

Promoting the Planetary Radio Science in the Lunar and Deep Space Explorations of China

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Abstract-Radio science experiments using the radio link between s/c and ground tracking stations have been playing important roles in lunar and deep space exploration since 1960s, which study the planetary atmosphere and ionosphere, lunar and planetary gravity fields and rotations, carry out precise orbit determination and relevant tests of general relativities. In Chinese lunar and planetary missions since 2004, based on very poor or limited s/c radio tracking conditions, research team improved the lunar gravity field and found new mascons, developed open-loop only OD method for Martian missions, and accomplished 1st round atmospheric occultation experiments for Mars and Venus. In future lunar landing mission and deep space mission of China, radio science experiments will also measure the lunar physical liberation and planetary rotations with very high precisions.

I. INTRODUCTION

The radio science experiment makes a virtue out of a necessity by using the radio propagation techniques that convey data and instructions between the spacecraft and Earth to investigate the planet's atmosphere, ionosphere, rings, and magnetic fields, surface, gravity field, GM and interior, as well as testing the theories of relativity. The experiments have been conducted by most planetary missions and are planned for many future ones. This is almost like getting science for free some way, and has been used also in Chinese lunar orbiting missions to carry out POD and estimate the lunar gravity field successfully.

Since 2004, lunar and planetary exploration missions have been started in China. Lunar orbiters of Chang'E-1/2 were launched in 2007 and 2010 separately[1]. A failed joint Martian mission with Russia, Yinghuo-1(YH-1) and Phobos-Grunt, was launched in 2011. Lunar landing mission Chang'E-3 will be launched in 2013. New Martian missions and asteroid missions are being promoted now.

Besides the payload mission times, a radio science (RS) experiments research team are also involved in above missions. This RS team using Chang'E-1 tracking data improved the lunar gravity field successfully. They also developed radio science receiver system, and connected to the IF and H-Maser system of Chinese VLBI stations. A series of radio occultation

experiments have been carried out. In the techniques, radio frequency transmission from MEX and VEX spacecraft, occulted by center planets, and received on Earth probe the extended atmosphere of the planets. The radio link is perturbed in phase and amplitude, the perturbation is converted into an appropriate refractivity profile, from which, information is derived about the electron distribution in the ionosphere, temperature-pressure profile in the neutral atmosphere, or particle size distribution of the ring material surrounding the center planet, in the case of a ring occultation. In Chang'e-3/4 and Luna-Glob landing missions, the two radio downlinks, S/X-bands or X/Ka-bands, will be used for different types of investigation about the physical mechanisms that brought the changes. We will use the signal to measure the lunar physical liberations, so as to improve the lunar interior studies together with LLR data. Above method may be used in Chinese Martian mission.

II. RADIO SCIENCES IN CHANG'E-1

Chang'E-1 was the first Chinese lunar orbiter mission, and its main scientific objectives were to obtain three dimensional images of the lunar surface, and to obtain the distribution of lunar elements[1]. Chang'E-1 was launched on October 24, 2007, and after multiple orbit adjustments, such as phase change, Earth-Moon transfer and lunar capture, it became a lunar satellite in a near-circular orbit with 200 km altitude and inclination ranging from 87.58° to 91.40, which is sensitive to low degree coefficients of lunar gravity field. During nominal mission phase of Chang'E-1 a large amount of range and Doppler tracking data were acquired, which could be used to develop lunar gravity field solutions. A lunar gravity field model labeled CEGM01 using only these data has been obtained by Yan et al[2]. It shows that Chang'E-1 orbital tracking data can contribute more to determining gravity field than Clementine, and they can be used to estimate the gravity field coefficients to degree and order 50 independently.

Using Chang'E-1 orbital tracking data, in combination with orbital tracking data of SELENE, Lunar Prospector, and historical spacecraft, a lunar gravity field model denoted

CEGM02 is developed, see Figure 1. Analyses show that due to its higher orbit altitude (200 km), tracking data of Chang'E-1 contribute to the long wavelengths of the lunar gravity field. When compared to SGM100h, formal error of CEGM02 coefficients below degree 5 is reduced by a factor of about 2~3.

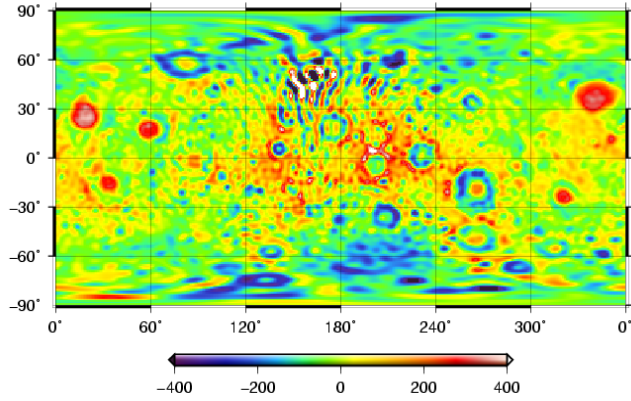


Figure 1. Free air gravity of the moon on the surface of reference radii 1738km (Unit: mgal).

Using the lunar gravity model CEGM02 and the topography model CETM-s01 of Chang'E-1 mission, we calculated the terrain correction for lunar free-air gravity anomaly (FAGA). The obtained lunar Bouguer gravity anomaly (BGA) reveals density irregularities of the interior mass, where the South Pole-Aitken (SPA) basin was found to be the largest mascon basin on the Moon. Another 8 middle size hidden basins are newly identified of showing strong BGA mascon feature. An example is shown in Figure 2. CETM-s01 and CEGM02 models also show some area with strong features of FAGA, BGA and topographic swells of hundreds kilometers in extent, where we identified 3 shield volcanoes with proposed underground magma chambers at the west area of Oceanus Procellarum[3].

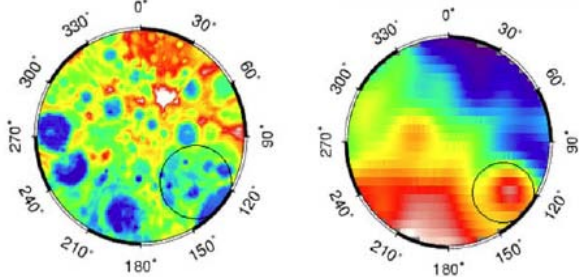


Figure 2. Newly identified Lunar Hidden BGA basins and Amundsen-Ganswindt at South pole area.

III. RADIO SCIENCES IN CHANG'E 3/4

China will launch the 1st lunar landing mission with a rover this year. A backup sister landing and rover mission, Chang'E-4, with identical payloads of Chang'E-3 will be launch and landed at different area of the Moon. They compose the main part of the 2nd phase of Chinese lunar

scientific exploration projects. Together with the various in-situ optical observations around the landing sites, missions will also carry out 4 kinds of radio science experiments, cover the various lunar scientific disciplines as well as lunar surface radio astronomy studies.

4 kinds of radio science experiments have been planned in Chang'E 3/4 landing missions: 1) HF and VHF dual-band penetrator radar on the rovers; 2) very low frequency through HF radio astronomy on the surface of Moon; 3) same-beam X-band Very Long Baseline Interferometry (VLBI) for precise positioning of rover; 4) precise radio phase ranging for lunar rotation and dynamics.

HF and VHF dual-band penetrating radar: the radar has center frequencies at 30MHz and 50MHz with bandwidth of 15MHz for each, linear polarized antenna to study the subsurface structure of landing area. In the mission LRS of SELENE/KAGUYA project, Japanese researchers obtained the lunar subsurface structure of 5~10 KM deep with resolution of dozens meters, where the igneous lunar basalt filling at mare area was firstly measured with the maximum thickness of 500~600 meters. Lunar regolith and lunar crust subsurface of shallower than 3km will be firstly studied by using the dual-band GPR on the rover with very high resolution. The thickness of regolith of the soft landing area will be measured [3].

Very low frequency radio astronomy: frequency from several KHz through 10MHz, single polarized dipole antenna, with a spectra analyzer. Due to the frequency truncate by ionosphere of the earth, cosmic radio signal with frequency below 10MHz will be absorb and reflect back to the space. We cannot receive the natural cosmic signal of this band on the ground. To overcome this problem, two sets of antenna and spectra receiver system are installed on the two landing missions separately. The spectra analyzers have frequency resolution better than 1KHz. This instrument is a kind of proto type or path finder for lunar surface low frequency radio network array, or for lunar far side low frequency array in the future. On the surface of the Moon, this payload will be first time to carry the studies of extra-terrestrial solar space VLF radio observations for solar radio burst, space particle flow, kilometric wave radiation, coronal mass ejections and planetary low frequency noise.

Same beam VLBI tracking: Two VLBI beacon transmitters with high stable oscillators are installed on the Chang'E 3/4 landers and the rovers separately. Beacons will transmit X band DOR wave or single carrier wave back to the Earth. The Chinese VLBI network and the new developed Chinese deep space tracking station will observe the DOR signal from two beacons simultaneously by the main lobe of each antenna. In the differential DOR observables, the effects due to the tracking station, the atmosphere and the ionosphere of the earth, as well as the effects due to the lunar rotation, tides and libration can be cancelled dramatically. Then, the high precise relative position of the rover to the lander of the same mission will be obtained at each observation point of the rover.

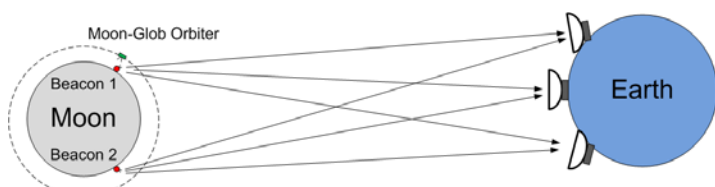


Figure 3. Lunar radio science by radio beacons in landing missions.

Lunar Radio Phase Ranging: Since early Luna and Apollo missions set 5 optical corner reflector systems on the surface of the Moon, Lunar laser ranging have been played key role on measuring the lunar rotation, Physical liberation and surface solid tides. However, the bad weather on laser site, the full Moon and new Moon phase may block the optical observation. Similar to Luna-Glob landers, together with the VLBI radio beacons, the radio transponders are also set on the Chang'E-3/4. Transponder will receive the uplink S/X band radio wave transmitted from the two newly constructed Chinese deep space stations, where the high quality hydrogen maser atomic clocks have been used as local time and frequency standard. The clocks between VLBI stations and deep space stations can be synchronized to UTC standard within 20 nanoseconds using satellite common view methods. In the near future there will be a plan to improve this accuracy to 5 nanoseconds or better, as the level of other deep space network around world. This experiment will improve the study of lunar dynamics [5], by means of measuring the lunar physical liberations precisely together with LLR data.

IV. RADIO SCIENCES IN CHINESE MARTIAN MISSION

Following the successful lunar mission of Chang'E-1, the first Chinese Mars Probe, Yinghuo-1, had been planned to launch in October 2009, delayed in October 2001, together with the Russia Phobos-Grunt landing mission. YH-1 was planned to explore the space weather of the Mars, and to test the deep space communication and navigation techniques. Difference from common deep space probe, the astronomical VLBI, open loop tracking method, like DOR/DOR, seam beam VLBI and 1-way Doppler, were used to determine the s/c orbit and position.

The RS team was responsible for developing the open loop tracking method in YH-1 mission Since 2007. The RS team developed a prototype radio science receiver successfully, based on digital radio technology with associated open-loop Doppler signal processing techniques to measure a spacecraft's line-of-sight velocity [4]. The prototype was tested in Chang'E-1 lunar mission relying on S-band telemetry signals transmitted by the satellite, with results showing that the residuals had a RMS value of ~ 3 mm/s (1σ) using 1-sec integration, which is consistent with the Chinese conventional USB (Unified S-Band) tracking system. Such precision is mainly limited by the short-term stability of the atomic (e.g. rubidium) clock at the uplink ground station. It can also be improved with proper calibration to remove some effects of

the transmission media (such as solar plasma, troposphere and ionosphere), and a longer integration time (e.g. down to 0.56 mm/s at 34 seconds) allowed by the spacecraft dynamics. The tracking accuracy can also be increased with differential methods that may effectively remove most of the long-term drifts and some of the short-term uncertainties of the uplink atomic clock, thereby further reducing the residuals to the 1 mm/s level. The experimental tracking data have been used in orbit determination for Chang'E-1. Successful application of the prototype to the Chang'E-1 mission in 2008 is valuable for the upcoming Chinese YH-1 Mars exploration project.

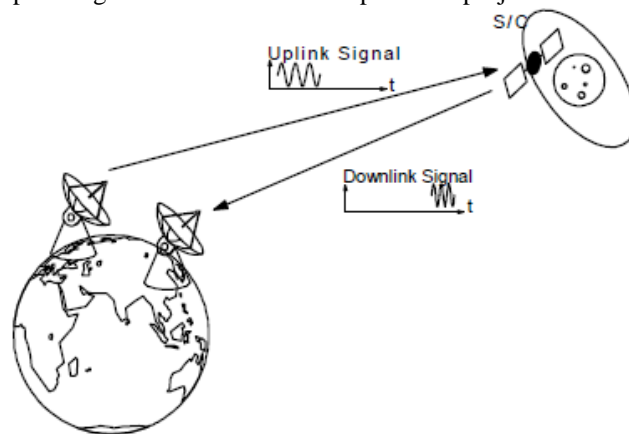


Figure 4. Radio link between ground stations and S/C.

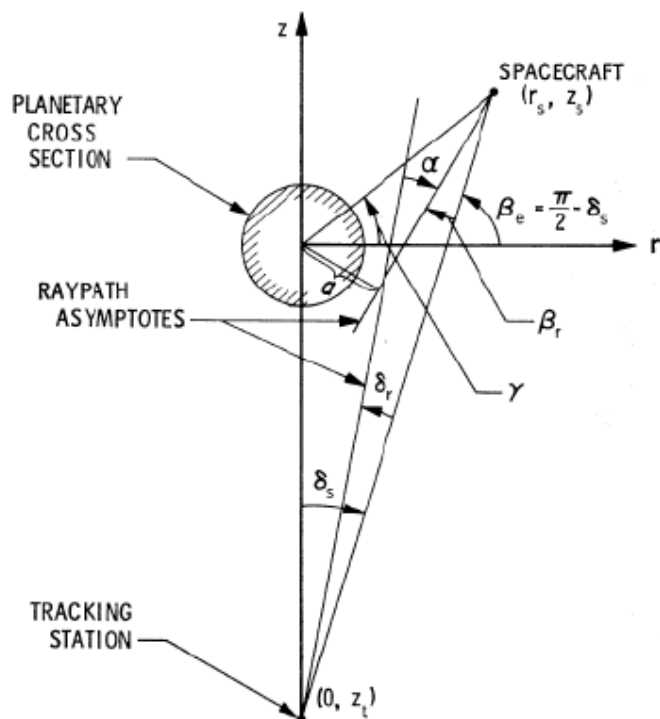


Figure 5. Raypath geometry of the radio occultation experiment following Fjeldbo et al. 1971 [6]

In YH-1 mission the Earth-based planetary radio occultation experiment had been planned [5]. In planetary radio occultation techniques, a radio signal transmitted from a

spacecraft is occulted by a planet (or one of its satellites) and received on Earth. See Figure 5. The perturbation of the radio link in phase and amplitude can be converted into an appropriate refractivity profile of the atmosphere by an inversion method in both occultation immersion and emersion. From the refractivity profile, information can be derived about the electron distribution in the ionosphere, temperature, pressure and molecular number density profiles in the neutral atmosphere, or particle size distribution of the ring material surrounding a planet, in the case of a ring occultation.

Additionally, RS team designed and developed Earth-based Planetary Occultation observation Processing system (SPOPs) for the joint Martian exploration project. Utilizing the open-loop and closed-loop Doppler residual data of the Mars Express radio occultation experiment provided by the ESA Planetary Science Archive (PSA) and the NASA Planetary Data System (PDS), the temperature, pressure, number density profiles of the Martian atmosphere and electron density profiles of the ionosphere are successfully retrieved. The results are validated by the released level 04 radio science products of the ESA MaRS group. See Figure 6.

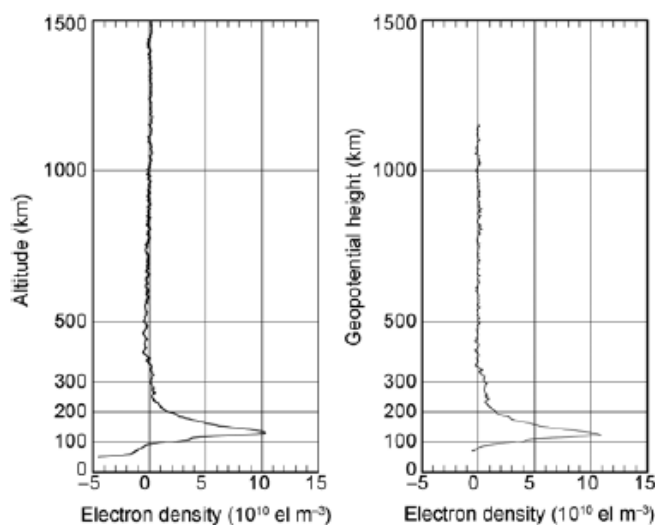


Figure 6. Example of Martian ionospheric profile: Derived ionosphere electron density profiles from the MEXMRS_0046 X-band observation (left panel) and the level 04 product given by MaRS (right panel).

The prototype receiver[7] was updated by the RS team [8]. Finally the multi-channel open loop Doppler receiver was developed for VLBI and Doppler tracking in Yinghuo-1 and Phobos-Glob Martian missions. Although the YH-1 mission failed together with Phobos-Grunt, the radio science technique for ground tracking and VLBI stations has been developed and tested using lunar and planetary missions.

A new Martian mission of China is under promoted and developed for launching during the window of 2018. 4 kinds of radio science experiments have been planned in this mission: 1) HF and VHF dual-band penetrator radar on the orbiter; 2) very low frequency through HF radio astronomy

during the cruise transferring orbit from the Earth to the Mars; 3) open-loop and close-loop radio tracking for precise orbit determination, so as to monitor the variations of long wave length gravity field components; 4) precise radio phase ranging for Martian atmospheric occultation. Above methods can be used in the next Chinese Martian mission.

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