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# Orbit optimization of Mars orbiters for entry navigation: From an observability point of view

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ABSTRACT

In this paper, the observability of orbiter-based Mars entry navigation is investigated and its application to the orbit optimization of Mars orbiters is demonstrated. An observability analysis of Mars entry navigation processing of range measurements to multiple orbiters based on Fisher information matrix is conducted. The determinant of Fisher information matrix is derived to quantify the degree of observability. The orbit optimization method based on the observability analysis is then proposed. Two navigation scenarios using three and four orbiters are considered in simulations. To verify the advantages of navigation performance, the orbiter-based and ground beacon-based navigation schemes are comparatively analyzed. In the simulation, an Extended Kalman Filter is used to examine the navigation accuracy. It is concluded that the proposed orbit optimization method is able to optimize the orbits of Mars orbiters with the maximum degree of observability. For the Mars entry navigation based on orbiters, a better configuration which is a main contributor to the observability, can be achieved. The navigation performance is more excellent than the ground beacon-based navigation. However, a diminishing return of navigation accuracy is obtained solely by increasing the number of orbiters.



## 1. Introduction

Pinpoint landing has been identified as a key advanced entry, descent, and landing technology for future Mars landing missions. The next generation Mars landers may be required to land within 1 km of predefined location with great scientific interest [1,2]. The capability of pinpoint landing not only maximizes the scientific return but also guarantees the landing safety in hazardous areas.

Mars entry, descent, and landing are fraught with engineering challenges. The autonomous navigation, guidance, and control techniques in the Mars entry phase are crucial for a successful pinpoint landing [3,4]. In the final approach phase, the time of ground-based data cutoff is typically at 6 h before entry, which leads to a relatively large initial state error at the entry point [5,6]. Meanwhile, the Mars entry is the most dangerous and uncertain phase due to a thin layer of unpredictable atmosphere. In order to reach a parachute deployment condition while meeting dynamic pressure and eliminating the initial error, the need for atmospheric guidance in the Mars entry phase had been emerged [4,7,8]. This also requires a precise state feedback. In these circumstances, an accurate navigation in the Mars entry phase is one of the fundamental technologies for a pinpoint landing.

Up to now, seven robotic systems have been successfully landed on the Mars surface. In the Mars entry phase, all of them relied on the dead reckoning navigation system

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inherited from Viking missions. In order to survive the aerodynamic heating, a heat shield is generally used. The IMU (Inertial Measurement Unit) is thus the only available navigation sensor. However, the lack of capability of eliminating initial errors, together with the accumulation of random noise degrades the navigation accuracy. Mars network-based entry navigation has thus been proposed to improve the navigation performance [9–12]. In the navigation scenario, radiometric measurements between the entry vehicle and radio beacons such as Mars orbiters or ground beacons could be obtained via high frequency transceivers. With the help of a navigation filter, the states of entry vehicle can be optimally determined.

The configuration of Mars network has to be optimized for future Mars landing missions. For one thing, the beacon configuration has significant impact on the navigation performance. For another, the number of beacons with navigation capability in the near future will still be limited. In previous research works, Pastor analyzed the navigation accuracy from EKF (Extended Kalman Filter) processing of radio measurements and chose the best configuration of ground beacons among possible beacon positions [13]. More theoretically, Yu investigated the observability of Mars entry navigation based on ground beacons and optimized the location of beacons based on the observability analysis [14]. Although these results are instructive for future Mars landing missions, the realization of this concept is difficult to achieve. Above all, till now there are no such functional radio beacons on the Mars surface. Even if we make effort to deliver several beacons on Mars, it will be a difficult task to place them just at the expected locations. How to obtain the precise position of these beacons will also be challenging. Furthermore, because the beacons can hardly move on the surface, the line-of-sight visibility constrains the size of area where the beacons should be located. This may result in an unsatisfactory beacon configuration during the entry phase.

Alternatively, using the operational orbiters around Mars serving as “moving beacons” for navigation may be a more practical choices. Currently, the Mars network contains two NASA orbiters (2001 Mars Odyssey and the 2005 Mars Reconnaissance Orbiter) [9]. The upcoming MAVEN (Mars Atmosphere and Volatile Evolution) mission may further increase the capability of Mars network [15]. How to process the radio measurements more efficiently from the orbiters is also worthy of investigation. Ely [16] firstly presented and discussed the navigation requirements, drivers, and metrics to arrive at a preliminary constellation design. Further, he optimized the constellations around Mars for navigation using the performance index of MPART (Mean of the Position Accuracy Response Time) [17]. Pirondini designed the Martian navigation constellations envisaged in the ESA's Martian Constellation for Precise Object Location program focusing on the number of orbiters and the coverage [18]. However, these research works mostly extended the optimization method of GPS (Global Positioning System) to the Mars network and mainly focused on the global navigation performance. In reality, the number of orbiters is too limited to achieve the global coverage. Therefore, a local navigation performance for specific mission does deserve further analysis. Furthermore, the relationship between configuration of Mars orbiters and the navigation performance has not been clearly understood. These unsolved issues offer the inspirations for our research.

Certain performance index has to be chosen in order to optimize the orbits of Mars orbiters. As a key index associated with the navigation capability, the observability of the navigation system is a preferred choice. Although significant attentions on the observability analysis have been received for linear and nonlinear dynamic systems [12,19–21], the analytical contribution of orbiter configuration to the observability can hardly be determined. On the other hand, from the estimation theoretic point of view, the lower-bound of the error covariance matrix can be estimated by the inverse of FIM (Fisher information matrix) according to the Cramér–Rao inequality [22]. Therefore, the observability of a navigation system can be analyzed by examining the FIM [23–25]. In this circumstance, some valuable analytic conclusions about the navigation design can thus be obtained.

This paper aims to solve the orbit optimization problem of Mars orbiters for Mars entry navigation. Unlike previous attempts, we focus on the local navigation performance from an observability point of view and try to derive the impact of orbiters' configuration on the navigation capability. First, the dynamics of Mars orbiter-based Mars entry navigation system is presented. Next, the degree of observability is defined and derived using Fisher information matrix. Following that, the orbit optimization problem is described in detail. Then, focusing on the Mars navigation scenarios using three and four orbiters, the orbit of each orbiter is optimized based on observability analysis. Furthermore, some useful conclusions about the orbiters' configuration and the navigation performance can be obtained. Finally, the advantages and accuracy of Mars orbiter-based Mars entry navigation are demonstrated by the simulations employing an Extended Kalman Filter.

## 2. Dynamics of Mars orbiter-based navigation system

It has been indicated that the high frequency radio signals such as UHF (ultrahigh frequency) signal could penetrate the plasma sheath around the entry vehicle during the Mars entry phase [26]. Based on this research, the radiometric measurements to the Mars orbiters can be obtained by ultrahigh frequency transceivers to help determine the entry vehicle's state (shown in Fig. 1). The Mars Science Laboratory mission also demonstrated the relay communication with MRO (Mars Reconnaissance Orbiter) in the entry phase via JPL's latest version of transceiver “Electra” [27], which paved the way for the Mars orbiter-based navigation in the near future. For orbit optimization of Mars orbiters, the dynamics of navigation system during entry phase should be firstly defined.

### 2.1. Dynamical model

The dynamical model of entry vehicle is described in the Mars inertial frame. A six-dimensional state of entry vehicle is defined as $\boldsymbol{x} = \left[\boldsymbol{r}^T, \ \boldsymbol{v}^T\right]^T$, where $\boldsymbol{r} = \left[x, \ y, \ z\right]^T$ and $\boldsymbol{v} = \left[v_x, \ v_y, \ v_z\right]^T$ are three-axis position and velocity vector respectively. The atmosphere of Mars is assumed to