Designing & Simulating Signal Acquisition for Inter-Satellite Laser Links

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Introduction

Before a link can be established, spaceborne laser interferometer based inter-satellite links must perform an intermediate signal acquisition phase whose complexity can vary according to the interferometer's design and the environmental constrains. The signal acquisition algorithms presented here are capable of autonomously performing spatial scans and (if necessary) laser frequency tuning. An interferometer simulator has also been developed in order to test the signal acquisition through Monte Carlo Simulations. The simulator is tailored to the GRACE Follow-On interferometer layout and external environment. Nevertheless, it can easily be adapted to simulate signal acquisition for other laser interferometer based missions such as eLISA.

Guidance Algorithms

The majority of laser terminals require a signal acquisition phase as there is a degree of uncertainty in the position of the target satellite (or ground station). This acquisition phase mainly consists in properly directing the laser beam towards its target and (if necessary) adjusting the frequency of the laser beam. The laser pointing can be achieved using continuous patterns, random patterns or combinations of the two.

Continuous patterns

These patterns scan the uncertainty area in a well defined sequence and cover the degrees of freedom of the problem in a finite time. The combination of patterns used to scan the spatial domain can not be arbitrary and the spatial scan has to be related to the frequency scan [1,2].

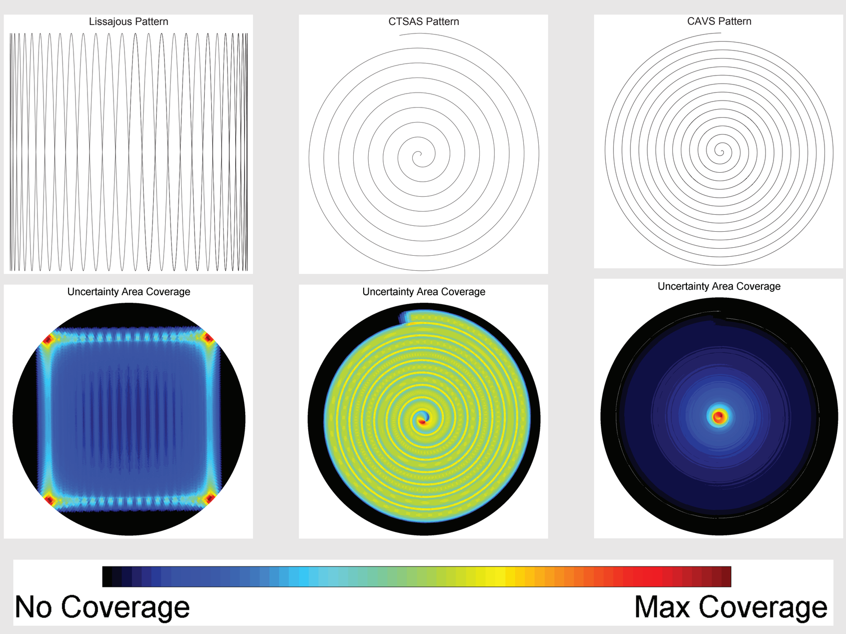
The general equation of continuous patterns is

$x(t) = A(t)\cos(k\omega_1 t^n)\sin(\omega_1 t^n + \delta)$

$y(t) = B(t)\cos(k\omega_2 t^n)\sin(\omega_2 t^n + \varphi)$

where $A(t) = a + ct^m$ and $B(t) = b + dt^m$.

- Without acquisition sensor: Geometrical and time [1-3] constraint.
- With acquisition sensor: Geometrical constraint.



Guidance Parameters

Parameter	Lissajous	CTSAS	CAVS
k	0	0	0
n	1	$\frac{1}{2}$	1
ω_1	$\frac{\pi\vartheta_L}{\vartheta_{unc} t_{acq}}$	$\sqrt{\frac{2\pi v}{\vartheta_L}}$	$\frac{\vartheta_L}{N_R K_F \vartheta_{FOV} t_{acq}}$
ω_2	ω_1 / N_p	ω_1	ω_1
δ	0	$\frac{\pi}{2}$	0
φ	0	0	$\frac{\pi}{2}$
a	ϑ_{unc}	0	$K_2 \vartheta_L \frac{\omega_1}{2\pi}$
b	ϑ_{unc}	0	$K_2 \vartheta_L \frac{\omega_1}{2\pi}$
c	0	$\sqrt{\frac{2\vartheta_L v}{\pi}}$	0
d	0	$\sqrt{\frac{2\vartheta_L v}{\pi}}$	0
m	0	$\frac{1}{2}$	0

Table : Continuous patterns tuning parameters. A detailed description of these parameters can be found in [3].

Acronyms:
CTSAS = Constant Tangential Speed Archimedean Spiral
CAVS = Constant Angular Velocity Spiral

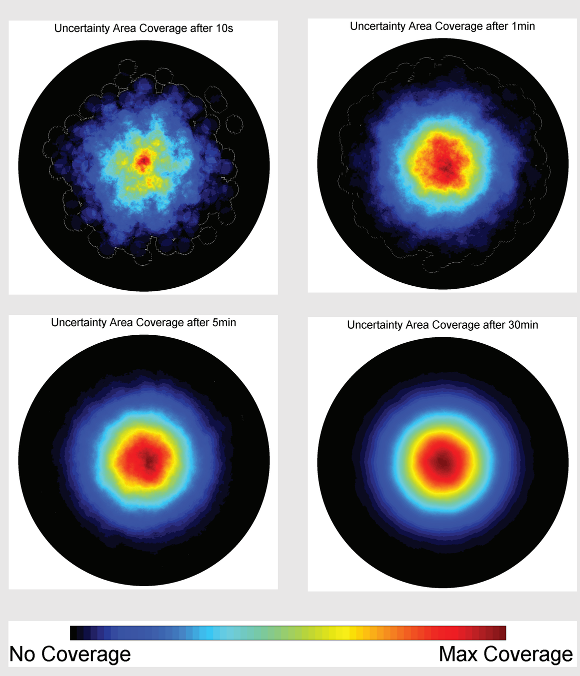
Random patterns

These patterns scan the uncertainty area using random pointing algorithms. The spatial guidance schemes can be arbitrary and are independent from the frequency scan.

Normal distributed random guidance

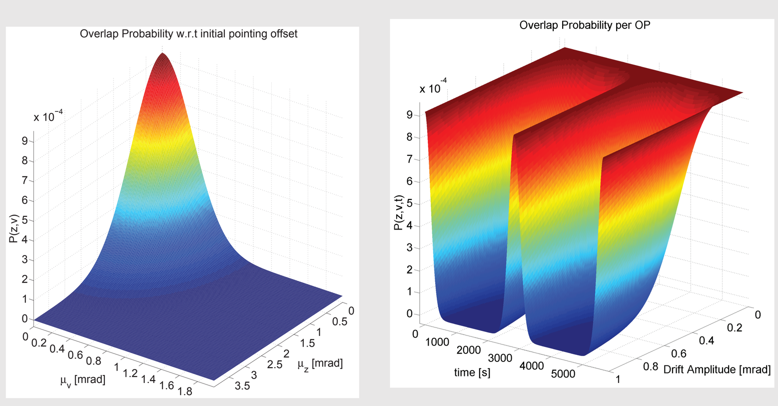
This guidance is preferred when acquisition is most likely going to occur in a region close to the center of the uncertainty area. The pointing spots are generated according to a normal distributed pdf with null mean and unitary standard deviation.

$$f(i) = \frac{1}{\sqrt{2\pi}} e^{-\frac{i^2}{2}} \quad i = x, y$$



With a normal distributed pointing, the probability of acquiring the signal is [3]

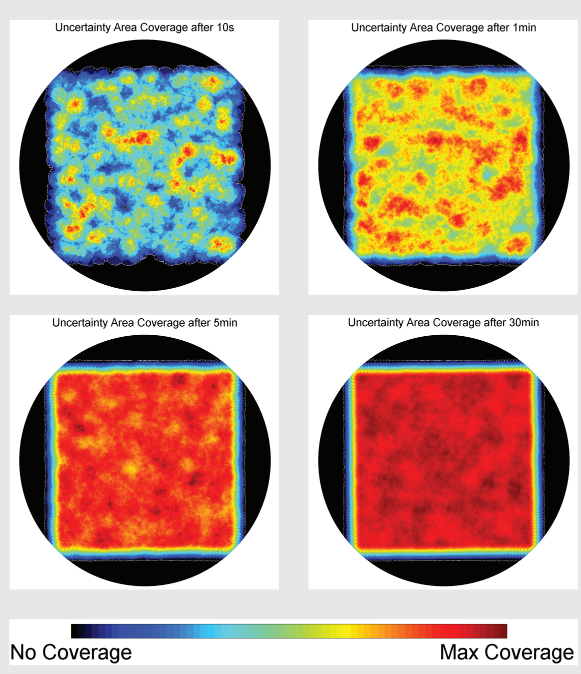
$$\left\{1 - Q_1\left[\frac{\mu_z(t)}{\sigma_z}, \frac{\vartheta_{FoV}}{\sigma_z}\right]\right\}\left\{1 - Q_1\left[\frac{\mu_v(t)}{\sigma_v}, \frac{\vartheta_L}{\sigma_v}\right]\right\}$$



Uniform distributed random guidance

This guidance is preferred when acquiring in the center or in the border of the uncertainty area is equiprobable. The pointing spots are generated according to an uniform distributed pdf.

$$f(i) = \begin{cases} \frac{1}{2\vartheta_{Unc}} & -\vartheta_{Unc} \le i \le \vartheta_{Unc} \\ 0 & \text{elsewhere} \end{cases} \quad i = x, y$$



With a uniform distributed pointing, the probability of acquiring the signal is

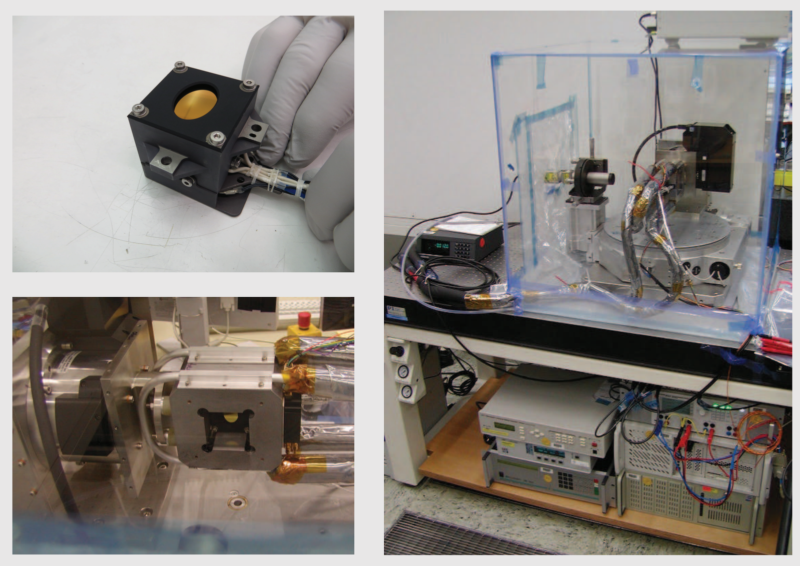
$$\begin{cases} \frac{3\pi^2 (K_L \vartheta_L)^4}{80 \vartheta_{Unc}^4} & d \le \vartheta_{Unc} \\ 0 & \text{elsewhere} \end{cases}$$

where d is the distance between the random generated pointing spots of the two satellites.

Acronyms:
pdf = probability density function
OP = orbital period

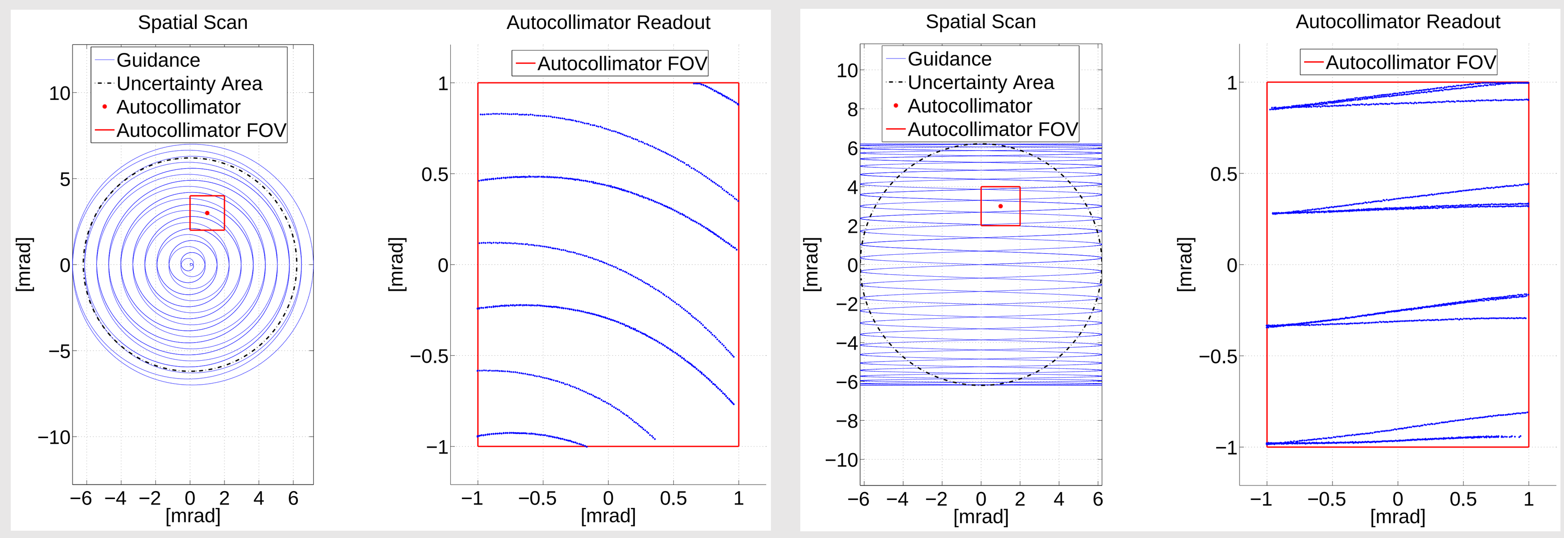
Steering Mirror Guidance Close-loop Control

The Fast Steering Mirror close-loop control has been tested with a real time steering mirror testbed. The steering mirror is mounted on a 2 degrees of freedom turntable (Pitch and Yaw angles) and is controlled with the Simulink simulator through a NI PCI-6052E card connected to a real time pc.



- laser wavelength: 1064 nm
- laser beam diameter: ≈ 40 µm
- autocollimator FOV: 1 mrad (voltage limited)
- FSM close-loop bandwidth: 1 kHz
- FSM position sensors: KD-5100 series
- Initial mount tip-tilt angles: 300 µrad Pitch and 100 µrad Yaw
- Area scanned: 6.5 mrad wide

Acronyms:
FSM = Fast Steering Mirror
FOV = Field Of View



Monte Carlo Simulation on Signal Acquisition

The acquisition algorithms employed are designed to cover a five degrees of freedom uncertainty area both in space and laser frequency without requiring any satellite-to-satellite or satellite-to-ground information exchange. The acquisition algorithms are tested simulating normal distributed (right-plots) and uniform distributed (left-plots) initial pointing offsets in presence of negligible and non-negligible long term pointing drifts. The system automatically switches to *Differential Wavefront Sensing* mode once the satellites detect light (*direct acquisition mode*).

Simulation Parameters

$t_{acq} = 6$ms
$\vartheta_{Unc} = 1.4$ mrad
$\vartheta_L = 130$ µrad
$\vartheta_{FoV} = 140$ µrad
$\Delta f_{max} = \pm 200$ MHz
$\delta f = 7$ MHz

Acquisition Algorithms

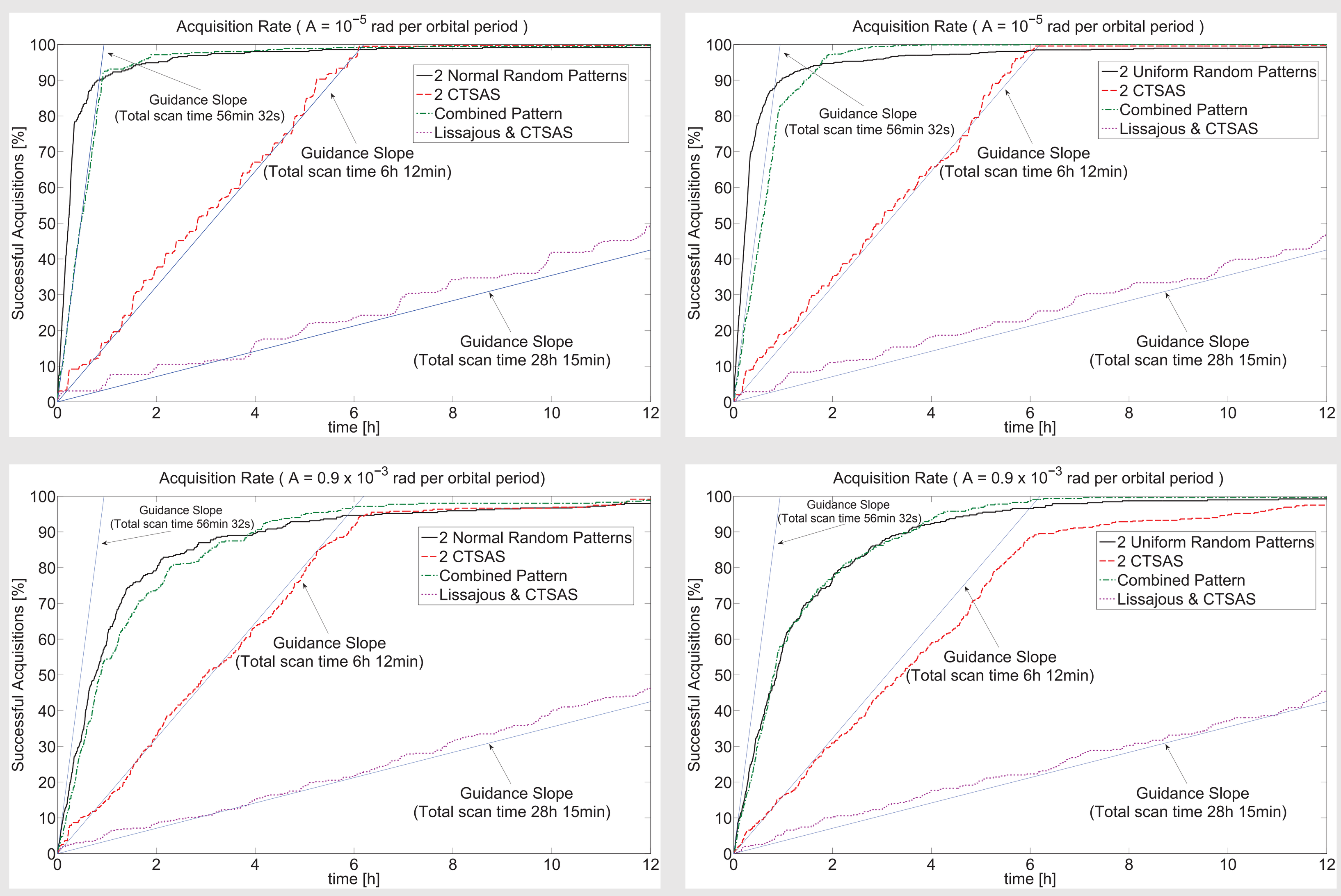
Guidance	Spat. Cycle Period	Freq. Tunings	Tot. Scan Time
2 CTSAS	6min 32s	57	6h 12min
Lissajous + CTSAS	29min 43s	57	28h 15min
Random Pattern	22s	57	/
Combined Pattern	59.5s	57	56min 32s

The frequency uncertainty domain is scanned using a discrete step function. The frequency is changed after a complete spatial cycle.
The *combined pattern* combines a normal distributed random guidance and a CAVS in presence of normal distributed initial offsets or a uniform distributed random guidance and a CTSAS in presence of uniform distributed initial offsets

Long term pointing drifts are modeled as sinusoidal functions on the Roll, Pitch and Yaw axis of the satellite. The amplitude (A) equals the maximum deformation due to thermal effects while the phase (φ_j) is a thermal bias related to the orbital position of the satellites when the acquisition sequence is initialized.

$$\epsilon_j(t) = A\sin\left(\frac{2\pi}{T_{orb}}t + \varphi_j\right) \quad j = x, y, z$$

Simulation results using normal distributes initial pointing offsets — *Simulation results using uniform distributes initial pointing offsets*



The guidance slope is theoretically derived assuming that, after the total scan time, the guidance algorithm has fully covered the five degrees of freedom and therefore the acquisition success rate is 100%.

References

[1] F. Ales, "Acquisition Algorithm of the Laser Ranging Instrument for the GRACE Follow-On Mission", Master Thesis, Rome, 19 July 2012.

[2] F. Ales, P. Gath, U. Johann and C. Braxmaier, "Modeling and Simulation of a Laser Ranging Interferometer Acquisition and Guidance Algorithm", Journal of Spacecrafts and Rockets, **51** (1), pp. 226-238, 2014.

[3] F.Ales, P. Gath and C. Braxmaier, "Multidimensional Signal Acquisition Strategies for Spaceborne Laser Interferometers", submitted to Aerospace Science and Technology.

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