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Chapter 12

On the History of Space Navigation Development*

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Ideas of Astronautics Pioneers: Creation of Space Navigation Systems

Astronautics pioneers understood well the importance of navigation systems (NS) to ensure space flight. Real spacecraft (S/C) motion will differ from a designed one due to launch errors and control influence errors. Therefore, we must perform, in time, the ground and/or onboard measurements of S/C parameters connected with S/C motion and determine the real S/C motion solving the reverse problem. If the motion differs from the designed one, essentially we must correct it by control influence to approach the real motion hoped for. Actually, the success of a space mission depends on the possibility of realizing effectively this program of navigation and control.

K. E. Tsiolkovsky suggested, in his pioneering work, the use of magnetic and Sun sensors to receive information about orientation, and for the motion control of the vehicle around its center of mass.[1,2]

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Ju. V. Kondratjuk offered to apply the optical (ground-based and onboard) gyroscopic sensors for vehicle navigation and control, as well as accelerometers for accelerations, motion and characteristic velocity determination.[3]

R. H. Goddard, in his own work and other works, discussed the possible use of optical and radio equipment for tracking the vehicle and its trajectory determination, as well as gyroscopes for the vehicle's stabilization, automatic onboard trajectory calculation and control.[4] In particular, he suggested the method of light signals for the determination of the position and the time of S/C arrival on the Moon's surface.

H. Oberth offered a gyroscopic and accelerometer system, as well as onboard optical osculations of planet angular diameter, and its position relative to other celestial bodies for autonomous navigation (AN).[5] He suggested applying the ground optical vehicle's observations, too.

F. A. Tsander offered to determine the distance from S/C to the planet by planet angular diameter measurement, and the S/C velocity by this diameter change rate.[6] This would allow the determination of the S/C orbit.

W. Hohmann proposed to determine the S/C distance and velocity relative to the planet by optical sighting of the planet.[7] He noted the necessity of some repeated S/C trajectory corrections.

R. Esnault-Pelterie noted the importance of vehicle actual motion knowledge and motion control.[8]

A. Sternfeld offered to determine the S/C distance to the Sun by temperature measurement, and the flight angle by optical sensor.[9] According to Lambert's theorem, this allows the determination of S/C trajectory.

Thus, theoretical astronautics had outlined the principles of navigation by the works of its pioneers in the pre-World War II period. It is interesting to note that they placed their main hopes on autonomous navigation.

The work connected with rocketry creation through the pioneer rockets of the 1930s, rockets of the Second World War (mainly German), and post-war ballistic and cruise missiles (mainly Soviet and American), became the basis for the period of space navigation. As a result, at the beginning of the Space era, navigation systems were created. They have allowed the determination of S/C motion parameters—mainly by onboard inertial gyroscopic navigation systems, and ground systems using ground measurements and processing them. The radio measurements of S/C range and Doppler velocity, range rate D relative to the ground-based station (GBS), and angles of GBS-S/C direction orientation were crucial in the latter navigation. Ground optical measurements of S/C sighting line orientation angles were used, too.

It must be noted that these navigation methods are actually the principal ones up to now. Navigation accuracy, operation speed, possibilities, and efficiency permanently grow by going to more advanced methods and systems. For example, the radio wave length of NS decreases. Another essential point in the development of navigation is the rise of the role of autonomous navigation using onboard measurements, onboard (and/or ground) data processing and motion parameters determination for both center of mass and around center of mass. This is connected with both development of navigation methods and complicating the problem to be solved.

Let us consider some bright stages in space navigation.

Navigation of the Earth Artificial Satellites

The orbiting of the world's first "Sputnik-1" satellite by the U.S.S.R., on October 4, 1957, inaugurated the new Space era for mankind. Ju. A. Gagarin's "Vostok" realized, on April 12, 1961, the first manned space flight. These flights and N. Armstrong's first steps on the Moon (July 21, 1969) were apparently the most brilliant events of Astronautics. And now, the Earth Artificial Satellites (EAS), which quickly developed from the first very simple Sputnik-1 to the Soviet Mir station, the USA's Space Shuttle system and the European Eureca laboratory, are the most important element of astronautics. Navigation of EAS, especially manned EAS (Soviet Vostok, Voskhod, Soyuz spaceships, Salyut, Mir stations, U.S.A.'s Mercury, Gemini, Apollo, Skylab, Space Shuttle, Apollo-Soyuz Test Project—ASTP), determined significantly the space navigation appearance. The S/C flight navigation and control are supported by the networks of GBS (so in ASTP in 1975 there were 8 Soviet GBS, and 14 GBS of NASA's Spaceflight Tracking and Data Network—STDN), by seagoing tracking stations on ships, and by special satellites. There are the special ground Computation Centers (CC), and the ground Mission Control Centers (MCC). So, there are well known MCC in Kaliningrad near Moscow, the Johnson Space Center (JSC) near Houston, European Space Operation Center (ESOC) in Darmstadt, etc.

Navigation support of the EAS is a sufficiently easier problem than for an interplanetary mission. However, there are some problems here. There are a great number of EAS now (manned, communication, navigational, meteorological, Earth resources observation, military, ecology, geodesic, astronomical, physical, geographical satellites, etc.). Their navigation is generally ensured by ground CC, MCC and networks of GBS. This leads to overloads in their work, and to the desire to apply autonomous navigation. EAS are often outside the GBS visibility zones, which leads to their service difficulties. There must be noted also the complicated structure of force fields near the Earth, especially for the high accuracy satellites. The reliability requirements, especially for manned and commercial satellites, as well as financial difficulties, are very important now, too. Because of these contradictory points, the navigation problem for EAS is not easy. The difficult history of manned EAS navigation systems confirms this. The well developed, universal, and reliable ground systems are central here. There is a lot of work in autonomous navigation systems (ANS), but they are not yet applied widely because of various reasons.[10] Nevertheless, the S/C designers (beginning with the first Vostok of Gagarin) incorporated in navigation support also elements of autonomous navigation to increase the mission reliability, especially in an emergency, as well as to increase the operation speed. It was the Soviet "Salyut" space station's autonomous navigation system that proved to be very interesting and effective from 1971.[11] It used both optical and radio measurements: the first version of its algorithm was created by the Keldysh Institute of Applied Mathematics (KIAM) and the Korolev "Energiya" Design Bureau (KEDB). The last stages of two S/C rendezvous generally use the onboard tracking, optical and radio measurements and processing, too. The use of the systems of the navigational satellites is also very effective now. However, the problem of navigation for EAS still seems to expect optimal solving.

Navigational System of the Soviet Luna-9 Station

The Moon's study is another very important part of space research. The Soviet Luna, American Ranger, Lunar Orbiter, Surveyor probes, and Apollo missions are well known. The Luna-9 station occupies a special place here. It was created as "E-6" S/C in the beginning of the 1960s, in the U.S.S.R., by S. P. Korolev's "Energiya" design bureau, for a soft landing on the Moon's surface. Then it was developed by the G. N. Babakin design bureau.[12] In the early lunar morning of February 3, 1966, this automatic S/C, created by Man, first landed on the Moon's surface and transmitted to the Earth the TV pictures of the neighboring lunar landscape with its small stones, which at once became famous to all people. This S/C was named "Luna-9" because some lunar S/C for solving other problems (encounter with the Moon, photography of the Moon's other side) and for testing E-6 systems had preceded it.

Luna-9 was a very complicated S/C for that time. Among a number of problems to be solved, the payload and navigation ones were especially important. To increase the final mass, the "weak" one, about 3.5 -days' trajectory for the flight to the Moon, was chosen. It was close to the optimal one. The possible S/C miss distance from the Moon was about 10,000 km due to launch errors. To determine, and optimally remove, this miss possibility, a quick orbit determination and correction was carried out, mainly by ground measurements and processing, in about 1.5 days of flight. It must be noted that there were no corrections in previous Soviet Lunar S/C. The errors in the correction and subsequent orbit determination resulted in trajectory uncertainty at Moon approach, and in difficulties for the orientation of retro-rocket axis along the actual velocity vector to be damped. To solve these problems, the autonomous navigation system was designed and worked out. It included optical sensors for sighting the Sun, Earth, and Moon, and it allowed the measurement of the angles between them (with an accuracy of about 1°), to determine the S/C position, and to provide the proper S/C orientation during correction and deceleration. Before deceleration using the Moon's angular diameter measurement, the reaching of the given S/C distance to the Moon's center (about 8,300 km) was fixed autonomously, for which the S/C-Moon's center direction was parallel to the S/C velocity near the Moon's surface. At this time, the retro-rocket axis was oriented in this direction and conserved relatively the celestial bodies to the deceleration ("Lunar vertical" method). The ignition time was determined by an onboard radio altimeter, which fixed the time for reaching the given altitude.[13]

It must be noted that this ANS was worked out by the design bureau which created, in the 1950s, the ANS for the Soviet "Burya" cruise intercontinental missile.[14] That is why, in considerable part, the Luna-9 ANS was perfect and reliable.

Later on, the Luna-9 ANS was developed and designed for the creation of the first Moon artificial satellite—Luna-10 S/C (March/April 1966). These S/C then realized some successful flights to the Moon later on (Lunas-11 through 14, 1966-1968). Their navigation systems (both ground and onboard) were essential steps forward, and they helped to state and solve a series of difficult astronautics problems, in particular, to create a new generation of Soviet Lunar S/C (Lunas-15 through 24, 1969-1976), which allowed the delivery of lunar rock specimens from the Moon's surface to the Earth and the self-propelled Lunokhod stations to the Moon.

Soviet Navigation Project for the Moon Manned Flyby

According to the Soviet program for mastering the Moon, the "L-1" Soviet S/C was worked out for manned flyby of the Moon.[15] Its "Alfa" ANS was an important stage in the development of the Soviet ANS (1966-1968). This system allowed the autonomous determination of the S/C orbit and orientation, their correction parameters for all parts of the mission—flight from Earth to Moon, flyby of Moon, flight from Moon to Earth—and mainly to ensure the reliability of S/C re-entry into the Earth atmosphere after flyby of the Moon. As navigation measurements, the onboard optical measurements of known stars elevation angles above the horizons of the Earth and Moon were employed. It was the new point in principle, that the S/C crew determined the orbit by measurement data with the help of an on-board computer (OBC). This OBC was rather imperfect technically: its read/write memory (RWM) had 64 words, read-only memory (ROM)—4096 words, average calculating operation composed about 64 instructions/s. Nevertheless, KIAM and KEDB (T. M. Eneev, E. V. Gaushus, K. K. Chernyshev *et al.*) managed to realize a whole universal navigation algorithm.[16] The ANS developed was tested by the cosmonauts in the ground-based simulator, in particular, during the automatic "Zond" probe mission, and it operated very well. It managed to solve all the problems of ballistic flight, and its operation characteristics were not worse than those of the ground NS, and they were sometimes even better. According to the project, as a rule, the ANS had priority over the ground-based system, but for the final flight part, before re-entry, it was joined into the principal navigation and control regime. Unfortunately, this project was not realized within the manned flights to the Moon.

U.S.A. Apollo Project Navigation for Lunar Manned Flights

It was the "Apollo" Project that became the important stage of astronautics (1968-1972).[17] The first man in Human history stepped on another celestial body. This project became possible due not only to the development of rocketry (Saturn-V), but also to the creation of the perfect navigation and control system (NCS), which allowed reliable and exact S/C trajectory and attitude determination, maneuvers calculation and execution at all stages of the mission.

The navigation system created represented the organic unity of three parts: inertial gyroscopic system (IGS), ground-based radio system (GBRS) and autonomous navigation system. The latter included two subsystems: optical and radio. The onboard optical subsystem allowed the sighting of stars and planets and the angular measuring connected with them. This provided the possibility to determine the S/C orbit and orientation in both orbital parts near the Earth and the Moon, and flight parts from the Earth to the Moon and back. The on-board radio subsystem allowed measuring the altitude above the planet surface and the range between two S/C, as well as the direction from one S/C to another S/C. Although main navigation generally used IGS and GBRS (and onboard radio data at rendezvous and landing), nevertheless ANS was also very important. It allowed orientation of the IGS axes, and was the good doubling system allowing the realization of full navigation. This made the mission essentially more reliable. It must be noted that the on-board computer was an important element of NCS. It was very perfect: RWM had 2,048 words, ROM - 36,864 words, about 30,000 additions/s, and 2,000 multiplications/s. It was connected with IGS, GBRS and onboard sensors, allowed to determine the S/C trajectory and orientation, to calculate the control influences for both nominal flight and emergency. Both automatic and manual operation regimes were possible.

The navigation and control system created became one of the most important elements of mission safety and success insurance, and raised the work in the navigational field for following projects to a new considerable level.

The Soviet and U.S.A. Lunar flights helped essentially to form space navigation for missions to distant planets, too.

Navigation for Interplanetary Missions

Interplanetary missions are apparently the most interesting and important for the scientific part of astronautics. The Soviet Venus, Mars, U.S.A. Mariner, Viking, Pioneer, and Voyager probes allowed a lot of brilliant discoveries to be made in the study of the Solar System and the Universe, although they investigated mainly the large planets and their satellites. These missions helped to form a considerably modern appearance in space navigation and control systems, too.

The higher complexity, depth and versatility of problems to be solved are typical for the modern interplanetary missions projects to obtain the maximum amount of scientific information at minimal expense. As a rule, the missions became multi-target ones. The scientists are especially interested now in the study of the Solar System's small bodies—asteroids, comets, meteors, small satellites of planets—because this gives the hope of solving the fundamental question of the Solar System's origin.

The prominent missions of Pioneer-10 (launched in 1972), Pioneer-11 (1973), Voyager-1 and -2 (1977) which continue their studies, as well as Vega (U.S.S.R.), Giotto (Europe), and Sakigake (Japan) S/C to Halley's Comet in 1986, bear witness to this. Vega investigated first Venus and then Halley's Comet. Giotto was directed, after flyby of that comet, to study the Grigg-Skjellerup comet (July 1992).[18] Sakigake prepared, after its flyby of Halley's Comet, for the study of the Honda-Mrkos-Pajdusakova comet (February 1996). The U.S.A. Galileo S/C, that is intended for a flight to Jupiter and its satellites, has investigated, along the way, the Gaspra asteroid (October 1991), and then it will fly by the Ida asteroid (August 1993). The Franco-Soviet Project Vesta foresaw the flight to some asteroids and a comet.

To realize those missions, it is necessary to have perfect navigation that has to be very reliable on long flights (of ten or more years), with high accuracy at great distance from the Earth (even if the celestial body orbit is not well known), with the ability to ensure the execution of various maneuvers, going well in emergencies.[19-23] High demands are put on both ground and onboard navigation. Accuracies of ground-based radio navigation improve, in particular, due to the transfer from meter wave length to decimeter and centimeter ones, interferometric measurements methods with use of extra galactic radio sources or quasars as reference points. In particular, this allows determination of direction to the S/C with an accuracy of about 0.01 arc. sec. To increase accuracies of target orbit knowledge, the ground tracking of these targets are drawn, and more exact theories of celestial bodies motion are worked out. The onboard AN becomes more perfect, too, and its role grows considerably. This is the use of CCD-matrix as a photodetector and other new physical methods, that allow a great increase in accuracy and operation speed of the optical systems. This allows higher accuracy of angular onboard measurements. The navigational onboard computer software is of great importance now. In particular, new methods of measurement data processing allow significant increase in navigational accuracy, too.

International cooperation is of great importance now, due to both collaboration on joint experiments and the necessity for more exact navigation. A good example of this cooperation was the Halley's comet investigation in 1986. The radio measurements by GBS of several countries were performed for the Soviet Vega; radio data by 70 m antennas of Soviet Deep Space Stations at Eupatoria and Ussuriysk, as well as Doppler data and Very Long Baseline Interferometry (VLBI) observations by NASA Deep Space Network's (DSN) 64 m antennas at Goldstone, Madrid, and Canberra stations. They were used for improved VEGA orbit determination. Then the VEGA onboard optical sightings of the comet were used for more exact guidance of the European Giotto (Pathfinder Project). This experience helped other following projects. So, a very interesting international project was realized for the radio observation of the (4179) Toutatis asteroid, which flew near the Earth in December 1992.[24] A radar signal was transmitted from the Eupatoria station and, after reflection from the asteroid, was received at the 100 m antenna at Effelsberg, Germany. This allowed the improvement of knowledge about the Toutatis orbit, as well as its figure and size.

Some Considerations of the Space Navigation Problem

This brief and, of course, incomplete review of space navigation history bears witness to its brilliant development from the first fluent ideas of the astronautics pioneers to the creation of effective navigation systems that allowed the realization of some still fantastic projects in sending man into space, space investigations, and the use of space for economics and the life of people. However, still more complicated and interesting problems, connected with deeper study of the Universe, and applying astronautics for the good of mankind, are seen in the future. This presents new and difficult problems for navigation.

The creation of navigation systems with higher intellectual levels, with the possibility of quickly processing a great deal of information, with good adaptation of unexpected changes of situations or emergencies, is very interesting now for navigational support of prospective projects. In particular, the importance of the following may be noted:

- o Universal autonomous devices for navigation support of the small celestial bodies study,
- o Universal autonomous device for navigation support of Earth satellite flight,
- o Navigation support of long, multi-target missions for the study of the Solar System with small electro-jet thrust,
- o Navigation support for ensuring Earth security against possible impact with another celestial body,
- o Navigation support for ensuring space ecology in the face of increasing space debris.[25-26]

The creation of space navigation systems for prospective complicated systems seems to require the international collaboration of scientists.

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