhere around the nominal trajectory at the pass start time. Since along-track errors develop both ahead of and following the nominal satellite position, then the search was performed by scanning both the trajectory arcs starting at the nominal satellite position and moving away from there forward and backward, respectively.

The angular speeds for the two antennas were determined by the need of keeping every point which moves with the satellite velocity in the antenna beam width for at least 1 sec (the time needed for auto-track acquisition). Once the boundary of the along-track dispersions have been reached, then the next major source of the uncertainty was taken into account namely the radial error. Thus the two antennas were pointed towards the nominal satellite position, but with a bias in the radial direction and the same *slow-fast scanning* mode as before was used to cover an along-track error region lying at a certain radial distance from the nominal trajectory. The radial bias was selected in such a way to overlap only slightly the already scanned region, to the extent needed to avoid gaps in the coverage of points (moving with satellites velocity) lying inside the beam width for at least 1 sec. The entire process of adding a radial bias and performing a slow, fast pair of scans was then iterated until the end of the pass for positive and negative radial biases.

The CSA output file can be logically split into pointing data segments corresponding to different radial biases. The antenna pointing angles in each pointing data segment of the CSA file allow to cover an along track region of sky (a strip) in the searching area. The search strategy adopted in the nominal scenario allowed to use the CSA program to generate files containing three complete pointing data segments within the available pass time. The first one was relevant to a strip covering the region of highest probability, that is the region around the nominal orbit. The antennas followed the satellite trajectory, scanning such an arc to take into account the along-track dispersion; then the CSA program generated other two pointing data segments corresponding to scans at lower and higher radii than the nominal orbit.

The CSA program estimated both the angular rate and the angular biases, so that ,

1) the satellite was maintained in the antenna FOV at least for the auto track acquisition time,
2) the sky region scanned by the antennas contained the most part of the along-track and radial dispersions,
3) the overlap between the strips was reduced as much as possible.

Two parameters were used in the algorithm in order to satisfy the requirements 1, 2, that is the scan duration and the FOV crossing time.

The covariance analysis showed that the uncertainty in the satellite position determination was due mainly to the along-track error, so that the scan duration is related to the amount of the along-track dispersion. The FOV crossing time is the time which a satellite passing through the antenna beam axis spends in the antenna FOV. This time has to be larger than the auto track acquisition time in order to allow even an off-axis satellite to be kept within the beam for at least the auto-track acquisition time.

The size of the cross-track and radial region effectively scanned by an antenna thus depends on the crossing time over acquisition time ratio.

CSA performance evaluation

To assess CSA performance, a set of software tools (testbed) has been developed whose purpose is both the automatic computation of some dynamical parameters relevant to the CSA itself, and the simulation of the acquisition process of one or several satellites from one or several ground stations in order to compute the acquisition probability for that scenario. Although this work has been performed specifically to simulate the IRIDIUM™ satellites acquisition by using a CSA, the software tools developed are generic enough to be used for the simulation of a number of scenarios relevant to a generic satellite mission analysis. In fact, the simulation software implements separately the trajectory simulation and statistical analysis, and the acquisition process simulation. In order to achieve a realistic implementation of the actual mission scenario, a statistical simulation approach was selected.

The simulation purpose is twofold. On one hand, given an externally provided CSA file containing time tagged pointing data (e.g. azimuth, elevation), it should be possible to compute the performances of this CSA file in terms of probability of acquisition and acquisition time. On the other hand, the trajectory simulation process should be used to provide some insight into the acquisition process itself, that is to produce input to the CSA such as, for example, the satellite state vector dispersions and their time evolution: this is a support function to the operational CSA, while the CSA performance analysis allows a quick assessment of the capabilities of the CSA under test.

The testbed software reads each CSA file and checks for satellite acquisition on each one of the sample trajectories generated during the Monte Carlo simulation. The number of trajectories generated may be selected depending on the desired accuracy in the determination of the acquisition probability. Azimuth and elevation data from the CSA file are interpolated separately.

The acquisition check is based on two parameters, that is the FOV and the acquisition time. The pointing error is the difference between the commanded pointing direction and the pointing direction at which the satellite can be found, evaluated at each sampling time (0.1 sec) throughout the entire pass duration of the particular sample trajectory considered. If this pointing error stays below the FOV parameters for a time interval longer than the acquisition parameter, then on that particular sample trajectory acquisition occurs. The computed statistical performance indexes are: the acquisition probability, the average acquisition epoch and the average acquisition epoch dispersion.

Simulation of the nominal scenario

Testbed approach

The CSA testbed aims at modeling the satellite acquisition process in the closest possible way to the real environment: to this purpose a Monte Carlo approach has been selected. This consists of the generation of a large number of different satellite trajectories representing a statistical population containing (practically) all the possible trajectories compatible with a given set of initial dispersion data.

The fact has to be stressed that CSA does not rely on any particular hypothesis about the shape of the state vector uncertainty distribution. In fact even if in the framework of the IRIDIUM™ task a Gaussian distribution was assumed for sake of simplicity, being CSA an algorithm tailored to perform operational work it relies on the best possible approximation to the real physical environment. The truth model adopted there was a statistical distribution whose initial parameters were assumed to be consistent with the available initial 99% percentile levels at orbit injection. The initial trajectory distribution was then generated according to a Gaussian distribution, for lack of better knowledge about its shape, even if a truncated Gaussian or a triangular were better approximations; anyway the nonlinear transformation between initial and final states following from the equations of motion produces a non Gaussian distribution at later times. Use of a Monte Carlo method allows for easy implementation of any meaningful initial distribution.

Probability levels approaching the 100% figure were considered, that is the tails of the trajectory probability distribution. In order to achieve confidence levels close to 100%, also trajectories with probability of occurrence very low were considered; these trajectories are strongly dependent on the details of the probability distribution. Meeting the 99% acquisition probability requirement meant to consider trajectories lying between the 0.5 and the 99.5 percentile level bounds.

Testbed description

The simulation approach is based on a pipeline of five main modules to be activated in sequence, and on several support modules. Each main module reads the same simulation setup file and, when appropriate, an intermediate file produced by the module previously run.

The five main modules, named CSATEST1-5, implement a Monte Carlo simulation of the satellite acquisition process, given a CSA file containing time tagged pointing data for a number of antennas at a ground site. For each complete simulation several performance indexes related to the given CSA file can be computed. The Monte Carlo trajectory simulation and analysis (modules CSATEST1-3) is kept separate from the CSA performance evaluation (modules CSATEST4-5); thus it is sufficient to run the first three modules once and for all to produce the statistical population and then a single run of CSATEST4-5 for each proposed CSA will provide the required performance data. When several antennas are used at the same ground station, each one should correspond to a CSA file, and CSATEST4 should be run once for each antenna, while CSATEST5 computes the combined performance data for the simultaneous search from several antennas. In case of a single antenna used, then it is sufficient to run CSATEST4 only.

Nominal scenario setup

The scenario considered in the simulations was the nominal one with two ground antennas and five satellites released by the DELTA launcher; the initial state vectors used throughout the simulations took into account separation effects, but satellite stabilization effects were neglected. These stabilization effects were accounted for in the initial covariance matrix adopted. The characteristics of the antennas used in the satellites searching where:

FOV (from antenna axis) = 0. 125 deg
maximum X rate = 5.0 deg/sec
maximum Y rate = 5.0 deg/sec
maximum X acceleration = 5.0 deg^2/sec
maximum Y acceleration = 5.0 deg^2/sec
elevation cut-off = 10 deg

The acquisition strategy adopted, providing the best results in terms of acquisition probability, was obtained by running twice the CSA program: the first run generated the CSA file of the antenna operating in *slow-scanning* mode, the second one generated the CSA file of the antenna operating in *fast-scanning* mode.

Simulation results

A number of simulations related to the nominal scenario was performed, dealing with different numbers of ground antennas at each site and with different elevation cutoffs (5 and 8 deg). Each simulation was performed by maximizing the acquisition probability during the search time. For each simulation three different search times were considered, namely, 100, 180, and 260 seconds. Results are summarized in the following tables.

Table 1: Acquisition probability (%)
(Time search = 100 seconds)

	1 antenna	2 antennas	3 antennas
10 deg	69.2	77.8	89.5
8 deg	76.9	83.5	92.3
5 deg	85.9	91.7	95.8

Table 2: Acquisition probability (%)
(Time search = 180 seconds)

	1 antenna	2 antennas	4 antennas
10 deg	77.1	86.5	96.6
8 deg	83.3	90.3	98.2
5 deg	90.7	95.3	99.3

Table 3: Acquisition probability (%)
(Time search = 260 seconds)

	1 antenna	2 antennas	4 antennas
10 deg	78.8	94.4	95.8
8 deg	84.9	95.2	99.3
5 deg	94.1	97.3	99.7

In these simulations the first pass occurred during the 2nd orbit after release. The results related to a single antenna are very sensitive with respect to the shape of the initial probability of distribution (Gaussian in that case): this led to a larger than expected acquisition probability. This depends on the fact that for a strictly Gaussian distribution, the bulk of that distribution is contained in a relatively small volume which is the one covered by just a single antenna.

In addition to the nominal scenario, which assumed a pass whose maximum elevation was above 10 degrees, the case was considered when passes whose maximum elevation was above 5 degrees were suitable for satellite acquisition. Then the first pass occurring during the 1st orbit after release was investigated: the result obtained was that there was an acquisition probability of practically 100% within 100 seconds by using a single ground antenna, as reported in the following tables. In these simulations the maximum elevation was 8.2 deg.

Table 4: Acquisition probability (%)
(Time search = 100 seconds)

Initial elevation	1 antenna	2 antennas
5 deg.	99.8	100

Table 5: Acquisition probability (%)
(Time search = 180 seconds)

Initial elevation	1 antenna	2 antennas
5 deg.	100	100

Alternative search strategies

The strategy adopted was the one able to produce the best results, that is the strategy maximizing the acquisition probability. The possibility of considering alternative search strategy, feasible in principle, is constrained by some rather obvious requirements:

- the search has to cover the most probable region first in order to reduce the average acquisition time;
- the search should cover as much as possible the error region;
- the most efficient search occurs at low elevation angles since there the antenna footprint is larger;
- it is better to avoid a priori assumption about the shape of the statistical distribution of the orbit state vector errors;
- the commanded angular speed and rates do not have to exceed specified limits.

The above mentioned requirements rule out most of the random search modes trying to get exhaustive coverage of the error region (e.g. raster or spiral scans).

The constraint of having to keep a satellite in the antenna beam width for a certain time implies that the main antenna motion in a program-track mode has to be in the direction of a satellite motion, that is along-track; this significantly reduces the possibility of adopting alternative strategies.

The requirement of having to scan the most probable regions first means that the scan motion should start around a nominal position and should continue moving away from that position towards the error region boundaries: this excludes a scan starting close to the boundaries and moving inward.

The requirement of trying to avoid particular assumptions on the distribution of the orbital state errors has a physical meaning. The assumption of a Gaussian distribution was misleading at least: for the CSA there was the need to reach the boundaries of the error region, while for a Gaussian distribution the most probable region is relatively small and far from the boundaries that is the 4 sigma levels.

The only degree of freedom left is how different scan arcs are allocated to the two ground antennas. A search strategy in which the antenna motion was side-by-side, that is in which the two ground antennas motion is coupled, was adopted and the results are presented below:

Table 6: Acquisition probability (%)
(Time search = 100 seconds)

Initial elevation	1 antenna	2 antennas
10 deg.		91.0

Table 7: Acquisition probability (%)
(Time search = 180 seconds)

Initial elevation	1 antenna	2 antennas
10 deg.		91.2

Table 8: Acquisition probability (%)
(Time search = 260 seconds)

Initial elevation	1 antenna	2 antennas
10 deg.		91.5

A comment about this result is that these simulations were performed maximizing the acquisition probability for a single antenna, since the second one just followed the first. Then, as in the single antenna scan results presented in the previous section, the acquisition probability figure is misleading since it is very sensitive with respect to the assumption of Gaussian error distribution.

As a final remark, we wish to point out that the CSA has been actually used during the actual IRIDIUM™ launches, and it performed as foreseen.