Acta Astronautica 95 (2014) 133–140

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

The optical communication link outage probability in satellite formation flying

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ARTICLE INFO

Article history:
Received 10 January 2013
Received in revised form
2 August 2013
Accepted 30 October 2013
Available online 7 November 2013

Keywords:
Satellite formation flying
Laser distance finder
Free-space optical communication
Free-space digital communication
Distance finding
Vibration
Jitter

ABSTRACT

In recent years, several space systems consisting of multiple satellites flying in close formation have been proposed for various purposes such as interferometric synthetic aperture radar measurement (TerraSAR-X and the TanDEM-X), detecting extra-solar earth-like planets (Terrestrial Planet Finder-TPF and Darwin), and demonstrating distributed space systems (DARPA F6 project). Another important purpose, which is the concern of this paper, is for improving radio frequency communication to mobile terrestrial and maritime subscribers. In this case, radio frequency signals from several satellites coherently combine such that the received/transmit signal strength is increased proportionally with the number of satellites in the formation. This increase in signal strength allows to enhance the communication data rate and/or to reduce energy consumption and the antenna size of terrestrial mobile users' equipment. However, a coherent combination of signals without aligning the phases of the individual communication signals interrupts the communication and outage link between the satellites and the user. The accuracy of the phase estimation is a function of the inter-satellite laser ranging system performance. This paper derives an outage probability model of a coherent combination communication system as a function of the pointing vibration and jitter statistics of an inter-satellite laser ranging system tool. The coherent combination probability model, which could be used to improve the communication to mobile subscribers in air, sea and ground is the main importance of this work.

1. Introduction

The increasing demand for high data-rate mobile wireless communication services is stimulating the development of innovative communication technologies and infrastructures. At present, both terrestrial-based communication system and satellite-based communication systems are well-established means for providing mobile communications services in urban areas [1]. However, terrestrial-based systems suffer from the difficulty of placing base stations in rural areas, along highways, or on the oceans due to installation and maintenance costs as well as backhaul infrastructure while satellite systems suffer from high transmitter power and the large antenna size of the mobile user. We propose to use substantially larger satellite antennas to overcome this disadvantage of satellite systems. However, difficulties arise in doing this due to the limitation of accommodating a large payload within launchers, the high risk associated with deployment mechanisms for a large antenna, and the high commercial value of communication satellites. Since it has

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http://dx.doi.org/10.1016/j.actaastro.2013.10.021

been shown that such problems cannot be overcome by a single satellite as proposed in various studies [2–5], in recent years, several space systems consisting of multiple satellites flying in close formation have been proposed [4,6–11]. Examples include the Gravity Recovery and Climate Experiment (GRACE) formation [6] for determining the Earth's gravity field, the planned deep space Laser Interferometer Space Antenna (LISA) to detect gravitational waves [7], missions such as Darwin [8] to detect extra-solar earth like planets, or interferometric synthetic aperture radar (SAR) missions such as TerraSAR-X and TanDEM-X [9], and technology demonstration missions such as PRISMA [10] or DARPA's future, fast, flexible, fractionated, free-flying spacecraft (F6) [11].

For these space systems to function properly it is important to accurately measure the distance between the satellites. Distance measurements between satellites are typically based on measuring the signal travel time between transmitter and receiver in a one- or two-way mode. Van Trees [14] provides the required estimation theory for distance measurement. Usually, distances between satellites are measured using a laser range finder. When using a laser range finder, the pointing between the transmitter and the target poses a challenge due to jitter of the pointing and tracking system. A mathematical model to describe the jitter and vibration of laser transmitter direction is described in references [2,15,16]. We propose to use the concept of satellite formation flying to communicate with mobile terrestrial and maritime users by synthesizing a large antenna in a virtual manner through connecting several satellites wirelessly and combining the communication radio frequency (RF) signal coherently. The associated network configuration is illustrated in Fig. 1. It depicts, by way of example, three satellites flying in formation and a terrestrial mobile subscriber. The collaboration and coordination between the satellites in the formation is achieved by exchanging information and communication signals in addition to performing distance measurements. The exchange of information, communication and ranging is done using a laser link, which provides a high data rate communication link as well as precise orientation and distance measurements [2,12,13,15,16]. We derive a mathematical model of the outage probability [17] of the coherent combination of RF signals as a function of the performance of the range measurement system. A communication outage occurs when the received RF signals from the satellites are combined out of phase. The phases of the communication signals are estimated using a laser range measurement system. The model takes into account the pointing system vibration and jitter statistics of the laser transmitter, the laser link parameters and the performance of the range measurement system. It is clear that handover in the inter satellite domain should consider while designing low-earth orbit (LEO) satellite communication system or LEO satellite networks. Handover is the process of transferring control between satellites and between satellite and terrestrial subscriber without loss or interruption of service.

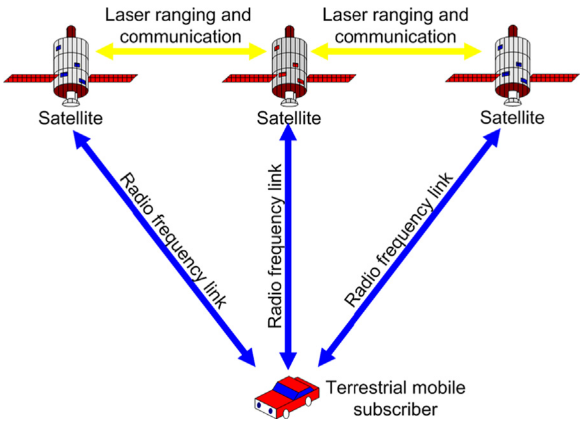

Fig. 1. Satellites flying in formation coherently combining the received signals from a terrestrial mobile user.

The remainder of the paper is organized as follows. Section 2 presents the model applied for formation flying which is applied to describes the temporal evolution of the relative positions of the satellites. Sections 3 and 4 present the concept of laser range measurement systems and a bound on range accuracy estimation (the Cramer–Rao lower bound). Section 5 describes the pointing error statistics model. Sections 6 and 7 use these statistic properties to establish a model which defines the outage probability of the communication system. Finally, Section 8 summarizes our results.

2. Formation flying modeling

Formation flying involves several spacecraft flying in a coordinated way to achieve a common mission objective. As we focus on a formation flying scenario for a telecommunication application, we limit our model to an Earth-bound orbit. Two main orbit types are discernable in that framework: a geosynchronous orbit (GSO) used by traditional commercial telecommunication missions with an orbital period which equals the Earth's sidereal rotation or a LEO which is used by telecommunication constellations such as Iridium or Globalstar. In the present paper, we restrict ourselves to a formation of satellites in LEO with a local to regional coverage.

To enable physical insight into relative motion, which is used for the subsequent simulation, we apply the analytical model of Hill–Clohessy–Wiltshire (HCW) [4,18]. The model considers two spacecraft in an Earth-bound orbit, one being selected as a reference spacecraft and the other termed deputy. Based on a dynamic model limited to Keplerian motion, a reference spacecraft on a circular orbit, and a spacecraft separation much smaller than the geocentric distance of the satellites, the relative motion may be described by the following Eqs. [4,21]:

$$\begin{aligned} &\ddot{x}-2n\dot{y}-3n^2x=0\\ &\ddot{y}+2n\dot{x}=0\\ &\ddot{z}+n^2z=0 \end{aligned} \tag{1}$$

where the mean motion n is given as

$$n=\sqrt{\frac{GM}{a^3}} \tag{2}$$

with the Earth gravity coefficient GM and the semi-major axis a. The coordinates x, y, z, refer to the Hill frame.