Assessment of Lunar Positioning Accuracy with PECMEO Navigation Satellites

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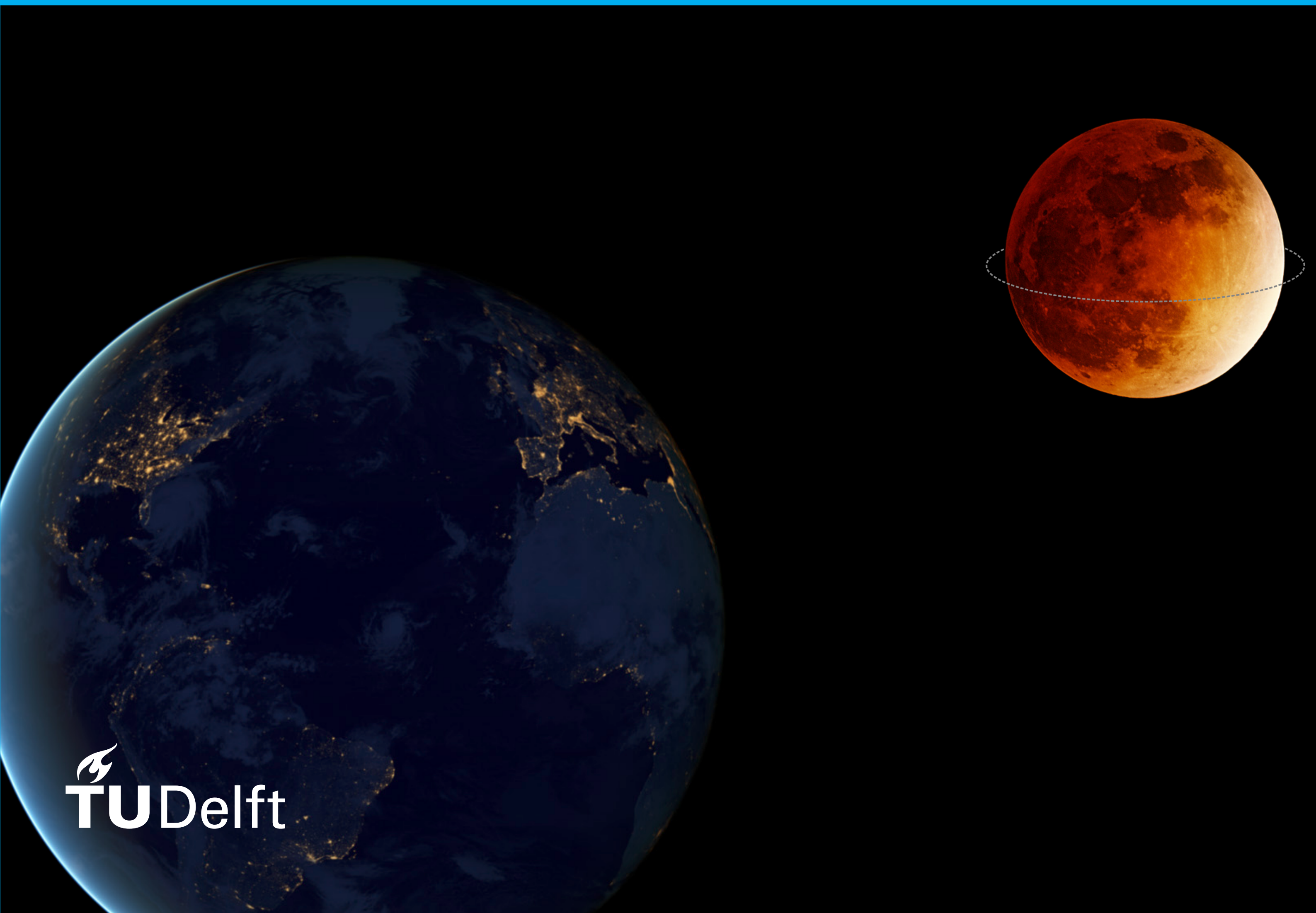

TU Delft

Assessment of Lunar Positioning Accuracy with PECMEO Navigation Satellites

by

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Preface

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M.A. Griffioen
Delft, December 2019

Abstract

Contents

1

Introduction

After the end of the US *Apollo* program in 1972 and the the Soviet *Luna* program in 1976, the popularity of the Moon as spaceflight destination saw a sharp decline. In the decades that followed, only a handful of spacecraft entered the Lunar gravity well with the purpose to stay. The recent years, however, once again saw numerous launches of robotic missions to the Moon, with many more planned. Moreover, various countries, including China, India, Japan, the USA, and Russia have plans for manned missions to the moon. The cherry on top of all this is the Lunar Gateway, in international effort to build a space station in Lunar orbit.

Many technological improvements since the 1970s enable these new space missions. Highly efficient electric propulsion will be used for orbit maintenance on the Lunar gateway. Flight computers have become much smaller and more powerful, with many CubeSats having greater processing capacity and more memory than the Apollo flight computer.

Add some papers to highlight this

Similarly, after the deployment of the first GPS satellites, its benefit navigation in low Earth orbit was realized quickly as well, with Landsat-4 carrying the first GPS receiver into Low Earth Orbit. The low power and mass requirements for GNSS receivers, combined with their fine accuracy makes them broadly applicable. Furthermore, as the satellite solves the navigation solution on-board, there is no need to continuously track and upload navigation data from the ground, potentially reducing operation infrastructure complexity and cost. Besides real-time navigation, this technology has been adapted for clock synchronization and post-facto orbit determination on many satellites. However, due to its low transmission power, nadir pointing, and the large signal travel distance, orbit determination using GNSS proves difficult in Lunar orbit.

This thesis proposes a new constellation of Earth orbiting navigation satellites to be used for in Lunar and cislunar navigation; LuNNaC, the *Lunar Near-side Navigation Constellation*. The purpose of such a system is to reduce the cost of future Moon missions. Furthermore, the thesis discusses the technical performance of such a system, with a focus on navigation accuracy, in order to investigate its potential.

The subsequent section will elaborate how Lunar exploration can benefit from the application of GNSS technology. Followed by this, the objectives and motivation for the research work are explicated. A brief overview of the NaviSimu tool, a tool for simulating navigation signals, is given. This is deemed necessary in order to provide the reader a framework of how the parts of the work are interconnected. The chapter concludes with an outline of the content of this thesis.

1.1. Application of GNSS technology to Lunar navigaton

1.2. Research objectives and motivation

1.3. Overview of Navigation Simulator

1.4. Outline

Chapter introducti some sort

The concept for using a PECMEO navigation constellation are elaborated in **??**. Based on navigation geometry, an initial optimization of the constellation, with the resulting design is presented. It further concerns a framework of assumptions made for the research, and the rationale behind these assumptions. Various alternatives for Lunar navigation are explained, and compared to the PECMEO navigation concept.

The first step to simulating navigation measurements, is to determine reference states and clocks for both navigation satellites and the receiver. **??** defines the reference frames worked with in this thesis. Furthermore, the developed satellite state and clock propagators are shown. An iterative interpolation process obtains the times at which observations are performed, which is elaborated.

?? elaborates on the various observations used for the navigation system. The Moon and Earth occasionally block the path for a signal, preventing it to reach the receiver. This, as well as the effect of neglecting ionospheric delayed signals is shown. Moreover, thermal noise on the observations will be explained, and it is shown how this effect is modeled using the link budget of the system.

Measurements are combined through navigation algorithms to form a navigation solution. The implemented snapshot point positioning least squares and kinematic least squares are elaborated in **??**

Finally, **??** gives the conclusions and recommendations from this research, and proposes further research.

2
PECMEO for Lunar navigation

LuNNaC is a...

This chapter will introduce the LuNNaC concept, including some of the conceptual design performed for the system and its satellites. Firstly, the concept of the system is introduced, with an explanation on some of the design decisions on the usage of some of the fundamental technologies for the system, such as the use of one-way ranging, and the application of GNSS to the system. Furthermore, the constellation design, in terms of its satellite orbits, is discussed by explaining then performed geometrical optimization. Afterwards, a section is dedicated to presenting assumptions on system implementation. In order to correctly simulate navigation performance, many parameters specific to the satellites are used. However, none of these are known due to the novelty of the concept. Hence, the assumption on the values for these parameters is discussed. Finally, the LuNNaC system is compared to a number of alternative solutions for Lunar navigation, in order to see how and where LuNNaC can contribute in the current collection of solutions.

2.1. LuNNaC

2.1.1. One-way ranging: multiple access and on-board processing

One of the major factors that enables the wide-spread use of GNSS systems is its multiple access feature, meaning that many users can use it simultaneously. This is achieved by making the satellites only transmit a generalized navigation signal to a broad direction. Determining the position of a receiver can be done directly by listing to those messages, and determining their timing, without the need for anything receiver specific or a reply. Therefore, a GNSS system can be used by anyone with a device capable of receiving the signals without degrading the system performance, removing the limit on the number of users. Whereas on Earth, every new cellphone, car or LEO satellite can determine their position using GNSS, the multiple access of LuNNaC will enable an inexpensive navigation solution for ever communication satellite, capsule or rover around or on the Moon.

This scaling is one of the opportunities of LuNNaC; although a large upfront investment is required, it will be future-proof by supporting any number of synchronous Moon mission. In contrast, ground station receive signals from satellites from which they determine their position. This quires the ground station to listen to such a satellite specifically, and therefore is not capable of tracking a large number of them in a parallel and continuous fashion. Hence, GNSS style one-way ranging is deemed the best ranging technique for such a system.

Furthermore, GNSS techniques are based on receiving devices capable of calculating a navigation solution on-board. For example, car navigation can be used without relying on external servers and/or services, by merely using the GNSS signals. Therefore, one can autonomously - without using an external party - drive to their destination. Thus, using the GNSS one-way ranging techniques allow for a higher level of autonomy than other ranging techniques.

Such autonomy is highly beneficial in Lunar spaceflight as well for three reasons: Firstly, less operators are needed for a highly autonomous satellite, reducing its operation cost. This will make the production of

Figure 2.1: Multiple access for GNSS (a) and LuNNaC (b).

s 2 and 3 identi-

commercial infrastructure, such as Lunar communication satellites, more attractive. Moreover, the number of points of failure can be reduced, as the system is less dependent on external factors, and the entire chain of obtaining a navigation solution is shorter. Finally, the independent return to Earth requirement for NASAs Orion capsule, as discussed in [], can be fulfilled for Lunar miss. With the use of LuNNaC, a Lunar mission does not require a communications link to Earth to determine its trajectory accurate enough for the return to Earth. Moreover, the obtained solution is not dependent on a human factor, as is the sextant currently used as independent system. Hence, cost of Lunar exploration can be reduced, while reliability and human safety is improved with the use of LuNNaC.

2.1.2. Usage of GNSS for ephemeris generation

Currently, using GNSS is one of the most accurate and reliable ways to determine the orbit of a satellite. Therefore, the concept for LuNNaC is to position the satellites in such an orbit, that is is capable of using the various GNSS signals for orbit determination of the satellite in the constellation. From this, the LuNNaC satellites can generate their ephemeres on-board in real-time, and make use of the advantages of existing GNSS by making the constellation highly autonomous and reliable.

2.2. Constellation design

The position of navigation satellites has a large influence on the quality of the final solution . Therefore, before any navigation performance can be determined, the orbits of the navigation satellites need to be known. Furthermore, although the purpose of this thesis is not to find the best possible constellation, a near-optimal constellation needs to be used for the assessment of system performance, as using a less-than optimal constellation will influence the navigation performance adversely, and therefore influences suggestions on further development.

Hence, an optimization of the satellite orbits within the constellation has been performed. A limited design space, using various constraints, as well as optimizing on navigation geometry rather than complete navigation accuracy reduce the complexity of the optimization. The former is discussed in the following section, after which the latter is discussed. Finally, the optimization results are discussed and the final constellation is presented.

2.2.1. Design space

2.2.2. Navigation geometry

2.2.3. Constellation optimization

2.3. Assumptions on implementation

2.3.1. Signal specifications

2.3.2. Effective isotropic radiated power

2.4. Navigation alternatives

2.4.1. Ground based ranging

2.4.2. Terrain relative navigation

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Orbit simulation and clock propagation

3.1. Reference frame definitions

3.2. Satellite state propagation

3.3. Propagation of local time and clock of a Lunar satellite

As predicted by theory of relativity, the elapsed time measured by two clocks differs

$$\frac{\partial t'}{\partial t} = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{3.1}$$

3.4. Determination of measurement times

4

Ranging observations

4.1. Obervation types

4.1.1. Code measurements

4.1.2. Phase measurements

4.2. Line of sight

4.2.1. Signal blockage

4.2.2. Ionospheric measurements

4.3. Measurement Noise

4.3.1. Link budget

$$free-spacelossfactor = \left(\frac{\lambda}{4\pi R}\right)^2 \tag{4.1}$$

$$P_N = kT_E B \tag{4.2}$$

$$SNR = \frac{P_S}{P_N} \tag{4.3}$$

$$C/N_0 = SNR \cdot B \tag{4.4}$$

4.3.2. Relation between error and signal strength

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Navigation algorithms

5.1. Point positioning

5.2. Kinematic least squares

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Conclusions and Outlook

A

Universal constants and celestial properties

B
Software dependecies

C
Implementation of Kepler orbits