An Interplanetary Network for Spacecraft Autonomous Navigation

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An interplanetary autonomous navigation network, named the Internet of Spacecraft (IoS), is proposed in this paper to enable a Solar System-wide autonomous navigation capability for spacecraft. This network consists of two types of spacecraft, namely host and client spacecraft. The former provide the absolute reference for the whole network, and the latter determine their positions by communicating with the host spacecraft or other client spacecraft. To investigate the performance of IoS, a detailed application scheme that supports a flight from Earth to Mars is developed and analysed. IoS is not a simple extension of the navigation constellation. It is independent of the ground tracking system and the configuration of the network is flexible in that any spacecraft-installed identical device can be added to it. Moreover, client spacecraft whose positions have been determined can also be regarded as host spacecraft and provide further navigation information to others. This paper aims to provide technical support for future deep space exploration.

1. INTRODUCTION.   Since the beginning of the twenty-first century, deep space exploration has become a hot issue again. Uncertainty and a hostile deep space environment put high demands on the accuracy and reliability of position for Deep Space Explorers (DSEs) (William, 2005). At present, navigation for DSEs is mostly performed by ground-based tracking and control systems. However, the long distance between DSEs and Earth brings large time delays and greatly degrades the consequent positioning accuracy. In order to improve the reliability and enhance the independent viability of DSEs, research on autonomous navigation systems for DSEs is necessary (Zheng et al., 2015).

As the number of spacecraft in simultaneous operation continues to grow, an enormous interplanetary communication network among different spacecraft and ground-based systems will be formed. Utilising this network to provide navigation services for DSEs is feasible. Since 2010, the National Aeronautics and Space Administration (NASA) integrated network for Space Communications and Navigation (SCaN) has been in its

definition phase. It is intended to integrate NASA's three existing network elements, that is, the Space Network, the Near Earth Network and the Deep Space Network into a single network. It is also responsible for providing communications and navigation services to space flight missions throughout the solar system (Jennings et al., 2009; Tai et al., 2012). More recently, in 2015, NASA proposed the Multi-Autonomous Positioning System (MAPS), which has already been implemented and routinely used for Martian communications, through the use of the Mars Reconnaissance Orbiter and Mars Odyssey spacecraft. The growth of MAPS will continue through the Mars Atmosphere and Volatile Evolution (MAVEN) project and future commercial Mars telecom orbiters (Anzalone et al., 2015). Both the integrated network for SCaN and MAPS rely extensively on ground-based operations for estimation and control of spacecraft trajectories. In order to reduce the dependence of navigation systems on ground-based operations and achieve more autonomy, a navigation reference that does not depend on artificial beacons is desirable.

In this paper, we propose an interplanetary autonomous navigation network which is independent of the ground system. It is named the Internet of Spacecraft (IoS) and it is composed of host spacecraft and client spacecraft. The former perform as the absolute reference that depends on some autonomous navigation methods and the latter is served by other spacecraft members of the IoS through inter-satellite links. In addition, this network is not a simple extension of the constellation. Its configuration is flexible such that any client spacecraft that has installed inter-satellite ranging equipment can be added into this network and client spacecraft can also be treated as host spacecraft after their positions have been determined.

The remainder of this paper is organised as follows. Section 2 describes the concept and the developed application mode of the proposed IoS network. Section 3 designs a specific application scheme that supports a flight from the Earth to Mars and Section 4 provides the conclusions.

2. THE GENERAL FRAMEWORK OF IoS. The IoS is an interplanetary autonomous navigation network which can cover the whole Solar System. The spacecraft of the IoS can be divided into two parts, namely host spacecraft and client spacecraft. The host spacecraft are settled near to some planets such as the Earth, Mars and so on. They form the absolute reference of the IoS and their positions are determined by autonomous navigation methods. The client spacecraft are launched for space missions on which inter-satellite ranging equipment is installed to communicate with others and their positions are determined by inter-satellite links. There are three navigation and communication modes for client spacecraft, which can be programmed for different flight phases. These three modes are described as follows.

Mode 1: client spacecraft determine their own positions by communicating with the host spacecraft.
Mode 2: client spacecraft obtain navigation information from the host spacecraft as well as their own equipment.
Mode 3: client spacecraft only communicate with other client spacecraft to get navigation information.

This network is not a simple extension of the navigation constellation. It possesses several characteristics and advantages. Firstly, the reference of IoS is independent of
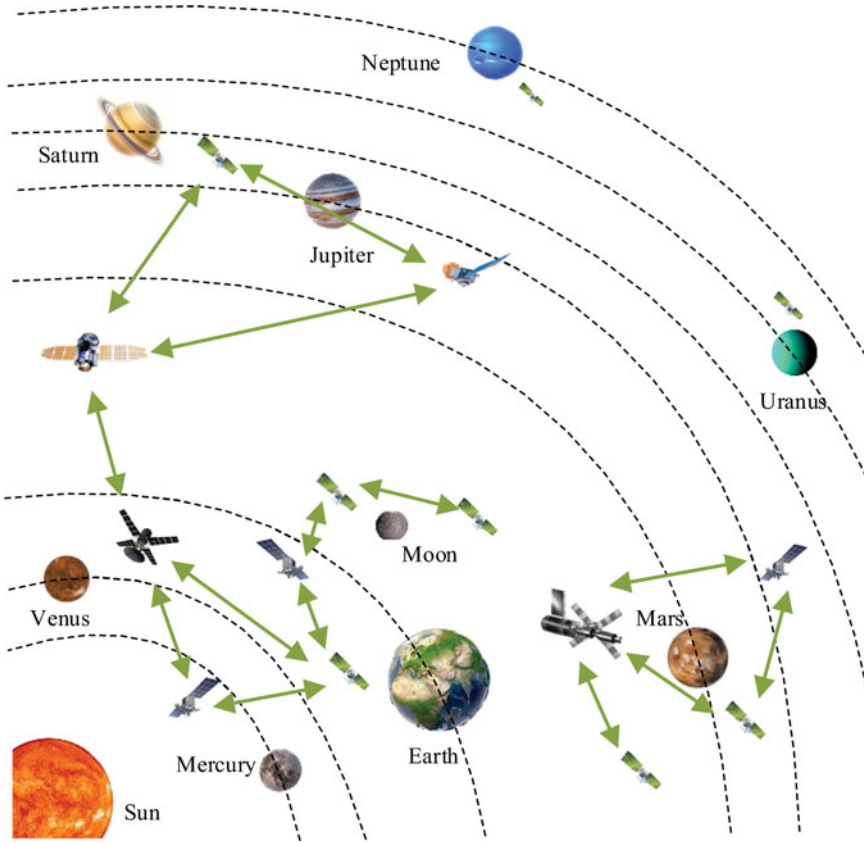
Figure 1.   A concept sketch of the IoS that covers the whole Solar System.

ground-based tracking and control systems. Their positions and velocities can be obtained by x-ray pulsar-based navigation (Sheikh and Pines, 2006; Sheikh et al., 2006; Wang et al., 2013), inter-satellite links or other autonomous navigation methods (Xiong et al., 2013). Secondly, both configuration of this network and numbers of the client spacecraft are flexible. We do not need to design the configuration of the whole network, and spacecraft installed with compatible inter-satellite ranging equipment can be added in this network and obtain an autonomous navigation service by communication with others. Finally, arbitrary IoS spacecraft can provide navigation information for the others. After determining their own positions, IoS spacecraft can transmit their position information. Thus, these client spacecraft can also be treated as host spacecraft.

Figure 1 shows a concept sketch of the IoS that can provide navigation information for the whole Solar System. As time goes by, the number of DSEs or interplanetary spacecraft will continuously increase. While they implement their own tasks, they can also be treated as newly joined spacecraft of the IoS at the same time, thus there would be more and more spacecraft in the IoS. As a result, this network would be upgraded, and its coverage could be expanded to further places. Finally, a highly reliable, efficient and low-cost interplanetary autonomous navigation network is expected to be formed.

3. A DETAILED DESIGN FOR IoS THAT SUPPORTS THE FLIGHT FROM EARTH TO MARS. Currently, Mars exploration is a hot space exploration topic (Bell et al., 2000; Grotzinger et al., 2012; Martin-Mur et al., 2013), and a specific application scheme for IoS supporting a flight from the Earth to Mars is designed in this section.

3.1. *Design of the IoS reference.* As introduced in Section 2, the host spacecraft are the absolute reference for the whole network. To design the IoS reference, the client spacecraft's space region should be first ascertained. Then, we need to design the orbit of the reference spacecraft to realise geometrical coverage of the client spacecraft. Next, the physical coverage should be guaranteed, that is, the signal intensity should be strong enough to be received. Finally, high-accuracy autonomous navigation methods should be applied to the host spacecraft. Therefore, we design the reference of IoS through these several aspects, that is including design of the orbit, design of the physical coverage and the autonomous navigation method applied for the reference.

3.1.1. *Design of the orbit.* The client spacecraft's space region, geometrical configuration and orbital stability are taken into account in designing the orbit.

Firstly, we consider that the target users are Mars probes. Their mission phases can usually be divided into a launching phase, cruising phase, and the orbit around Mars (Miele and Wang, 1999). As shown in Figure 2, the launching phase is located in the Earth's sphere of influence. Then the spacecraft takes a long journey along an interplanetary orbit around the Sun, which is the cruising phase. After that, the spacecraft inserts into orbit around Mars. All of these phases should be covered by the IoS.

The host spacecraft should be placed near a planet and it is influenced by the gravitational force of the Sun, thus the dynamical model of the host spacecraft can be regarded as a Circular Restricted Three Body Problem (CRTBP). The communication and navigation constellation can be arranged around the libration points of the CRTBP to support autonomous navigation for DSEs (Bhasin and Hayden, 2004; Kulkarni et al., 2005). So, the Sun-Earth libration points and the Sun-Mars libration points are chosen for the host spacecraft.

Figure 3 shows the relative location of Sun-Earth libration points and Sun-Mars libration points, which are respectively denoted as $EL_1 \sim EL_5$ and $ML_1 \sim ML_5$ (Meng et al., 2015). Considering the long distances from EL_3, EL_4 and EL_5 to Earth and from ML_3, ML_4 and ML_5 to Mars, the signal propagation loss will be enormous. In addition, the transfer trajectories of Mars probes are mostly direct trajectories (Luo, 2013), and with consideration of energy, the electromagnetic beam angle should be limited, thus the host spacecraft should be put at only one side of the Earth or Mars.

Finally, we select a cluster of orbits around the libration points to arrange the host spacecraft. As the normal amplitude of the Halo orbit is large enough, spacecraft on this kind of orbit will not be covered by celestial bodies. Therefore, if the host spacecraft is located in the Halo orbit, it will possess higher dispersity and smaller linearity. Moreover, the stability of this orbit is better. Therefore, the Halo orbits around EL_2 (or EL_1) and ML_2 (or ML_1) are chosen for a host spacecraft. Figure 4 shows the specific space configuration scheme of a host spacecraft by taking the L_2 libration points as an example.

3.1.2. *Design of the reference's physical coverage.* Because of the broad geometrical coverage and far operating distance of the IoS, the problem of signal propagation is very serious. It is necessary to analyse the intensity of the navigation signal to ensure physical coverage.
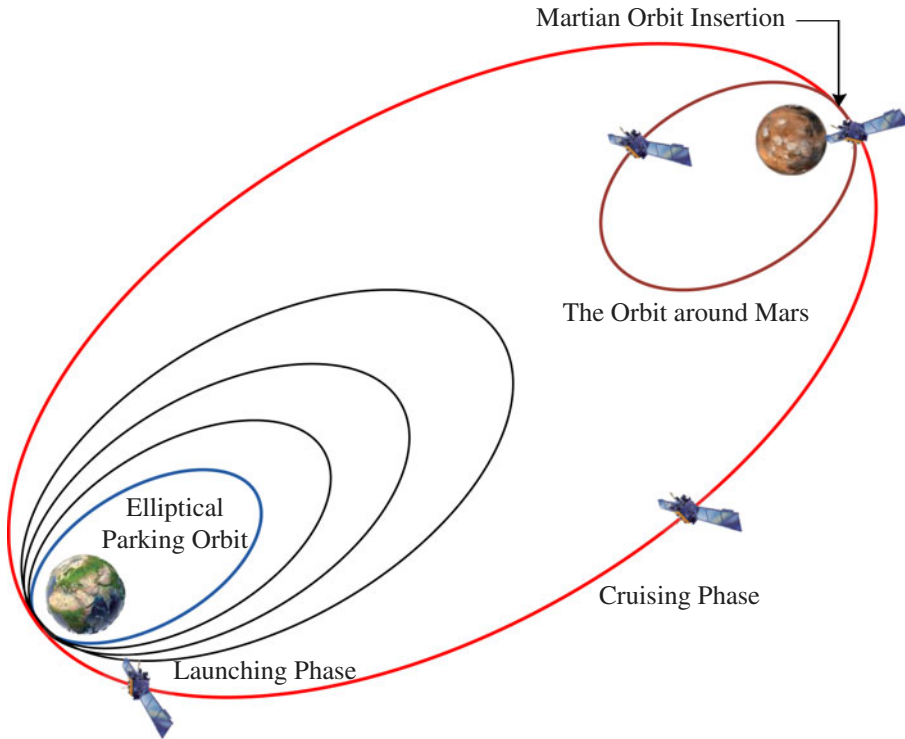
Figure 2.   Schematic of flight phases in Mars exploration.

Generally speaking, navigation signals propagate in the form of electromagnetic waves, and the formula of signal propagation loss is

$$Los = 32 \cdot 44 + 20 \lg d(\text{km}) + 20 \lg f \,(\text{MHz}) \tag{1}$$

where f is the operating frequency and d is the propagation distance. When f or d is doubled, the signal propagation loss will increase by 6 dB. So, the maximum signal loss can be analysed to reflect the effective navigation distance of the reference.

The Global Positioning System (GPS) is the most used global navigation system and GPS satellites can be analysed to help confirm the corresponding parameters of the host spacecraft. Table 1 shows some parameters of the GPS satellites (Meng and Chen, 2014). Technical improvements should allow the parameters to be improved over time and the navigation distance would consequently be lengthened.

The intensity of the emission signal is related to the beam angle. The formula of the signal gain relative to the beam angle α is $10 \times \lg G_T(\alpha)$, where

$$G_T(\alpha) = \frac{2}{1 - \cos \alpha} \tag{2}$$

Due to the long operating distance of the host spacecraft, its beam angle does not need to be so large as that of GPS, and a 6° angle is enough to cover a range of 78,500 kilometres from the geocentre and 54,900 kilometres from Mars' centre. According to Equation (2),
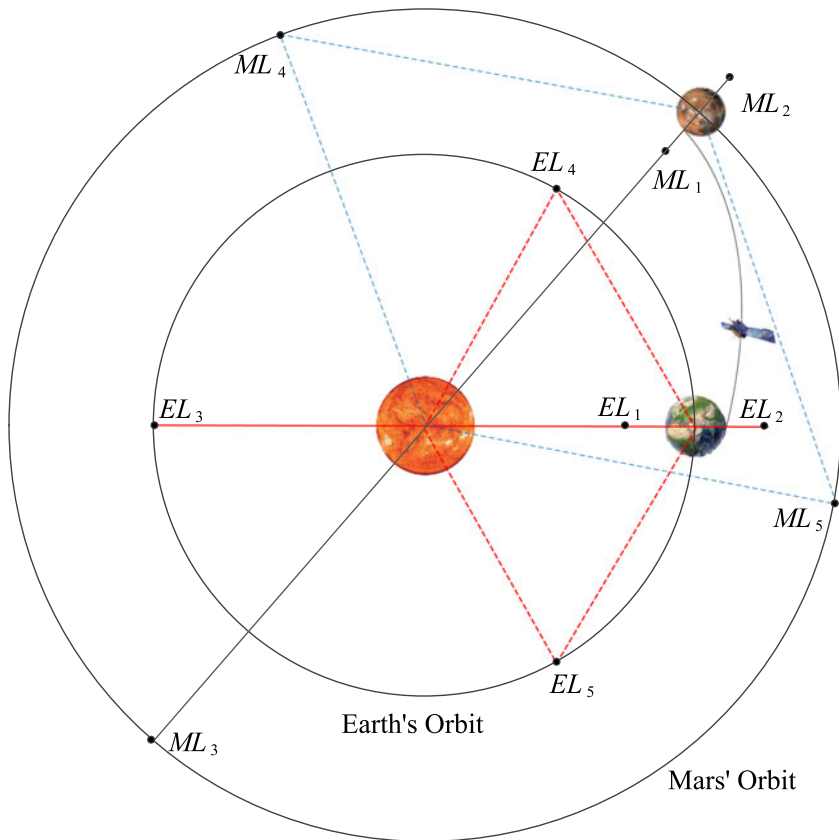
Figure 3.   Libration Points of Sun-Earth and Sun-Mars systems.

the signal intensity can be strengthened to 25·6 dB, which is an improvement of 11 dB compared to GPS. In addition, in order to enhance the anti-interference ability, the transmitting power of GPS-III satellites will improve by one hundred times over older satellites (Sun et al., 2004), and the input power of the satellite antenna will consequently improve by 20 dB. Moreover, the Signal to Noise Ratio (SNR) of the receiver may reach 25 dB/Hz by applying the weak signal acquisition technique (Grant and Dodds, 2009; Karunanayake et al., 2004).

On the basis of the above analysis, the propagation path loss can increase by 46 dB over that of GPS, and the navigation distance is about 200 times further than GPS, that is, 4×10^6 km, which is much longer than the distance from EL_2 and ML_2 to the Earth and Mars respectively.

We utilise simulated data to analyse whether the effective navigation distance can cover the cruising phase. Table 2 shows the initial state of a transfer trajectory from the Earth to Mars in the heliocentric inertial coordinate system (Luo, 2013). Combining the planetary ephemeris DE405, this trajectory is simulated, and it is shown in Figure 5.

Figure 6 shows the distance from this transfer trajectory to EL_2 and ML_2. As shown in Figure 6, the configuration scheme mentioned in Section 3.1.1 can provide navigation
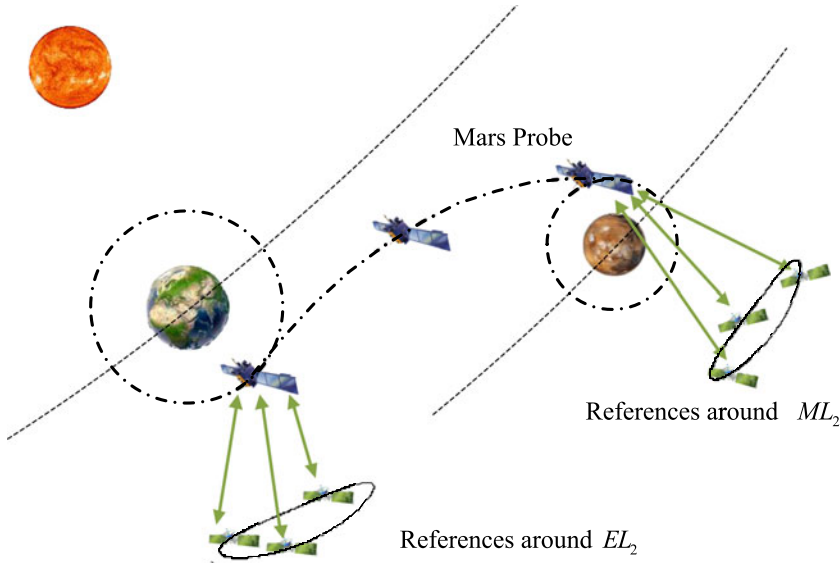
Figure 4.   The configuration of the host spacecraft around EL_2 and ML_2.

Table 1.   Parameters of GPS satellites.

Parameters	Value
Beam angle	$21 \cdot 3°$
Transmit antenna gain	$14 \cdot 7$ dB
Signal to noise ratio (SNR) of received signal	40 dB/Hz
Navigation distance	20180 km

Table 2.   Initial states of an Earth-Mars transfer orbit
in the heliocentric inertial coordinate.

State-vector component	Value
X [km]	$4 \cdot 4825 \times 10^7$
Y [km]	$1 \cdot 2887 \times 10^8$
Z [km]	$5 \cdot 5869 \times 10^7$
$\dot{X}$ [km/s]	$-31 \cdot 5034$
$\dot{Y}$ [km/s]	$7 \cdot 2765$
$\dot{Z}$ [km/s]	$4 \cdot 7646$

information for the start and end of the cruising phase, which is significant so that a Mars probe can obtain an accurate insertion state.

3.1.3. *The autonomous navigation method applied for the host spacecraft.*   Realising high-accuracy autonomous navigation of the host spacecraft is the foundation to guarantee the positioning precision of the IoS. Hill (2007) proposed an autonomous navigation method in libration point orbits that only uses inter-satellite links. However, the convergence speed of this method for the Sun-Earth and Sun-Mars system is rather slow. X-ray
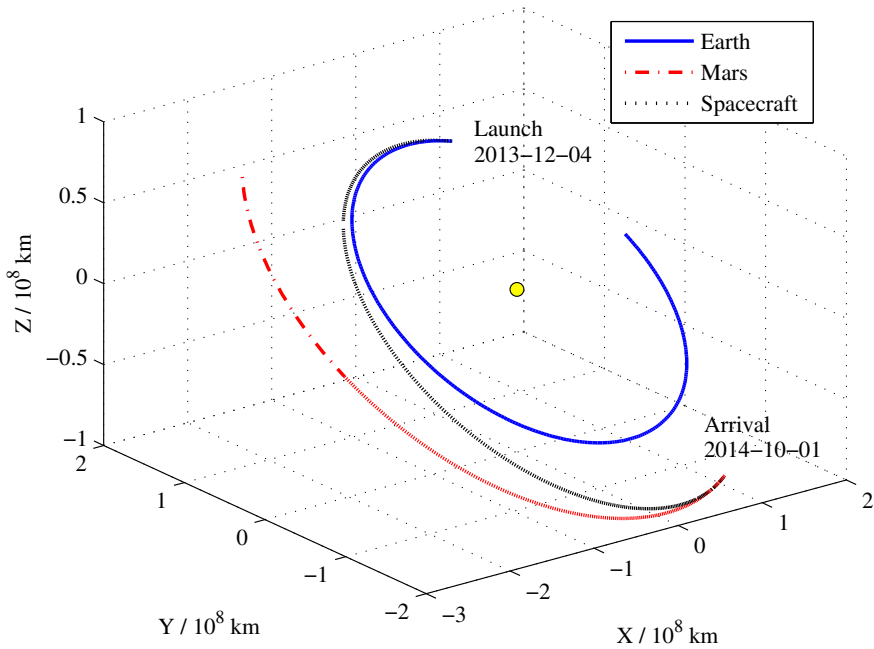
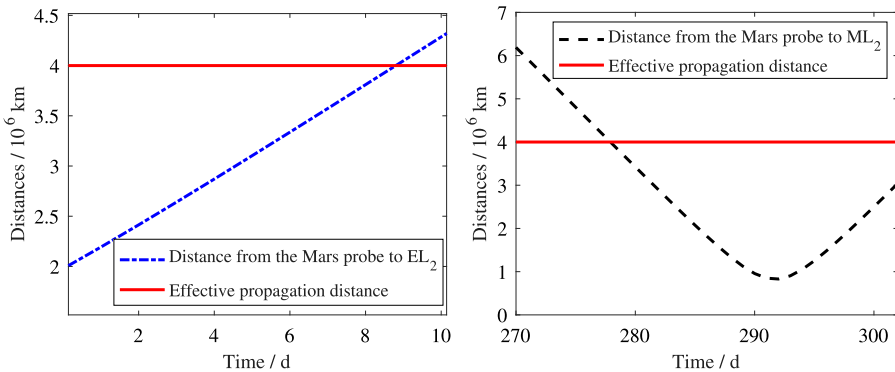Figure 5.   The transfer trajectory from the Earth to Mars in the heliocentric inertial coordinate system.

Figure 6.   Distances from the Mars Probe to EL_2 and ML_2.

pulsar navigation is a newly developed autonomous navigation method, which can provide high-accuracy absolute information for DSEs (Wang et al., 2014; Wang and Zheng, 2016). Thus, we apply x-ray pulsar-based relative navigation and inter-satellite links in this paper to realise autonomous navigation for host spacecraft. Their measurements are respectively the difference between the pulse time of arrivals and the distance of two spacecraft. Its specific principle can be found in Emadzadeh and Speyer (2011). Table 3 shows the parameters of the chosen pulsars (Sheikh and Pines, 2006; Sheikh et al., 2006), and the x-ray background radiation flux is taken as 0·005 ph/cm^2/s (Dennis, 2005). Table 4 shows the initial state of the Halo orbits around EL_2 and ML_2 in the synodic reference frame (Parker et al., 2006), where [L] and [T] are respectively the normalised units of length and time.

Table 3.   Parameters of chosen pulsars.

| Parameters | Pulsars | | |
	B0531+21	B1821−24	B1937+21
Right ascension angle [deg]	83·63	276·13	294·92
Declination angle [deg]	22·01	−24·87	21·58
P [s]	0·0334	0·00305	0·00156
W [s]	$1·7 \times 10^{-3}$	$5·5 \times 10^{-5}$	$2·1 \times 10^{-5}$
F_x [ph/cm^2/s]	1·54	$1·93 \times 10^{-4}$	$4·99 \times 10^{-5}$
p_f [%]	70	98	86

Table 4.   Initial states of the Halo orbit around EL_2 and ML_2.

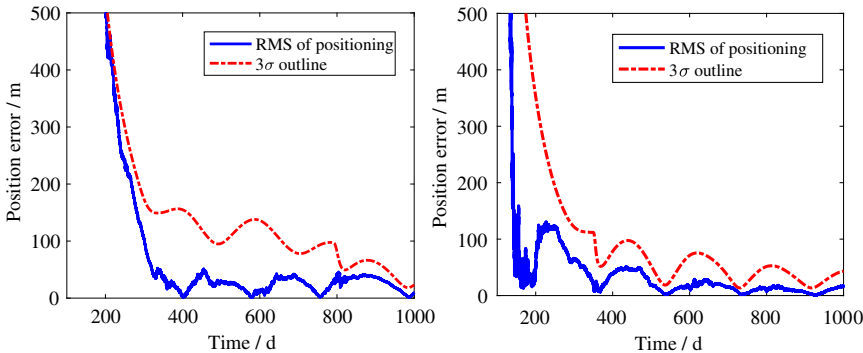| State parameters | Location of the Halo orbit | |
	Around EL_2	Around ML_2
x_0/[L]	1·008320655353143	1·003857250806226
y_0/[L]	0	0
z_0/[L]	0·000744256879882	0·000737122161894
v_{x0}/[L]	0	0
v_{y0}/[L]	0·009958906346744	0·005044116911458
v_{z0}/[L]	0	0

Figure 7.   The position estimation error of host spacecraft around EL_2 and ML_2.

The z-axis amplitude of the Halo orbit is 2×10^5 km, and host spacecraft are distributed every equal phase. The initial state errors are respectively taken as 10 km and 10 m/s, the error of inter-satellite links is 1 m, and the observation period is 3,600 s.

We apply an Unscented Kalman Filter (UKF) to investigate the performance of this navigation method. Figure 7 shows the position estimated errors and 3σ outlines of the host spacecraft around EL_2 and ML_2, and it can be seen that the positional accuracy can reach the order of 50 m.

3.2. *Navigation modes of client spacecraft.*   After the host spacecraft have determined their own positions, they can provide a navigation service for the client spacecraft, which only need to carry the inter-satellite ranging equipment. Note that when one client
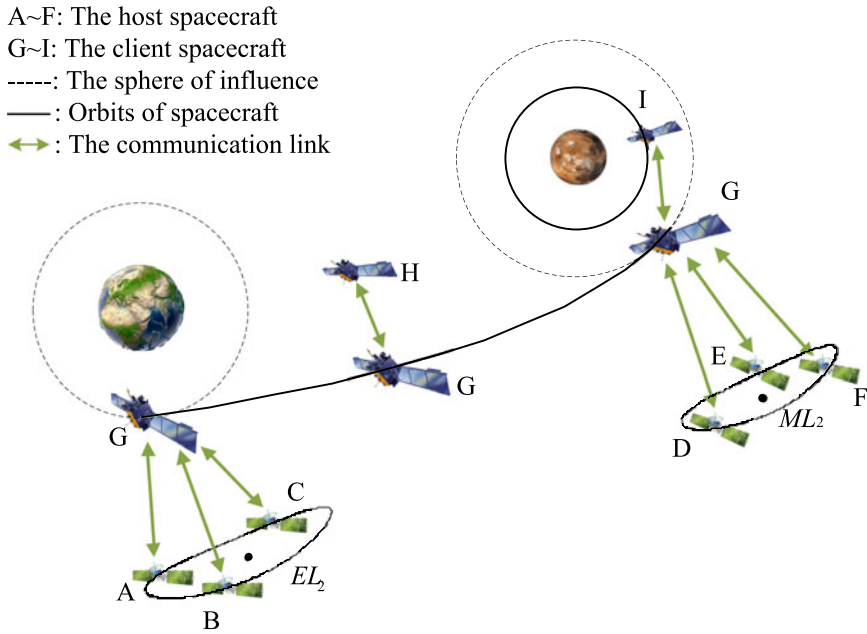
A~F: The host spacecraft
G~I: The client spacecraft
-----: The sphere of influence
——: Orbits of spacecraft
←→ : The communication link

Figure 8. Schematic of the client spacecraft's navigation modes in the IoS system that can support a flight from the Earth to Mars.
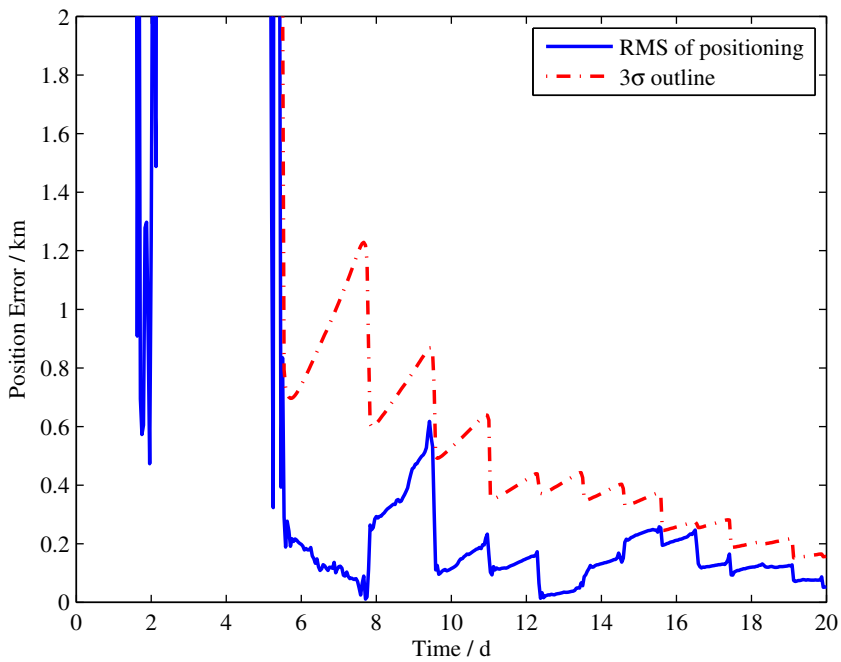

Figure 9.   The position error of the client spacecraft for Case 1.

Table 5.   Initial states of the spacecraft G and H in the heliocentric inertial coordinate system.

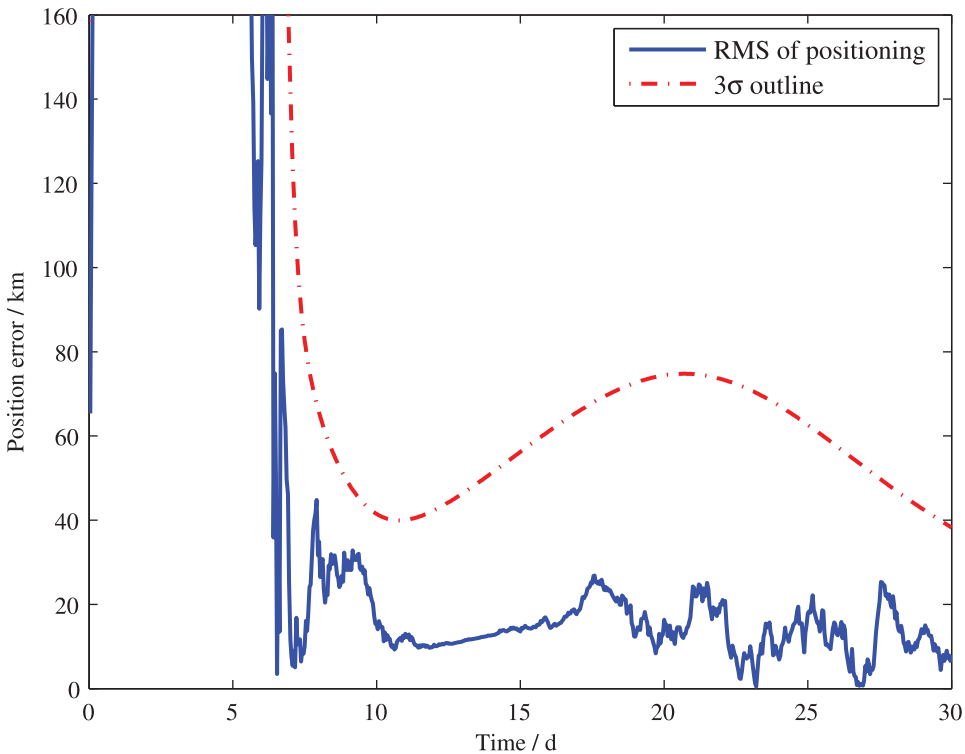| State Parameters	G	H
X [km]	$5 \cdot 8903 \times 10^7$	$5 \cdot 8845 \times 10^7$
Y [km]	$1 \cdot 2503 \times 10^8$	$1 \cdot 2505 \times 10^8$
Z [km]	$5 \cdot 3475 \times 10^7$	$5 \cdot 7786 \times 10^7$
$\dot{X}$ [km/s]	$-30 \cdot 5362$	$-30 \cdot 5568$
$\dot{Y}$ [km/s]	$9 \cdot 6449$	$9 \cdot 5980$
$\dot{Z}$ [km/s]	$5 \cdot 7845$	$-3 \cdot 7258$

Figure 10.   The positioning error of the client spacecraft for Case 2.

spacecraft has been positioned, its position can be transmitted to others in the form of a directional "request-response" mode.

With the increase of the rate of space missions, the IoS will be continuously expanded and improved. The subsequent spacecraft can program the communication links according to their own requirements and choose one or several nearby spacecraft from the IoS to realise their own autonomous navigation.

Combining the designed scheme of the reference of the IoS in Section 3.1, navigation modes of the client spacecraft are analysed. Figure 8 shows different navigation modes of the Mars probe at different phases, which have been mentioned in Section 2. A, B and C are host spacecraft at the Halo orbit around EL_2. D, E and F are the reference around ML_2 and

Table 6.   Orbit elements of the client spacecraft that are near Mars (Lightsey et al., 2008).

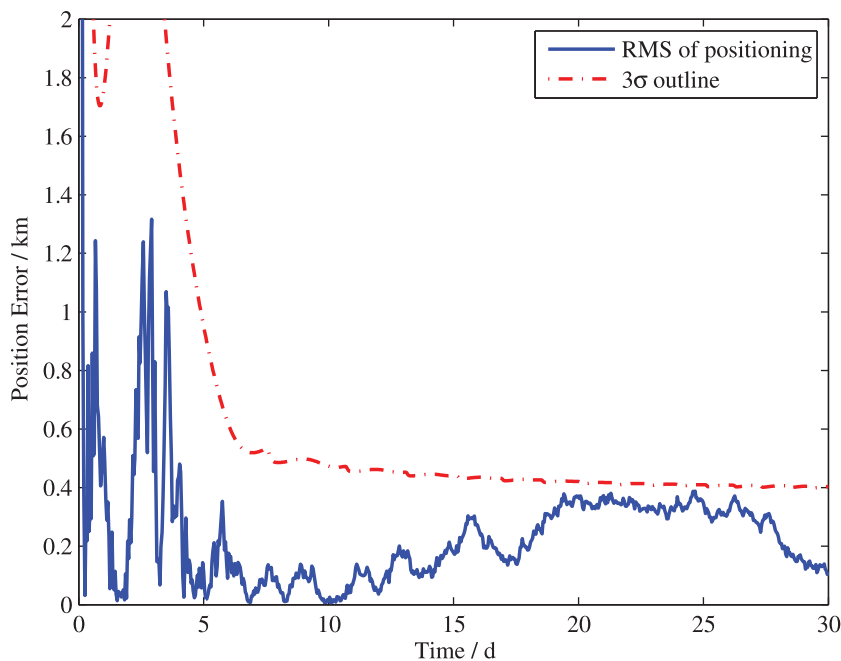| Orbit elements	G	I
Semi-major axis [km]	−5432·0	3684·5
Eccentricity	1·617	0·010
Inclination [deg]	44·1	93·0
Longitude of node [deg]	91·9	278·0
Argument of periapsis [deg]	297·2	270·0

Figure 11.   The position error of the client spacecraft for Case 3.

the spacecraft G is the Mars probe whose communication links have been programmed, H is another client spacecraft that is within the communication scope of G, and I is a Mars Orbiter that can provide navigation information to others.

The Mars probe G can choose different host spacecraft or client spacecraft at different flight phases. Three different cases are designed to investigate the performance of the corresponding navigation modes.

Case 1: The spacecraft G is located at the initial stage of the cruising phase and can be covered by the host spacecraft. Therefore, it can choose the host spacecraft around EL_2 as the communication target.

The initial states of G in this case are the same as those in Table 2, and its position and velocity errors are respectively 10 km and 10 m/s. The navigation interval is 3,600 s, and the error of inter-satellite links is taken as 50 m considering the position error of host spacecraft which was analysed in Section 3.1.3. Figure 9 shows the result of the UKF and the 3σ outlines. It can be seen that the position error can converge within six days and reach a precision of about 1 km. Therefore, the Mars probe can insert into the cruising phase with smaller state errors.

Case 2: The spacecraft G's flight segment is still the cruising phase, but it cannot receive the signal of a host spacecraft in this scheme. It could choose another client spacecraft (the spacecraft H in Figure 9) within its communication scope to modify its state. Table 5 shows the initial states of G and H of this case. The simulation conditions are taken as the same as that in Case 1. The positioning result is shown in Figure 10, which can reach an accuracy of 40 km (3σ).

Case 3: The client spacecraft G has inserted into Mars' sphere of influence and the host spacecraft around ML_2 and a Mars Orbiter (the spacecraft I in Figure 8) are chosen to provide the navigation service. Table 6 shows the orbit elements of the Mars probe G and the Orbiter I, the position errors and velocity errors are taken as 1 km and 1 m/s. The other simulation conditions are the same as those in Case 1. Figure 11 shows the results of this case, and the position errors are within 500 m.

The above three cases represent three different navigation and communication modes of the client spacecraft of the IoS. Our results show that the IoS could provide a high-accuracy navigation service for a Mars Probe during its whole flight. Furthermore, this continuously updated network can play an important role for missions to Mars as well as other deep space exploration missions.

4. CONCLUSIONS. An interplanetary space-based autonomous navigation network named the Internet of Space (IoS) is proposed in this paper. This network is composed of two parts, host spacecraft and client spacecraft. The former forms the absolute reference of the IoS, and the latter has installed an identical inter-satellite ranging device to communicate with other spacecraft through a "request-response" mode.

To describe the IoS in more detail, a specific application scheme supporting a flight from the Earth to Mars was developed and analysed. The Halo orbits around EL_2 and ML_2 are chosen for host spacecraft and the feasibility of this scheme was verified by analysing the signal intensity of the reference. Our results show that if the navigation information is transmitted in the form of electromagnetic waves, and the development of science and technology is taken into account, the effective navigation distance can reach 4×10^6 kilometres, which can cover the initial and end stage of the cruising phase for a Mars mission. X-ray pulsar-based navigation using time-differenced measurement and inter-satellite links are applied to navigation for the reference and its positioning accuracy can reach around 50 m. Three navigation modes of the client spacecraft were programmed according to the different navigation distances for different flight phases. Results show that a Mars probe can obtain high accuracy autonomous navigation information for the whole flight.

As the number of deep space exploration missions increases, an IoS would be continually expanded and upgraded to provide more abundant navigation information and could eventually be expected to cover the whole Solar System.

REFERENCES

Anzalone, E., Becker, C., Crump, D. and Heater, D. (2015). Multi-spacecraft Autonomous Positioning System: LEO Demo Development. *29th Annual AIAA/USU Conference on Small Satellites*, SSC15-VI-4.

Bell, D. J., Cesarone, R., Ely, T., & Edwards, C. (2000). Mars network: a Mars orbiting communications and navigation satellite constellation. *Aerospace Conference Proceedings*, IEEE, **7**, 75–88.

Bhasin, K. and Hayden, J. (2004). Developing architectures and technologies for an evolvable NASA space communication infrastructure. *22th AIAA International communications satellite system conference and exhibit, Monterey*, 1180–1191.

Dennis, W. W. (2005). *The use of x-ray pulsars for aiding GPS satellite orbit determination*. Master dissertation, Air Force Institute of Technology.

Emadzadeh, A. A. and Speyer, J. L. (2011). Relative navigation between two spacecraft using x-ray pulsars. *IEEE Transactions on Control Systems Technology*, **19**, 1021–1035.

Lightsey, E. G., Mogensen, A. E., Burkhart, P. D., Ely, T. A. and Duncan, C. (2008). Real-time navigation for Mars missions using the Mars network. *Journal of Spacecraft and Rockets*, **45**(3), 519–533.

Grant, H. and Dodds, D. (2009). A new comparison of averaging techniques used for weak signal acquisition with application to GPS L_5 signals. *Proceedings of the Institute of Navigation GNSS conference, Savannah, GA*, 2610–2616.

Grotzinger, J. P., Crisp, J., Vasavada, A. R., Anderson, R. C., Baker, C. J., Barry, R., Blake, D. F., Conrad, P., Edgett, K. S., Ferdowski, B., Gellert, R., Gilbert, J. B., Golombek, M., Gomez-Elvir, J., Hassler, D. M., Jandura, L., Litvak, M., Mahaffy, P., Maki, J., Meyer, M., Malin, M. C., Mitrofanov, I., Simmonds, J. J., Vaniman, D., Welch, R. V. and Wiens, R. C. (2012). Mars science laboratory mission and science investigation. *Space Science Reviews*, **170**, Nos. 1–4, 5-56.

Hill, K. (2007). *Autonomous navigation in libration point orbits*. Ph.D. thesis, Graduate school of the University of Colorado.

Jennings, E., Borgen, R., Nguyen, S., Segui, J., Stoenescu, T. and Wang, S. Y., Woo, S., Barritt, B., Chevalier, C. and Eddy, W. (2009). Space Communications and Navigation (SCaN) Network Simulation Tool Development and Its Use Cases. *American Institute of Aeronautics and Astronautics*, August, 1–11.

Karunanayake, M. D., Cannon, M. E. and Lachapelle, G. (2004). Evaluation of assisted GPS (AGPS) in weak signal environments using a hardware simulator. *Proceedings of the Institute of Navigation GNSS conference, Long Beach, California*, 2416–2426.

Kulkarni, T. R., Dharne, A. and Mortari, D. (2005). Communication architecture and technologies for missions to moon, mars, and beyond. *Space exploration conference: continuing the voyage of discovery, Orlando, Florida*, AIAA, 2005–2778.

Luo, H. J. (2013). *Orbit design and optimization of Mars probe*. MSc thesis. Harbin, Harbin Institute of Technology.

Martin-Mur, T. G., Kruizinga, G. and Wong, M. (2013). Mars Science Laboratory Interplanetary Navigation Performance. *AAS/AIAA Space Flight Mechanics Conference, American Astronautical Society,* Paper 2013–232.

Meng, Y. H. and Chen, Q. F. (2014). Outline design and performance analysis of navigation constellation near earth-moon libration point. *Acta Physica Sinica*, **63**(24), 1429–1438.

Meng, Y. H., Zhang, Y. D. and Chen, Q. F. (2015). *Dynamics and control of spacecraft near libration points*. Science Press, Beijing.

Miele, A. and Wang, T. (1999). Optimal transfers from an Earth orbit to a Mars orbit. *Acta Astronautica*, **45**(3), 119–133.

Parker, J., Anderson, R., Born, G., Fujimoto, K., Leonard, J. and McGranaghan, R. (2006). Navigation Between Geosynchronous and Lunar L1 Orbiters. *AIAA/AAS Astrodynamics Specialist Conference*, 13–16.

Sheikh, S. I. and Pines, D. J. (2006). Recursive estimation of spacecraft position and velocity using x-ray pulsar time of arrival measurements. *NAVIGATION, Journal of the Institute of Navigation*, **53**, 149–166.

Sheikh, S. I., Pines, D. J. and Ray, P. S. (2006). Spacecraft Navigation using x-ray pulsars. *Journal of Guidance, Control and Dynamics*, **29**, 49–63.

Sun, H. T., Wang, C. Q. and Feng, J. D. (2004). Current situation and development of anti-jamming technology of GPS system in USA. *Electro-Optic Technology Applications*, **19**(3), 57–63.

Tai, W., Wright, N. and Prior, M. (2012). NASA Integrated Space Communications Network. *SpaceOps 2012 Conference*, 1275818.

Wang, Y. D. and Zheng, W. (2016). Pulse Phase Estimation of X-ray Pulsar with the Aid of Vehicle Orbital Dynamics. *Journal of Navigation*, **69**(2), 414–432.

Wang, Y. D., Zheng, W. and Sun, S. M. (2014). X-ray Pulsar-based Navigation Using Time-differenced Measurement. *Aerospace Science and Technology*, **36**, 27–35.

Wang, Y. D., Zheng, W., Sun, S. M. and Li L. (2013). X-ray pulsar-based navigation system with the errors in the planetary ephemerides for Earth-orbiting satellite. *Advances in Space Research*, **51**(12), 2394–2404, 2013.

William, H. B. (2005). Deep impact mission design. *Space Science Reviews*, **117**(1/2), 23–42.

Xiong, K., Wei, C. L. and Liu, L. D. (2013). Autonomous navigation for a group of satellites with star sensors and inter-satellite links. *Acta Astronautica*, **86**, 10–13.

Zheng, W., Wang, Y. D. and Tang, G. J. (2015). *X-ray pulsar-based navigation: theory and applications*. Science Press, Beijing.