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TABLE OF CONTENTS

GRAPHICS DISCLAIMER ii

THERMAL CONTROL TECHNOLOGY OF DFH-2A COMMUNICATION SATELLITE, by Li Wanlin 1

RUSSIA MAINTAINS ITS MILITARY SUPERIORITY IN SPACE, by Xu Xing 6

MAJOR SPACE ACTIVITIES OF SPACE SHUTTLE COLUMBIA ON ITS STS-52 MISSION, by Xu Shan 10

SATELLITE DEVELOPMENT TRENDS IN TAIWAN, by Wang Wei and Hong Bo 13

DEVELOPMENT OF STRAPDOWN INERTIAL GUIDANCE, by Lin Jin 25

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THERMAL CONTROL TECHNOLOGY OF
DFH-2A COMMUNICATION SATELLITE

Li Wanlin

Beijing Space Vehicle General
Design Department)

ABSTRACT: This paper describes the thermal control technology on the Chinese-made DFH-2A communication satellite. Flight temperature telemetry data for the DFH-2A are analyzed.

1. Introduction

The Dong Fang Hong No. 2A (DFH-2A) is a communication satellite made in China with spin-stabilization and geostationary features. To date, three satellites of this type are in orbit, of which the first has already operated in orbit for more than 4y. Telemetry data from the satellites show that the temperatures of all instruments and parts in the satellites remain stable within the design range. This paper describes the thermal control technology of the DFH-2A communication satellite and highlights an analysis of its in-orbit flight temperature data.

2. Outline of Thermal Control Design

The major purpose of the DFH-2A thermal control system is to ensure thermal equilibrium as well as the normal temperature range of all instrument units and parts in the satellite throughout the flight and working life.

According to thermal control design, the system mainly relies on passive control, supplemented with electric heating. A retransmitter is provided with thermal control technologies including heat tube, secondary surface mirror (OSR), and radiator.

The main body of the DFH-2A satellite is cylindrical, with a waist-band installed in its mid-section as a heat-sink surface for the onboard instruments. The external surface of the waist-band is designed with thermal control measures such as aluminum bright anodic oxidation and secondary surface mirror.

The upper and lower ends of the satellite, respectively, are fitted with a solar shield and a heat-insulating shield to protect against direct sunlight and to insulate against heat losses from the instruments. The heat-insulating shield can also insulate against the high temperature effect of the feathering flow of combustion gases that occurs when the apogee engine is ignited.

The external surface of the solar shield is covered by several layers of heat-insulating material and a film type secondary surface mirror. The thermal-insulating shield consists of several layers of high temperature heat-insulating material with its external surface having a sprayed-on high-temperature-resistant coating with high emissivity.

The thermal control measures taken for instruments and parts in the satellite are as follows:

--to acquire a desired temperature for satellite take-off, the apogee engine is equipped with several layers of heat-insulating material and an electric heater plus another electric heater, whose temperature is modulated by ground personnel;

--the antenna system has a sprayed-on thermal control coating and is covered by several layers of heat-insulating material;

--the hydrazine bottle and hydrazine pipeline are provided with an electric heater and several layers of heat-insulating material;

--the reaction thruster is provided with a high temperature electric heater and several layers of heat-insulating material while its support--especially designed thermal control measures;

--the spin-stabilization components are equipped with an electric heater and several layers of heat-insulating material;

-- a cadmium-nickel storage battery has a white sprayed-on paint coating with high emissivity.

The other instruments are either spray-painted, coated with gold, or covered with several layers of heat-insulating material depending on their heat value of dissipation.

3. Thermal Control Technology for Retransmitter

The retransmitter is one of the effective items of equipment onboard the communication satellite and also a key part of its thermal control design. The retransmitter contains a traveling-wave tube amplifier and a solid-state amplifier. They are provided with, based on their large heat value of dissipation, a small heat-transfer area and limited space for mounting, and thermal control measures including heat tube conduction, secondary surface mirror and radiator.

(1) Thermal Control Technology for Traveling-Wave Tube Amplifier

The traveling-wave tube amplifier is composed of a traveling-wave tube and a traveling-wave tube power supply.

Heat dissipated from the traveling-wave tube is transferred, through the heat tube, to the specially designed traveling-wave tube radiator. To the external surface of the radiator there is cemented a secondary surface mirror while the external surface of the traveling-wave tube has a dark sprayed-on paint coating with high emissivity.

The heat dissipated from the traveling-wave tube power supply is transferred outward through the corresponding waist-band, in-satellite heat-sink plate, and mounting base plate. To the external surface of the waist-band there is cemented a secondary surface mirror while its internal surface has a white sprayed-on paint coating with high emissivity. Heat dissipated from the high-power transistors in the traveling-wave tube power supply is transferred along the heat tube to the in-satellite heat-sink plate. Four special metal bedpieces are installed on the mounting base plate.

The traveling-wave tube, while switched off, is charged with a compensation electric heater to maintain its storage temperature.

(2) Thermal Control Technology for Solid-state Amplifier

The heat dissipated from solid-state amplifier is transferred through the heat tube to its specially designed radiator. To the external surface of the radiator there is cemented a secondary surface mirror while its internal surface has a white sprayed-on paint coating with high emissivity.

A short heat tube is installed on the mounting plate of the solid-state amplifier, which is used to transfer heat dissipated from element devices inside the amplifier and to maintain a uniform plate temperature.

The external surface of the solid-state amplifier has a dark spray-paint coating with high emissivity.

The solid-state amplifier, when switched off, is charged with a compensation electric heater to maintain its storage temperature.

4. Analysis of Telemetry Temperature Data of Satellite in Flight

An analysis of telemetry temperature data obtained during the flight of DFH-2A indicates that the temperatures of all instruments and parts in the satellite remain stable within the design range. The maximum temperature of the retransmitter rises from 100 to 140°C at the end phase of its lifetime compared to its initial phase as a result of degradation of thermal control materials. The analysis also demonstrates that various thermal control materials used in the satellite exhibit stable performance indicators as required by the designer. It is believed, therefore, that the thermal control design for DFH-2A has proven to be successful.

RUSSIA MAINTAINS ITS MILITARY SUPERIORITY IN SPACE

Xu Xing

Recently, the Russian military space department has been actively engaged in launching new missile-warning satellites, photographic reconnaissance satellites and ferret satellites, aimed at maintaining its space prowess at roughly the same level as the former Soviet Union in some vitally important military areas. The space military prowess formerly targeted at the United States and NATO states has now been oriented to observing the movements of other CIS states since the breakup of the former Soviet Union as well as to evaluating potential threats from them.

Following three consecutive flight failures, Russia eventually achieved a success in launching the towering SL-16 launch vehicle designated Skytop. The restored launch of Skytop had a profound impact on the prospects of the commercial marketplace and military applications and particularly, on the launching of advanced ferret satellites.

Although Russia reduced its space program spending, the number of its space flights was still 50% more than the United States in 1992 alone. By mid-December 1992, Russia had completed a total of 47 space launches, far surpassing the total number of space flights in other countries during the same period. In this period, the United States completed 27 launches while China, Japan and India carried out 12. Despite the fact that Russia conducted one-tenth the number of launches in 1992 (59) compared to 1991, in some critical military areas, however, launch activities in this country are being restored or kept at the same level as before.

The spending cutback in the Russian space program more or less affected its number of in-orbit reserve satellites, yet some special military-oriented satellites still retain their major capabilities.

The military-oriented satellites launched in Russia in recent years are listed below:

1. Missile warning satellites: On December 25, 1992, Russia launched a new missile-warning satellite named Cosmos 2222, which brought the total number of its in-orbit warning satellites to nine. These satellites exhibit a warning capability equal to the maximum warning capability of the former Soviet Union during the cold war.

2. Advanced ferret (elint) satellites: To strengthen its power in confidential information acquisition, Russia recently launched two new ferret satellites, Cosmos 2221 and Cosmos 2219, with the capability of intercepting communications in Russia's neighbors. Cosmos 2221, a third-generation ferret satellite, was launched on November 24, 1992 from the Prithisk Launch Site by an SL-8 rocket. The advanced fourth-generation ferret satellite Cosmos 2219 is the most complex and highest-cost satellite ever built in Russia. This satellite was launched successfully for the first time from the Tyurantam Launch Site on November 17, 1992 by an SL-16 rocket, following its three failures, respectively, incurred in 1990, 1991 and 1992. The dip angle of the satellite orbit was 71°. This satellite was intended for a joint operation with another third-generation ferret satellite

launched in 1990. The foregoing description indicates that at least three Russia satellites of its type are now operating in orbit, raising Russia's space information intercepting capability ability to the highest level during peacetime.

Cosmos series satellite made in the former Soviet Union

3. Strategic reconnaissance satellites: On November 20, 1992, Russia launched a new military-oriented photographic reconnaissance satellite, Cosmos 2220, from the Prithisk Launch Site, which entered an orbit with a dip angle of 67.20°. This satellite was used to replace another photographic reconnaissance satellite scheduled to return on the day of the launch with military films. To date, at least two such satellites are performing their routine operations in orbit: one is a fourth-generation return photographic reconnaissance satellite, the other is a fifth-generation digital imaging satellite, which shows that Russia still possesses quite strong space reconnaissance capability.

4. Military-oriented navigation satellites: Recently, Russia launched a military-oriented navigation satellite Cosmos 2218. So far, Russia has a total of six navigation satellites,

constituting the largest military-oriented navigation satellite group.

5. Communication satellites: With a huge Proton launch vehicle, Russia recently launched a new live-broadcast television and communication satellite, Gorizont, which again proves that Russia still maintains its ability to launching sophisticated civilian geostationary satellites. On December 3, 1992, a new satellite, Molniya-3, was launched from the Prithisk Launch Site, resulting in a total of six Molniya satellites that Russia has (the maximum rated capacity).

MAJOR SPACE ACTIVITIES OF SPACE SHUTTLE COLUMBIA ON ITS STS-52 MISSION

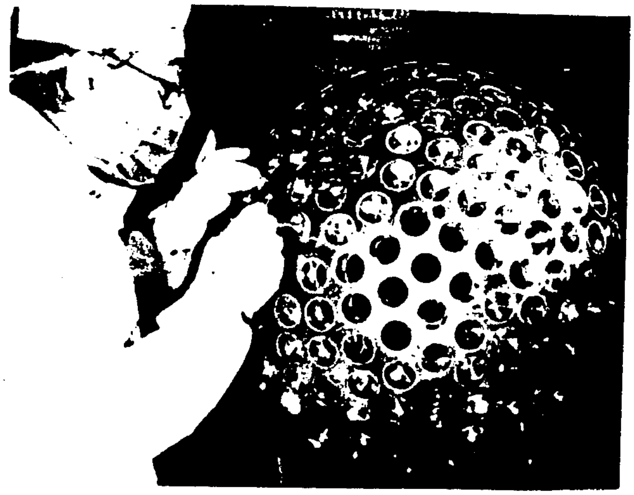
Xu Shan

On October 22, 1992, the space shuttle Columbia was launched from the Kennedy Space Center to conduct a nine-day STS-52 mission. The two major assignments to be accomplished during this flight included: (1) launching a Laser Geodynamics Satellite-2 (Lageos-2) made in Italy and (2) performing three tests with the U.S. Microgravity Effective Load (USMP-1) device. In addition, crew members also completed many other tests, most of which were associated with medicine.

On October 23, the Lageos-2 was deployed in a 296 by 302km space shuttle orbit and then, was sent via an Italy Research Transitional level (IRIS) rocket to a circular orbit at designated altitude of 5900km.

As a first test of its kind ever held, the USMP was scheduled to perform a number of microgravity experiments. Originally, this test was planned to be conducted during a U.S. Microgravity Laboratory (USML) flight mission in June, 1991. However, the USMP failed to be carried as planned because the mission needed a flight time extension and required an additional low-temperature fuel tank, leaving no room for USMP.

Both USMP device and Lageos-2 satellite were mounted in the cargo compartment of the space shuttle. The microgravity test



Italian Lageos-2 Satellite

turned out to be so successful that the Lambda experiment and the Mephisto crystal growth experiment period could be extended. The former experiment was intended for a study on liquid helium, while the latter was designed and supported by the French space and atomic energy agencies. Both experiments were completed as expected on the seventh day of the flight. More data were collected during the rest of the flight. All these tests were considered as a start on remote sensing scientific research on future space stations and a series-built free-flight platforms. For the first time ever, the equipment on board enabled scientists on the ground to perform real-time adjustment and effective accuracy adjustment over the experiments and acquire desired results.

Apart from the above two major experiments, the Columbia crew also accomplished many subsidiary tests, most of which went on successfully during two-thirds of the flight.

One of the tests, though, was temporarily suspended due to a computer defect, but returned to normal condition after the defective computer was replaced with a back-up computer, suggesting the need to carry more portable computers on similar flights.

One of the subsidiary tests involved a Canadian payload with many discrete elements. A Canadian astronaut on board conducted the test with these elements. Nevertheless, since it amounted to half the flight, part of work was done by other crew members so as not to exhaust the Canadian crew member.

SATELLITE DEVELOPMENT TRENDS IN TAIWAN

Wang Wei and Hong Bo

Today, as aerospace science and technology has brought enormous economic benefits to mankind, Taiwan has attached more and more importance to satellite development and application. Particularly in the late eighties, Taiwan had drawn up an ambitious blueprint for its aerospace technology targeting "self-development of satellite and setting up of an aerospace science and technology mechanism through a satellite research program so as both to expedite the enhancement of Taiwan's overall science and technology level as well as its relevant industries, and, at the same time, to accomplish its goal of stimulating domestic patriotic enthusiasm and building up a well-recognized image internationally in promoting its foreign relations."

In the past few years, after an in-depth and repeated consideration, the think tank from the concerned departments finally hammered out a science and technology development program, the largest of its kind ever in Taiwan's history: the Satellite Development Initiative. In recent years, with support from some western countries such as the United States, a series of measures was taken to speed up the advancement of this satellite program.

1. Establishment and Streamlining of Related Institutions

To develop aerospace science and technology, in early 1988, an eleven-member "Aerospace and Space Industry Development Committee" was established in Taiwan. Later in 1990, with two years of preparation and efforts, a "Leading Group of National Aerospace Science and Technology Development" under the "National Science and Technology Committee (hereinafter referred to as "National Science Committee") was founded, making a commitment to the overall planning and coordination for satellite development.

At the same time, a "Laboratory Preparation Department under National Aerospace Program" was also set up, which, in 1991, was designated as a responsible institution in charge of organization and implementation of the satellite program.

The backbone of this department consists of nine senior scientists with Dai Guangxun, an invited American Chinese aerospace expert (deputy manager of the intercontinental ballistic missile department at TRW, Inc. in the United States) as director, and Rong Kai (director of the Satellite Systems Department Center of the U.S. Aerospace Company, as deputy director. And its head office is based in Taipei, with several divisions, including Systems Department, Component Development, Research Department as well as Mission Undertaking Department, among which, the Systems Department serves as the heart of this satellite program and takes responsibility for future satellite assembly. The foregoing four departments are based respectively in Chengong University in Tainan, in the Scientific Development Zone in Xinzhu as well as at Central University in Zhongli.

In addition, the "Aerospace and Space Industry Technology Development Center" was built exclusively by the Taiwan Industry Technology Research Institute in an effort to meet the needs of satellite development. Under this influence, other research bodies also followed suit by making substantial adjustments to their respective research departments and institutions by expanding their organizational scale to reinforce their scientific and technical strengths.

2. Aspiration for Overseas Technical Support and Cooperation

With its poor infrastructure in the scientific and technological fields, Taiwan realized that seeking foreign technical support and cooperation for its aerospace technology is a short-cut for the rapid development of its aerospace technology, and is also an important key to ensuring the accomplishment of the satellite program. Hence, Taiwan, during the early preparation of the satellite program, chose the way of attracting foreign technical know-how as a major guideline for overall aerospace science and technology development.

The basic pattern of foreign technology importation is to keep their eyes on refined technologies in global market and endeavor to assimilate them as much as possible; for the unassimilated, simply adopt a "take-in" policy by putting them directly in use. In recent years, Taiwan has sent a great number of expert delegations to some related overseas enterprises and labs for study as an effort to attract foreign support and cooperation, and to explore the possibility of purchasing foreign patented technology and equipment.

Earlier, in June 1992, the Announcement Conference on the "Satellite Launch Preparation Program" was first held officially in Taiwan, which drew great attention from overseas consulting firms and experts concerned. As many as tens of foreign specialists from countries such as the United States, Canada, France, Germany, Israel and the like, participated in this gathering at which over 40 proposals were submitted showing their interest to get involved in this satellite science and technology experiment program.

It was learned that up till now, Taiwan has signed a dozen agreements with more than ten overseas companies and institutions such as the U.S. Aerospace Bureau, TRW Company, TAL Company, MDA Company from Canada, as well as companies and institutions from France and South Africa on satellite design, system technical support, equipment importation, application of ground stations, scientific experimentation, personnel training, management consultation, etc. which has created the most favorable conditions for the implementation of this satellite program.

3. Recruitment and Training of Aerospace Personnel

Undoubtedly, talented staff play a major part in the development of aerospace science and technology, which, however, is a bottleneck for Taiwan's aerospace technology advancement. Thus, Taiwan places personnel recruitment and training on its top agenda, for which major efforts have been made in the fields as follows:

1) Launching a wide-ranging "Talent Scout Campaign" both at home and abroad. Apart from creating opportunities for its experts and scholars specializing in related fields from institutions and universities such as the Industrial Technology Research Institute, Zhongshan Science Academy, Central Meteorology Bureau, Taiwan University, Chengong University, Central University and so forth, to participate in the satellite program, Taiwan makes efforts to search back and forth between Taiwan and some western countries such as America for possibility of inviting overseas Chinese back to Taiwan with a promise of high salaries.

Sources said that Dai Guangxun, the recruited director of the space planning department and Rong Kai, deputy director, respectively, earn [per month] up to 310,000 new Taiwan currency (equivalent approximately to $1,900 U.S. dollars) and 230,000 new Taiwan currency (equivalent approximately to $8,500), ranking only the second and third in salary level among technical staff in Taiwan, and even far ahead of Nobel Prize winner Li Yuanzhe (150,000 new Taiwan currency per month, approximately $5,800 U.S. dollars). It is also reported that Taiwan has recruited nearly 250 experts and specialists both at home and abroad to reinforce its satellite development.

2) Taking the initiative to conduct training program for aerospace technology personnel

A training class has been scheduled exclusively by Taiwan "National Science Committee" as part of the aerospace personnel training program, based on which, 200-300 technical staff is expected to be trained within 15 years as mainstay of satellite development. During this 15 years, some experienced aerospace experts both at home and abroad will be invited to give lectures on satellite related technologies in line with different phases of satellite development, and also some staff are going to be deliberately selected to go overseas for further studies following their home-based training. In doing so, as Taiwan believes, the overseas satellite technology can be gradually transferred to Taiwan.

In February 1992, some 28 university professors with great learning in different academic fields as the first group were sent to Johns Hopkins University in the United States for a 9-week satellite engineering training. In September of the same year, another 30 were dispatched to the laboratory affiliated with the French National Aerospace Research Center for "practical training."

Still, Taiwan takes a great interest in signing further personnel exchange programs with related institutions and companies from developed countries in Europe and America in the hope of developing a well-trained technical force equipped with the advantages of both European and American satellite technology and ultimately paving the way for its future endeavor.

4. Drawing up the Satellite Development Blueprint

The development of Taiwan's satellite program has undergone up-and-down periods. As early as in March 1990, the "National Science Committee" proposed a "Five-Year Satellite Development Plan", namely, within 5 years, 10 billion new Taiwan currency equivalent approximately to $370 million US dollars would be made available for the self-development of a satellite launching system, a ground receiving system, a space probe rocket and so on.

As part of this plan, a 100-kg scientific experiment satellite was scheduled to be launched into low orbit 200-300km from the earth. Nevertheless, this program had to be revised by the "National Science Committee". That in part was due to the related infrastructure failing to keep up with the program requirements, and most importantly, this plan was officially opposed by the U.S. government, which claimed that Taiwan's development of a satellite launching system was purely out of military concerns, therefore the research program regarding this system development was discouraged, and the sale of satellite launching technology and some complete sets of related equipment to Taiwan was restricted.

In August 1991, though, a new satellite development plan--the "15-Year Satellite Development Program" was initiated by the "National Science Committee", which won an approval on October 20 of the same year. According to this project, an investment of 13.6 billion new Taiwan currency (equivalent approximately to $500 million US dollars) was planned for this project with authorization of other foreign countries to be responsible for satellite launching. Respectively, in year 1997, 2001, and 2006, the launch of one self-developed small-scale multipurpose experimental satellite per year is scheduled.

Obviously, by comparing the new plan with the old plan, there are two points that need to be addressed; (1) the new plan appears to slow down its pace in satellite development, which can be seen from the delay of the first satellite launching from 1995 to 1997, and (2) research expenditures were sharply curtailed, that is to say, instead of investing 10 billion new Taiwan currency in 5 years (an average of 2 billion each year), only a total of 13.6 billion new Taiwan currency within 15 years (an average of 907 million each year) was budgeted. The annual research expenditures were decreased by 40.8%. (3) The research on the satellite launching system, among other things, was temporarily put on hold, which led to a modification of the plan with the focus shifting from self-satellite launching to the authorization of other countries for the launch.

According to a Taiwan newspaper, Taiwan is scheduled to launch its first satellite in 1997 with its name designated as China Satellite--1. This satellite weighs up to 400 kilograms, with an effective load of 58 kilograms, which includes a potential-block analyzer, an mass spectrometer, an ultraviolet sunlight light meter, a high-energy particle analyzer, an approximately 10-kg marine color camera, etc. In addition, along with a propulsion system, a fuel and solar energy battery panel, this satellite is equipped with a minicomputer as well, capable of processing instructions sent from the ground mission control center through digital program control, with the rate of data receiving and transmission up to 2,000,000baud. Finally, to ensure the satellite location in the orbit and transfer to other orbits, this satellite as such has eight to twelve vernier thrusters with a 400-W satellite power supply.

The major mission of "China Satellite-1" is assumed to conduct three experiments covering space physics, earth and marine remote survey and telecommunication technology, with space physical research accounting for half of the total tasks.

Upon liftoff, the satellite will, based on the aspects of its mission, circumnavigate the earth in four different orbits, which have an included angle of 35° with the equator; the first orbit is a circular orbit 300km from earth; the second orbit is elliptical, with a perigee only of 200km and an apogee of 1000kkm from earth, in which the satellite is supposedly to travel for 6mo; the third orbit has a perigee of 300km and an apogee of 800km, around which the satellite is scheduled to travel for 1y, and the last orbit is circular, 600km from earth, in which, the satellite is to stay for over 2y.

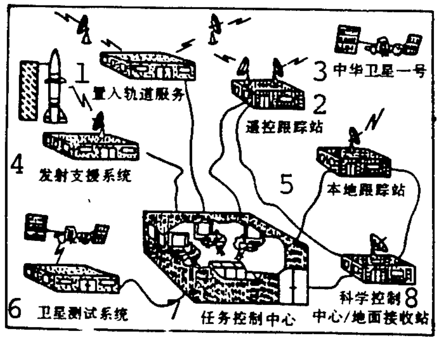
The satellite is scheduled to undergo a one-month test in the first orbit, particularly on its satellite location correction and its various functions. The major mission in the second and third orbits involves several space physical research projects mainly in fields such as large scale electrodynamic and magnetohydrodynamic quantitative analysis in sun-earth interaction, low-latitude (a range of 30° Lat. S. and Lat. N.) ionospheric layer structure, the effect of solar radiation on the atmosphere, as well as the abnormal phenomena high above the equator, etc. The mission on the fourth orbit involves marine telemetry measurement, resource surveying, and telecommunication technology experiment, including data collection and research on the relationship between marine colors, temperature variation and circulation, slip flow; identification of water front circulation, as well as tropical and subtropical climatic patterns in continent coastal regions, and the like. In addition, reliability tests of microwave electronic elements and integrated circuits as well as relevant television broadcast tests are also to be conducted by the satellite.

Since the distance of different orbits from the earth varies, the time that "China Satellite-1" takes to travel around the earth varies 90 to 96 minutes. It will circle the earth at least 15 times a day, and even 16 times, mostly. Thus, this satellite will presumably travel around the earth at least 10,000 times in the span of 2y. Optimistically speaking, under normal conditions, it will be able to operate for 4y travelling around the earth over 20,000 times. The following space science and technology research mission will be alternatively carried out by "China Satellite-2" after its liftoff.

As for the satellite launch, Taiwan will adopt its strategy of "selecting the launch site outside the island, while exercising launch control inside the island," i.e., its self-developed satellite can be launched through a launch vehicle by an authorized country while technically the rocket take-off controlled through remote control will be ultimately conducted inside the island, synchronized with the on-site launch countdown outside the island. The client offering the satellite launch service is initially chosen from the United States. In August 1992, though, the "National Science Committee" in Taiwan officially claimed that Taiwan will not rule out the possibility of authorizing mainland China to launch its satellite if the relations across the strait between Taiwan and mainland China significantly develop.

For omnidirectional reception of data from the "China Satellite-1", Taiwan plans to set up three resource ground stations, respectively, in Taiwan, South Africa, and the United States, among which, the one in Taiwan is going to be based in the Central University in Zhongli. This station had undergone initial design and examination by the MDA Company from Canada in early March 1992, had completed construction in June 1992, and will be put into use as planned in February 1993. And the installation of the receiving equipment is scheduled between

April and May 1993 and the various tests are going to be done in July 1993.



Schematic diagram of "China Satellite-1" implementation system

1 - Entering orbital service
2 - Remote tracking station
3 - China Satellite-1
4 - Launch support system
5 - Local tracking station
6 - Satellite test system
7 - Mission control center
8 - Scientific control center/ ground receiving station

Presently, as for matters concerning the establishment of resource satellite remote tracking stations in Africa and the United States, the agreements with these two countries has been literally reached. At the same time, Taiwan decided to build in Xingzhu a mission control center and a satellite manipulation command ground station as a base for launch command, tracking, and orbit control.

Orbital Analysis of Taiwan's "China Satellite-1" in Four Phase

Phase	Perigee (km)	Apogee (km)	Dip (deg)	Period (min)	Stay time	Scientific missions
1	300	300	35	90.52	1mo	Test, satellite location correction, and various functions
2	200	1000	35	96.69	0.5y)	Aerospace
					)	physical
3	300	800	35	96.65	1y)	research
4	600	600	35	96.09	2y	Marine telemetry, resource surveying, telecommunication technology experiment

On January 17, 1992, the first meeting was reportedly held by the Taiwan Aerospace Planning Department since its establishment, during which the initial phase strategy of satellite program was outlined, including screening and training of technical personnel, system engineering operation, selection of aerospace scientific research programs, and selection of overseas interests for cooperation, determination of budget and funding for 1992 operation, examination of 1993 budget program, etc.

Also at this meeting, the "15-Year Satellite Development Program" was announced to commence starting from the day. The four divisions under the "Aerospace Planning Department" have entered the initial preparatory phase. For instance, overall planning and preparation for the tests of various future labs and satellite assembly are under way at the System Development Department located at the aerospace and space test site of Aerospace and Space Science and Technology Research Center under Chengong University. Again, the Satellite launch Preparation

Research and Development Center in the Xinzhu Scientific Zone is planning and processing related instruments and equipment needed for satellite development. Also, a group of 22 senior engineers was sent to several United States-based astronautical companies to inspect and collect data on the element development program by Component Development Department attached to the Industry Technology Research Institute. For now, as claimed by sources from Taiwan," the satellite program is going well."

Speaking of the prospects of Taiwan satellite development, the media in Taiwan have different views. As Dai Guangxun, who returned from the United States to participate in this program, expressed it, " I am quite confident about the entire program, and believe the launch of the scheduled satellite will surely be successful." Likewise, Huang Xiaozhong, an aerospace expert who returned from the United States ten years ago, equally expressed his optimism about this program. Yet many insisted that it is not realistic for Taiwan to develop satellites on the grounds that (1) Taiwan lacks a solid industrial background as well as a strong scientific and technological foundation; (2) Taiwan has no sophisticated technical force; (3) Taiwan lacks sufficient scientific research funding. In other words, they asserted Taiwan is not ready for developing satellites at all and worry that the satellite program, like many other projects, may have an ambitious beginning, but end up an unhappy failure due to insufficient capability, which might both constrict Taiwan's international image and domestically hurt its people's self-esteem. Apparently, despite Taiwan's strong determination in satellite development, the problems and difficulties can by no mean be excluded and they may stand in the way of the development of this program.

DEVELOPMENT OF STRAPDOWN INERTIAL GUIDANCE

Lin Jin

Beijing Research and Design Institute
of Automation Engineering

ABSTRACT: After a brief historical review, strapdown inertial guidance is introduced and the general trend of development of strapdown inertial guidance technology is described. The trend has become especially clear with the latest achievements of optical gyros. Finally, a mathematical formalism for describing the attitude movement of rigid bodies, quaternions, and the concept of hybrid navigation are explained.

Introduction

It is understood that the concept of "guidance" originated with the birth of modern missile technology. Technically, guidance is a process of guiding a missile automatically flying to a designated target. To achieve this objective, it is necessary to collect data pertinent to the missile flight path with a sensitivity device that can reflect the vehicle motion state parameters, as well as to have the capability of obtaining information about the target and then, by comprehensively processing all the data gathered, to obtain control and guidance signals for guiding the missile to the target followed by correction of the flight trajectory by the mission command center to accomplish the mission.

Guidance is a fast-growing multidisciplinary field generated in response to the needs of modern warfare. In fact, the demand for various kinds of precision guidance has promoted the development of many modern technologies including the fine mechanics treatment, radio-electronic technology, optoelectronic technology, microelectronic technology, precision measurement, computing technology, control technology, etc.

The need for anti-jamming and concealment in military confrontations stimulated the development of autonomous "inertial guidance" technology. To meet the basic requirements of guidance, a reference coordinate system should be established to describe missile motion. The fundamental principle of mechanics reveals that it is possible to build up an inertial space reference coordinate system by using the fixed axis features or precession features of high speed rotors. Accordingly, different gyro instruments based on this principle can induce the attitude angle of the vehicle coordinate system relative to the inertial coordinate system.

The accelerometer, whose working principle resembles the basic principle of a spring scale, can be used to measure the imitating acceleration produced by all the resultant forces acting on the flight vehicle except gravity. Thus, on the basis of fundamental principles of mechanics, plus ingenious engineering design, the prototype of modern inertial guidance system was first mounted on the V-2 missile. The positioning gyro and axial direction accelerometer (commonly referred to as inertial instrument) were directly mounted on the V-2 missile body in fixed connection, which can be called strapdown inertial guidance in modern technical terminology. Certainly, this was only the initial phase of this technological development.

Historical Review

In flight mechanics, the rocket thrust acts on the vehicle coordinate system while aerodynamics acts on the velocity coordinate system, with the difference of the two coordinate systems acting as an uncertain pneumatic attack angle. Therefore, the output of the axidirectional accelerometer mounted on the longitudinal axis of rocket in fixed connection cannot truly reflect rocket flight acceleration, and in addition gravity action is not available for direct measurement by an inertial instrument.

The output of the axidirectional accelerometer is merely a characteristic volume called imitating acceleration, which signifies rocket flight characteristics. To calculate the actual rocket flight velocity and location, it is needed, apart from the axidirectional accelerometer mounted in the rocket longitudinal direction, to install a normal-direction and a transverse-direction accelerometer in its normal direction and in its transverse direction so as to acquire the complete components of all the resultant forces acting on the three axes of the missile body coordinate system except gravity. Also, it is necessary to act conversely on the output of accelerometer mounted in strapdown form to the inertial coordinate system by making use of data provided by the gyro instruments concerning the angular location and angular velocity of the missile body coordinate system relative to inertial space. Then, it is required to compute individual components of gravity in the inertial coordinate system based on the given gravity field mathematical model and finally, to calculate the three axial components of rocket flight velocity in the inertial coordinate system through primary integration as well as three axial components of rocket location in the same system through secondary integration.

Such navigation computational formula proved to be so complicated that it is literally inconceivable to perform such a large volume of computations on board the missile, especially during the initial phase of missile technology development. Under this circumstance, the early guidance systems of launch rockets and missiles, designed in different countries, were by no means based on navigation calculation of accurate velocity and location measurement; instead, they were accomplished with careful analysis of flight mechanics and rocket characteristics followed by compensatory and correction measures taken with different approaches.

As is known, the thrust change of a rocket engine is the most important factor that affects flight velocity. Therefore, the most primitive measure was to utilize primary integration of the axidirectional accelerometer output, which reflected overall the effect of the thrust change of the rocket engine as well as the compensatory volume of a constant as the characteristic volume of the guidance equation to control engine switch-off moment for a range precision.

Later, the guidance system was improved with different technical approaches adopted in different countries. Generally speaking, the Soviet Union focused on overall rocket design technology. They adopted the engine-modulating closed circuit guidance system to overcome interference in the axial direction (engine flow deviation, specific thrust deviation and liftoff weight deviation, etc.), and used the pitch loop amplification method to solve for interferences in the normal direction (wind, engine thrust line inclination and missile body centroidal deviation, etc.). The United States, on the other hand, was concerned more about instrument manufacturing technology, with its efforts made on setting the accelerometers at an optimal angle in inertial space, which approached the trajectory dip angle of the velocity vector at the switch-off point. China, among other matters, concentrated its attention on guidance theory, developing, based on perturbation theory and invariability principle, an external interference complete compensation system and using a rather simple guidance device which is economically affordable by the nation's financial capability to enable the entire system to arrive at a guidance precision equivalent to that derived from navigation computation in linear range. In short, all these efforts made in different countries represented the first-generation technological level since the advent of rocket technology.

Development

The ever-increasing precision requirement continuously pushed guidance technology forward, through which new inertial devices were invented one after another, microelectronic and computational technologies were upgraded from time to time, and in addition, the capability of light mass and high speed missile-borne miniature computers was improved to a great extent.

In the mid-sixties, the capability in areas such as in-missile real-time processing of preceding coordinate conversion, gravity model, and navigation calculation was reached, and conditions required for realizing the primitive concept of replacing a physical electromechanical platform with a mathematical platform became mature.

In 1969, on the way back to earth from space, the main guidance system (platform system) on the Apollo lunar module exhibited a fault and it was not until a back-up emergency guidance system (strapdown system) was switched on that the safe return of Apollo to the earth became possible, which created a bizarre impact across the world and was a milestone in the development of the strapdown inertial guidance system. Historically, the strapdown system installed in Apollo was still based on traditional liquid floating gyro technology. Since the strapdown gyro, subject to effects from vehicle motion, shows a wide dynamic state range to make the precision of the same liquid floating gyro lower while applied to the strapdown system than when it is applied to a platform with a small angle working range.

Virtually speaking, when the requirements of the strapdown system were satisfied by digital computer technology, gyro technology was correspondingly required, through new development, to achieve a high precision measurement within the wide dynamic state range. And following a long, tortuous process of research and development, a dry turning gyro which was based on the ingenious flexible connector working principle--dynamic turning gyro--came to life. Currently, the dynamic turning gyro has gone into production in many countries. Practice shows that the newly borne gyro can successfully be applied to strapdown inertial guidance and thereby is on the cutting edge in this area.

Lasers first became known publicly in the sixties, which enabled the Sagnac effect, discovered early in 1913, to enter the domain of recent scientific and technological applications. Almost simultaneously, technically advanced countries began to do research on the idea of "laser gyro". Instead of high-speed rotors used for traditional electromechanical gyros, the laser gyro relies on a laser beam which runs along a closed optical path. The point is that the difference of the turning frequency generated when the laser beam is transmitted along a closed optical path in the forward direction and in the reverse direction, is used to measure the angular rotation rate of the gyro carrier relative to inertial space. This kind of ring-shaped laser device, though called a "laser gyro" in conventional inertial navigation terminology, actually contains no movable mechanical parts nor a high-speed rotor as a symbol of traditional gyro. It is an optical device, which possesses the same goniometric function as an electromechanical gyro. Under this scenario, efforts made in past years to reduce the mechanical frictional moment and the knotty technical problems encountered in developing various suspension technologies have been shifted to a new area of optical processing and technology.

The idea of laser gyro appears to be acceptable, yet its technology involves a large number of new techniques including super-level polishing, high-level film coating, precision processing of optical materials, etc. as well as new technologies and new materials. For this reason, though its research and development started in the early sixties, the first laser gyro test flight was conducted with success in the United States in the mid-seventies. And it was not until the early eighties that a nationwide appraisal conference of laser gyro inertial navigation systems was held in the United States. That meeting was a great success, which led the laser gyro strapdown inertial navigation system into a phase of practical use.

Since the precision of the Sagnac effect is proportional to the length of optical path, the laser gyro should not be made too small if high precision is required. Yet it will be difficult for laser gyros of this size to accomplish a super-small strapdown inertial system.

In 1967, the research staff at the University of Utah, in the United States, came up with a concept of developing a Sagnac-effect rotational velocity sensor with optical fiber as material. This concept attracted great attention because, by using numerous turns of extremely fine optical fiber coils, the extremely long optical path could then be achieved in a very small size. As a result, a considerable number of laboratories and companies began to become involved in the development of laser gyros. The optical path of the laser gyro had to be made of an optical material through precision machining. When this optical cavity was aerated and tightly sealed, the gas inside, excited by an electrode, could generate a laser beam in the optical path. In addition, since the optical fiber gyro used optical fiber to produce the Sagnac-effect optical path, it could do without precision machining and without a lens with a carefully made film coating.

Nevertheless, development of optical fiber gyro was by no means an easy task due to many new technical difficulties brought about with introduction of photoelectric technology and optical integration. In 1983, the Draper Laboratory at the Massachusetts Institute of Technology started, with its own funds, a research program on turning-type optical fiber gyros, which was later financially supported by the United States Strategic Defense Initiative Office and the Army. In 1987, signing an agreement with the U.S. Army, the foregoing lab focused on developing a turning-type optical fiber inertial measurement complex, including a small solid-state accelerometer applied to that combination.

It was estimated that a complete three-axis inertial measurement combination would weigh less than half a kilogram. This combination, as a part of an advanced technology test missile of the outer space reentry warhead interceptor branch system (ERIS) developed by the U.S Army Strategic Defense Command, underwent its first test flight in 1991 yet no details of performance data were disclosed. The command chief maintained that the advancement of the turning-type optical fiber gyro triggered technological competition on optical gyros and moreover, the interference type optical fiber gyro and the ring-shaped laser gyro were also making significant progress. The person in charge of the ERIS interceptor-missile project shared the vision of technological competition. He observed that the ring-shaped laser gyro, undergoing steady advances, was likely to replace the turning-type optical fiber gyro as a technological alternative for the ERIS interceptor-missile. It is still hard to tell which one will gain the upper hand.

General Trend

Generally speaking, the strapdown inertial navigation and guidance system, based on optical gyros, has made striking progress. Among the huge carrier rockets which are under vigorous development in different countries in the nineties, the Ariane-5 developed by Europe Aerospace Department and the giant liquid hydrogen and oxygen engine carrier rocket H-1 constructed by the Japan Cosmos Development Committee are both based on laser gyro strapdown inertial guidance, whereas the giant solid-fueled carrier rocket with a diameter 2.5m produced by the Japan Cosmic Science Research Institute relies on optical fiber gyros.

Various ground and outer space kinetic-energy weapons included in US Star Wars Program are all based on strapdown guidance systems such as ERIS, the ground interceptor-missile as mentioned above. Riton Industry Inc. developed a three-axis entirely solid-state inertial measurement combination, specially designed for SDI outer space interceptor-missile. This combination involves optical fiber gyro technology, miniature silicon accelerometers and other large-scale integrated circuits. Smith Inc. constructed an optical fiber gyro strapdown inertial measurement combination for the light external atmosphere advanced projectile (LEAP) listed in the Strategic Defense Initiative program, weighing less than 42.5kg with power consumption less than 8W.

Viewing from the general trend of technological development, from ball bearing gyro, pendulum accelerometer plus electromechanical solution devices including gear mechanisms, program cams, spherical plate integrators, etc.--all used for missile technology in the forties up until the optical gyro free of movable mechanical parts, solid-state accelerometer and miniature computer--all used for high-level strapdown inertial guidance systems in the nineties--this process of development, long and tortuous, took half a century and involved painstaking labor devoted by several generations of scientists and technicians. However, macroscopically and historically, a main trend of technological development looks simple and clear. The needs for the development of aerospace technology, missile technology, and sophisticated defense-oriented kinetic weapons have gradually, step by step, pushed the strapdown inertial guidance system of small bulk, light mass, high reliability and high precision into the historical arena.

Quaternions

With the appearance of the new high precision strapdown type gyro, which takes increments of rotational angle around the vehicle axis as the output, the mathematical method used to describe attitude movement of a rigid body has also achieved new developments. Among various methods explaining attitude movements of a rigid body, the Eulerian angle method is a classical one. Striking as it is, the Eulerian angle method can probably cause singularities. This method, involving many triangular functions and leading to many computational requirements, may give rise to many problems when used to deal with arbitrarily large vehicle attitude control. Cleverly, applied mathematicians adopted quaternions, an abstract mathematical tool proposed by Hamilton in the 19th century, to describe the attitude movements of a rigid body and they succeeded.

The quaternion method can provide not only graceful mathematical forms, but also rather simple computations without singularities points and therefore, it well fits computations in strapdown control, navigation and guidance. A quaternion consists of a scaler and three hyper-imaginary components. The angular velocity components of a vehicle's three axes, directly measured with a strapdown type velocity gyro, form the coefficient matrix of a quaternion differential equation, which can solve the four-quaternion component functions varying with time. These quaternions can form the coordinate conversion matrix from missile body coordinates to inertial coordinates. In this way, by using the missile-borne computer, the strapdown acceleration output can be easily converted from missile body coordinates into inertial coordinate output, just like three accelerometers mounted on a physically stable platform in inertial space. In addition, the attitude control and guidance law can also be expressed directly with quaternions. Thus, quaternions have become a complete algorithm.

Combined Navigation

Strapdown inertial guidance can not dodge the intrinsic weaknesses of inertial elements. Despite the fact that various new inertial elements have constantly created new precision records, errors arising from gyro drift and accelerometers accumulated over time. It is natural that with long-term operation of inertial navigation system, the accumulated errors will eventually increase considerably. Therefore, along with constantly seeking new approaches to raise the precision of autonomous inertial navigation system, it is equally important to formulate a hybrid navigation system so as to correct the errors.

The Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS)--the two global positioning navigation satellite systems, which are scheduled to be deployed in the mid nineties, are ideal partners of strapdown inertial navigation. A wide variety of practical systems are now under active development in different countries around the world. One of them, based on autonomous inertial navigation is to correct the accumulated errors of inertial system by introducing high precision navigation information of global positioning system, which will not diverge with time. And instead, the inertial navigation system can provide the global positioning receiver with additional information to help its Doppler tracking loop rapidly acquire and track high dynamic state. In this way, they can supplement each other and make up each other's deficiencies. Another method is to use low-cost miniature strapdown gyros as an attitude and course system while getting positioning navigation data of the carrier from the global positioning system.

With the ever-increasing advancement of modern technology, strapdown inertial guidance technology is experiencing a profound revolution in the nineties.

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