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Geostationary Satellites Collocation

Preface

The geostationary satellite should fly along a special orbit occupying a very limited region which is confined by the satellite longitude above the equator of the Earth. In order to utilize the limited orbit resources efficiently, the satellite is required to be maintained in a dedicated position, and what is more, sometimes it is collocated with two or more satellites sharing the same location. As a result, a safety collocation strategy needs to be deployed to diminish collision risks of the collocated satellites.

The main strength of this work is targeted at the latest scientific questions and engineering requirements arising from the maintenance for geostationary satellites resided in narrow allocative positions, and collocated geostationary satellites operated by the same or different organizations. There are some publications related to those topics in recent years, some of those investigations are referenced in this book.

Peter Berlin (2004) The Geostationary Application Satellite is a comprehensive investigation about the satellites in geostationary orbit, which covers the space environment and mechanisms of orbit and attitude of geostationary satellite, the structure including thermal, power, propulsion, and application payload, as well as telemetry, tracking and command system.

Donald Jansky (1987) Communication Satellite in the Geostationary Orbit is a monograph about geostationary satellite application, which focuses on signal processing and payload designation as a key spot in space communication.

Hephaestus Book (2009) Artificial Satellites in Geosynchronous Orbit represents a new publishing paradigm, which collects disparate materials about geosynchronous orbit into a cohesive informative book; some contents come from Wikipedia articles and related comments.

E. M. Soop (1994) Handbook of Geostationary Orbits is a masterpiece by honored Professor Soop, who had got good relationship with the organization the author backed. This book covers the orbit perturbation and practical maneuver related resources for geosynchronous satellite, and details of orbit correction techniques for maintaining of ESA's satellites.

Li H. N. (2010) Geostationary Satellite Orbit Analysis and Collocation Strategies was published in Chinese by the National Defense Industry Press in 2010. The contents focus on the orbit perturbation analysis for the geostationary orbit, and the mathematical and physical principle of orbit maneuver and collocation strategies for multi-geostationary satellites. After receiving some professional reviews and readers's comments for this work, I always think I'd had a chance to respond those constructive advises and to reflect the latest engineering requirements. A chance's coming, the China News Press Association has announced this work was nominated to publish internationally funded by China Classical International Publish project (2014).

The book targets at the latest scientific questions and engineering requirements arising from the maintenance of geostationary satellites resided in narrow allocative positions, and collocated geostationary satellites operated by the same or different organizations. It aims to find solutions for deploying a safe and reliable collocation control. It focuses on the dynamic foundations of geostationary orbit, the orbit perturbation analysis on geostationary satellites, as well as the physical principles of orbit maneuvers explained in mathematics, which are available to engineers of different backgrounds to have the initiative to penetrate with knowledge that encourages the insight for engineering solutions. Moreover, the book presents some practical techniques and mathematical models to help readers master the corrective method for planning maneuvers of geostationary satellite station keeping. Engineers and scientists in the fields of aerospace technology and space science can benefit from this work.

The author is grateful in particular to China Xi'an Satellite Control Center (XSCC), which made this book possible by giving permission for the publication of the development results, and the State Key Laboratory of Astronautic Dynamics (ADL) for providing financial and administrative support, with which the author is affiliated. XSCC has operated four pairs of satellites sharing the same longitude slot respectively for each pair, and in addition, a satellite of XSCC is collocated with a Russian and a Japanese satellite, the three sharing the same longitude slot, which serves as an engineering background to fully ascertain the solutions mentioned in this book.

Special thanks are given to Xin Lei, Dong WeiHua and Wang RongHui for their effort in performing some translation and word processing for the manuscript. The book has also greatly benefited from the assistance of many colleagues, who have provided the book with invigorating discussions during the time that the book was being prepared, as well as helpful suggestions and constructive reviews when the book is finished. In addition, the author wishes to express his sincere gratitude to Yuan Jing for being such a supportive and understanding wife during a long time, without which the book could not have been written. Last but not least, the final acknowledgement is to the publisher's reviewer, who has provided encouragement and useful comments to the book.

Xi'an, China Hengnian Li
September 12, 2012

Contents

Chapter 1
Introduction

Abstract The inherent characteristics of the geostationary orbit are introduced in the context of a very simple dynamic problem, and the current status of geostationary satellites is presented simply to arouse two topics, on which this book will focus.

1.1 General

It was Sir C. Clarke, the author of *2001, a Space Odyssey*, who published an article entitled "Extra-terrestrial Relays" [1] in October 1945, in which he proposed that three satellites, placed 120° apart, on a specific orbit that over the Earth's equator would be able to provide reliable worldwide radio communications. He argued that because of such a specific orbit on which the satellite orbits the Earth in exactly the same time as the Earth rotates on its axis, the satellite could be kept over the dedicated locations on the Earth at all times. It is worth noting that his article had been published almost 20 years, until 1963, when America launched the first geostationary SynCom2 and successfully broadcasted the Tokyo Olympic Games. From then on, about several hundred satellites, which belong to different organizations, have been located above the Earth's equator to serve different missions for communication, navigation, and data relay functions.

Three connective segments are required to insert the geostationary satellite into orbit position. There are the powered segment, the transfer orbit segment, and the geostationary capture segment. The launcher puts the satellite at about 200 km height above the Earth and leaves the satellite into a transfer orbit with its perigee altitude as 200 km and its apogee altitude as 36,000 km or a bit higher than 36,000 km and its inclination equals the latitude of the launch pad, which is called the geosynchronous transfer orbit (GTO) or super geosynchronous transfer orbit (SGTO), respectively. For example, the orbit inclination of the satellite launched

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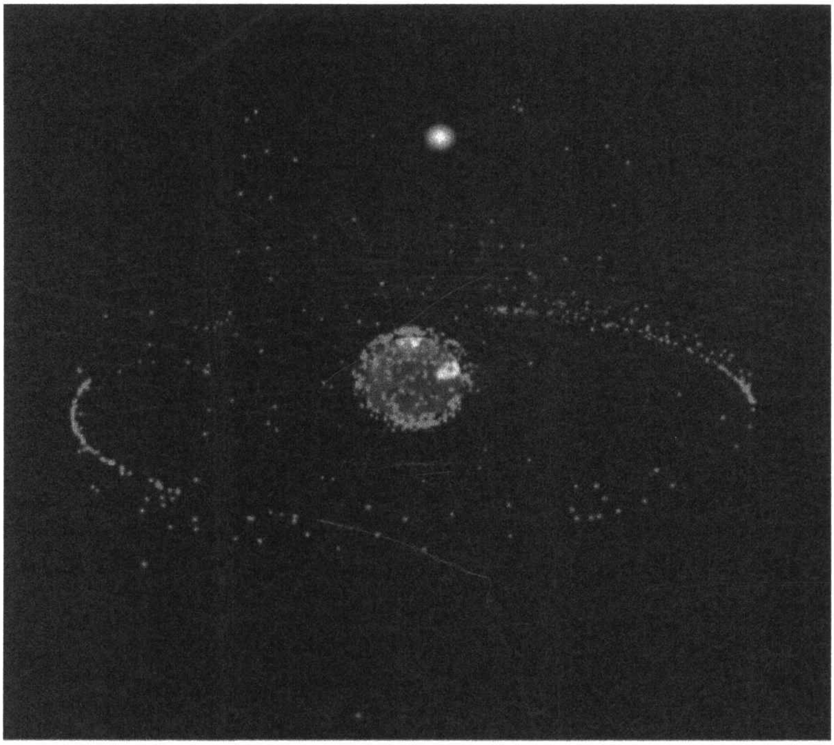

Fig. 1.1 A snapshot of geostationary satellites population

from China Xichang Satellite Launch Center by the Long March rocket should be near 28.6°, while the orbit inclination of the satellite launched from Kourou by Ariane rocket should be around 7°. After some orbit controlling maneuvers, the satellite will be transited to the geostationary capture segment, where the orbit is almost a circle and the inclination is almost zero. After some orbit modification, the satellite will be put into working position, where the satellite is fixed relative to the rotation of the Earth. Figure 1.1 illustrates that geostationary satellites populated the geostationary ring above the Earth's equator.

In general, there are two types of orbit maneuvers required to inject the spacecraft from the GTO orbit into the geostationary orbit. The apogee motor is scheduled to fire about 4–10 times to put the satellite into the near geostationary orbit, which is called the orbit transfer maneuver as illustrated in Fig. 1.2. After that, several miniature velocity changes are scheduled to compensate for the errors induced by the uncertainties of apogee motor burns. The consumed fuel that makes up almost the half weight of the satellite increases the flight velocity at apogee from 1.6 to 3 km/s. The greater the inclination of the GTO orbit, the more fuel consumed for the satellite to transfer into the geostationary orbit. For example, for transferring into the geostationary orbit, the GTO orbit with an inclination of 28.6° requires a velocity increment of about 1.8 km/s, while the one with an inclination of 7° requires a velocity increment of about 1.5 km/s. If the apogee

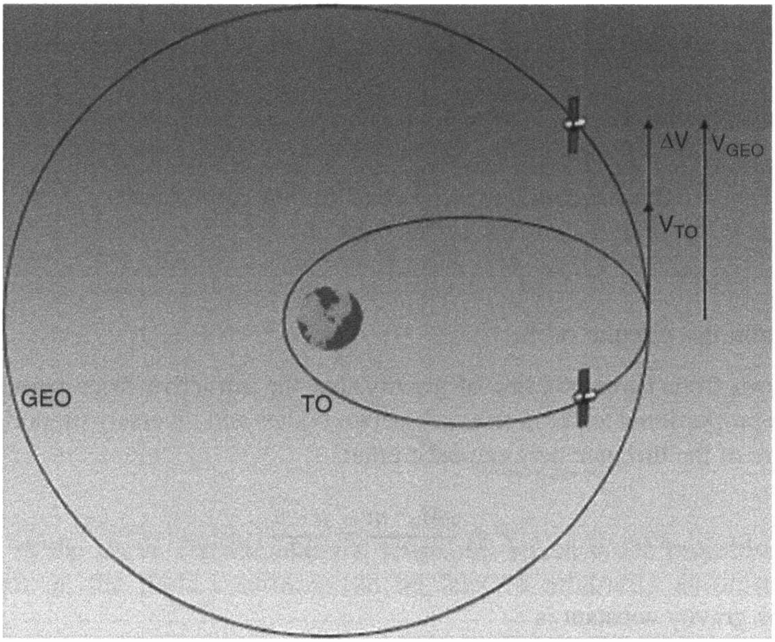

Fig. 1.2 Orbit transferred by firing apogee motor

motor's impulse specific propellant (Isp) is 300 s, the consumed fuel will be 40–46 % of the weight of the satellite, which means that the mass of the satellite will remain the half after the satellite is put into the geostationary orbit.

1.2 The Geostationary Orbit in Math

A perfect geostationary orbit is a mathematical conception that can be realized only based on that the Earth is a spherical symmetric body, the satellite is not influenced by other forces except the central gravity attraction from the Earth, and the central body rotates around its spin axis with a constant angular velocity. According to Newton's law of gravity, the perfect geostationary orbit is of the characteristics below:

1. The period is equal to one sidereal day.

The time it takes the Earth to complete one rotation is one sidereal day, which equals the time it takes any one primary plane to pass the same direction in inertial space. There is a minor difference between it and one solar day. The Earth's rotation rate is known with a very high accuracy, and the value adopted by International Earth Rotation Service (IERS) [2] is

$$\omega_e = \frac{360.98654°}{86400.0^s} \cdot \frac{\pi}{180°} = 7.292115 \times 10^{-5}(\text{rad/s})$$

One sidereal day is

$$\text{One sidereal day} = \frac{2\pi}{\omega_e} = 23^h56^m04^s = 86164.0^s$$

2. The orbit is a circular orbit.

It is known from Newton's law of gravity that the attractive force between two bodies is proportional to the masses of the two bodies and inversely proportional to the square of the distance between each other

$$F = \frac{gM_e \cdot m}{r^2} = \frac{\mu \cdot m}{r^2}$$

where the gravity constant is

$\mu = gM_e = 398600.4415(\text{km}^2/\text{s}^3)$ (in JGM-3 [3]).

The centrifugal force of the spacecraft's motion in the orbit must balance the attractive force. Suppose the geostationary orbit with radius r, and rotation rate w_e,

$$F_r = m\omega_e^2 \cdot r = \frac{\mu . m}{r^2} = F$$

So the radius of a perfect geostationary orbit should be

$$r = \sqrt[3]{\mu/\omega_e^2} = 42164.2\,(\text{km})$$

3. The plane is identical to the equator plane of the Earth.

When the line from the center of the Earth to the center of the spacecraft rotates with the orbit motion, there will form a plane, which is called the orbit plane. If there is an inclination between the orbit plane and the equator plane, the spacecraft will trespass the equator twice a day, and it will result in a relative motion to the observer from the Earth. So being geostationary, the spacecraft should orbit on the equatorial plane, flying in the same direction as the rotation of the Earth.

4. The nominal longitude is the only free parameter.

The size of the geostationary orbit is determined by balancing the force of the Earth's gravitation, the orbit plane is decided by the equatorial plane to finish the relative motion, and the constant angular rate is required to accommodate the even

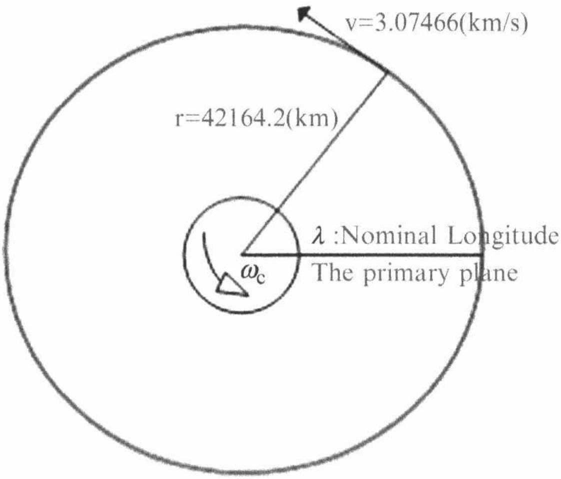

Fig. 1.3 The geostationary orbit seen from the north pole of the Earth

rotation of the Earth. But the nominal longitude, which is the projection of the spacecraft on the Earth's surface, can be selected arbitrarily as illustrated in Fig. 1.3.

In practice, the geostationary orbit only exists instantaneously; the spacecraft will not stay absolutely in the same position relative to the Earth because additional forces acting on it will change the shape of the orbit, the orientation of the orbit plane, and the spacecraft longitude. Nevertheless, the perfect geostationary orbit is useful as an approximate description of the real case, since all the other forces from the Moon, the Sun, and the non-spherical part of the Earth's gravity are small in comparison to the central attractive force. It is very important to discuss the relative motion which is caused by the additional forces [4].

1.3 The Status of Geostationary Satellites

The geostationary satellite should fly along a special orbit constituting a very limited region in space. The region is confined by the radius distance and the orbit plane. The former should be close to the geostationary radius, and the latter should be approximately overlapped with the equatorial plane. The only free parameter is the satellite's nominal longitude above the equator of the Earth. In 1971, the World Administrative Radio Conference (WARC [5]) recognized the geostationary orbit as limited natural resources like the frequencies for terrestrial radio communications, and in 1973, the allocation of the geostationary longitude position on an "equitable access" basis, which was administered by the International Telecommunication Union (ITU) later, was added to the responsibilities of WARC. Many nations, although without technology to access space, requested the geostationary positions for possible future use just because of the fear of losing the opportunities to access to this limited resources. Until 2006, there were 2,350 pieces of geostationary satellite application registered in WARC. In 1976, a claim by a group of equatorial nations for sovereignty over the geostationary longitudes above their territory did not obtain a positive response by the space accessible states [6].

In order to utilize the limited resources efficiently, it is required to maintain the satellite residing in the dedicated position allocated by WARC, and sometimes two or more satellites are collocated, sharing the same location. For example, ESA's Olympus communication satellite was operated from 1989 to 1990 in the longitude slot $19.0^\circ \pm 0.07^\circ$ in collocation with one German and two French satellites [7]. Xi'an Satellite Control Center (XSCC) has operated four pairs of satellites sharing the longitude slot $\pm 0.1^\circ$, and another satellite is collocated with one Russian satellite and one Japanese satellite. They are sharing the same longitude slot with a dead band of $\pm 0.1^\circ$ [8].

In consideration of that, the typical shared dead band is 100 km wide in longitude as well as in latitude and 50 km wide in the radial direction. The satellite operators have realized that the potential risk of physical collision between collocated satellites is not negligible. A safe collocation strategy should be deployed to alleviate any collision risk of collocated satellites.

1.4 The Framework of the Book

The main strength of this work targets the new scientific questions and engineering requirements which arise from maintaining the satellite residing in a very narrow position allocation and collocating multi-geostationary satellites which are governed by same or different organizations. The work covers dynamic foundations of orbit converged to the geostationary orbit, orbit perturbation analysis especially for geostationary satellites, as well as physical principles of orbit maneuvers explained in mathematics, which are available to engineers in different backgrounds to have the initiative to penetrate with knowledge that encourages the insight for engineering solution, as well as the practical techniques, and application cases presented to assert the algorithms and mathematical models for specific engineering requirements.

Chapter 1: *Introduction*. The inherent characteristics of the geostationary orbit are introduced in the context of a very simple dynamic problem, and the current status of geostationary satellites is presented simply to arouse two topics, on that this book will focus.

Chapter 2: *Orbit Motion Foundations*. An attempt is made in this chapter to figure out the main ideas concerning the motion of the Earth, time systems, space reference systems, as well as the non-perturbation Kepler orbit. The problems dealt within this chapter make use of definitions used in a wide variety of scientific fields, such as astronomy, geodesy, celestial mechanics, timekeeping, and satellite tracking and controlling.

Chapter 3: *Geostationary Satellite Motion*. There is no absolute stationary orbit for the geostationary orbit to reside in. Special attention we pay in this chapter to the geostationary satellite's relative motion to the Earth's rotation motion. We will illustrate the orbit motion of real geostationary satellite with the rotational Earth in inertial space.

Chapter 4: *Geostationary Orbit Perturbation*. The perturbation motion equations of geostationary orbit are established via Lagrange equation and are discussed due to the non-spherical part of the Earth's gravitational attraction, the gravitational attraction of the Sun and Moon, and the Solar radiation pressure, respectively.

Chapter 5: *Harmonic Analysis Geostationary Orbit*. The characteristics of the perturbation period of the geostationary satellite are analyzed. The spectral decomposing algorithm is established to identify periodical motions from the high-precise osculating ephemeris, and an identification algorithm of periodical motions based on singular value decomposition is presented.

Chapter 6: *Correction Geostationary Orbit*. The relation between the relative motion of geostationary satellite and station keeping elements is proposed. The orbit correction equations of radial/tangential/normal impulse thrust and continuous thrust are put forward and the common property of in-plane correction and normal correction is analyzed.

Chapter 7: *Maintenance Geostationary Orbit*. The principles, strategies, and algorithms of the station keeping of geostationary satellite are discussed. For north/south station keeping, the design of inclination confined ring and the calculation of inclination control target for single satellite and collocated satellites are discussed. The relation between control moment and local satellite time is also discussed, and a specific case simulation of the control process is given. For east/west station keeping, the complicated situation of coupling control of the drift rate and eccentricity is analyzed, including the distribution strategy and the pulse execution algorithm of single pulse, dual pulses with the same direction, dual pulses with opposite direction, and three pulses. This chapter covers the principles, strategies, and algorithms of the station keeping of the geostationary satellite which should be well grasped by satellite engineers.

Chapter 8: *Collocation Prototypes and Strategies*. A detailed assessment of the strategies used for efficient management of collocated satellites is provided. The relation between the separation distance with uncertainty of OD and the orbit element offset is built for each pair of collocated satellites. And some new strategies are addressed to meet the current needs of sharing a slot by four GEO satellites. The theory and algorithms for each satellite to locate the eccentricity and inclination are put forward, and the simulation is carried out to ascertain that if there are orbit offset with those strategies, the minimal distance could ensure not only the physical separation but also the radio frequency (RF) separation.

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