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AEROSPACE APPLICATIONS OF NAVIGATION SATELLITES

by

Yao Yu, Zhang Liyu

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Aerospace Applications of Navigation Satellites

Authors: Yao Yu, Zhang Liyu

(Aerospace Industry Company, Research Institute No. 704)

I. Introduction

The United States' Navstar Global Positioning System (Navstar-GPS) and Russia's Global Navigation Satellite System (Glonass) are the new-generation global satellite radio navigation systems each developed separately in the 1970s. Their appearance fundamentally changed the concept of global navigation.

The GPS satellite system is composed of a constellation of 24 satellites at an altitude of approximately 20,000 kilometers, distributed in orbits at six equivalent intervals. The orbital planes are at 55 degrees relative to the included angle of the equator, and there are four satellites in each orbital plane. The satellites' orbital planes are approximately circular, and their period of revolution is about 11 hours and 58 minutes. This satellite distribution can ensure that anywhere in the world, at any time, at least four satellites are provided for observation. Similarly, the Glonass system will also deploy 24 satellites. Glonass satellites are positioned on three orbital planes at intervals of 120 degrees, their orbital altitude is approximately 19,000 kilometers, their orbital inclination is about 65 degrees, and their period of revolution is 12 hours. GPS and Glonass each have their own individual characteristics and advantages but, as of now, most users' receivers can only receive satellite signals from one of the systems. Development of an integrated receiver that can receive satellite signals from both GPS and Glonass will certainly raise navigation accuracy by a large margin. GPS and Glonass are two mutually independent systems but, in recent years, integrated use of both systems has become possible. Integrated receivers can either receive GPS or Glonass signals alone or use a combination of their signals, and can provide more complete navigation service than using only one of the systems can.

There are broad prospects for applications of navigation satellites in the aerospace field: they can be used in controlling space launches (of space shuttles and space vehicles, for example); confirming flight paths; navigation and positioning of reentry vehicles; landing

operations and satellite tracking; multiple-target surveying of spacecraft; and so on. By making appropriate combinations with other navigation systems, it will be possible to form a composite navigation system. In recent years, Research Institute Number 704 has carried out research of space applications of navigation satellites, and this paper introduces two application systems for discussion.

II. GPS Retransmission Positioning System

To precisely determine the revolution orbits of space vehicles, it is necessary to give highly accurate position and speed data. In situations where there are multiple emitters, it is necessary to have the ability to track multiple targets simultaneously. The appearance of GPS provided us with an excellent method to do this. At present, rocket-borne repeater schemes are widely used in space vehicle experiments.

Rocket-borne repeaters receive signals from visible satellites, convert frequencies and mix in pilot frequency signals, and use the S band to retransmit to the high-dynamism,

Page 159

multiple-channel target receivers of ground stations. Having precisely determined the position of the ground station, the target receiver performs positioning and speed measurement of the rocket by measuring the distance and rate of distance change between the satellite, the rocket, and the surface. A benchmark receiver is deployed on the surface in order to increase precision. Pilot frequency signals are used to eliminate the effects of frequency differences and to form a differential measuring system with the target receiver.

III. Integrated GPS/Glonass High-Dynamism Receiver System

1. Feasibility of an Integrated GPS/Glonass Receiver

Glonass and GPS are basically similar in the areas of system setup, navigation positioning principles, operating frequencies, signal data structures, ephemerides, and so on. Thus, combined usage of the two is feasible. When these systems operate independently, even if GDOP [Geometric Dilution of Precision] is severely limited, there is still dead space that cannot be covered. If the two systems are combined, the number of available satellites will increase

greatly, GDOP will decrease, and system accuracy will rise.

Just like GPS, Glonass uses dual frequency transmission methods to eliminate the propagation error caused by the ionosphere. GPS uses code division multiple access (CDMA), and Glonass uses frequency division multiple access (FDMA). The 24 Glonass satellites take up 24 channel frequencies, and the channel frequencies are distributed as follows:

$$f_i = f_0 - i\Delta f$$

where	$f_0 = 1602 \text{ MHz}$	(L ₁ frequency band)	$\Delta f = 0.5625 \text{ MHz}$
	1246 MHz	(L ₂ frequency band)	$\Delta f = 0.4375 \text{ MHz}$

$$i = 1, 2, \dots, 24$$

Both use biphasic shift keying (BPSK) modulation methods to transmit pseudo-range and navigation ephemeris data for range finding. The Glonass code bit rate for the C/A code is 0.511 MHz, its code length is 1 ms, its P-code bit rate is 5.11 MHz, and its code bandwidth is only half that of GPS.

In the Glonass system, transmitted data can be divided into two kinds: one is manipulable numerical information, with a renewal rate of 30 minutes. These data are defined at 15 minutes practical time before transmitting, and required data are obtained by the user with the help of recurrence 15 minutes after this time. This kind of data includes: satellite time scale data, time scale data on the satellite clock relative to Glonass system time, data on radiated frequencies and deviations from their standard values, and data on satellite positioning and velocity. The other kind is non-manipulable data, such as almanac data and the system's renewal rate of 24 hours. It includes all predicted satellite states, satellite orbital parameters, corrected parameters of Glonass system time, and so on. Glonass uses frame groups to transmit the complete almanac of the whole system and the ephemeris data of the frame-transmitting satellite. It takes 2.5 minutes to transmit a frame group. Each frame group contains five frames, and transmission of each frame takes 30 seconds. A frame contains 15 sub-frames, the first sub-frame takes two seconds to transmit, and transmits 100 bits of information. The first through fourth frames are used to transmit the satellite's own ephemeris, the fifth is used to the satellite's number and the corrected value of its system time, and the sixth through the fifteenth are used to transmit the almanac. A frame group transmits the entire almanac for 24 satellites.

2. Technical Methods to Realize an Integrated GPS/Glonass Receiver

Because the operating frequencies of GPS and Glonass are not completely identical, it is necessary to first develop an antenna that is compatible to both GPS and Glonass.

Even if they both operate on the same frequency, since their carrier frequencies and code frequencies are different, it is necessary to design

Page 160

a controllable frequency synthesizer that can simultaneously receive the local frequencies and clock frequencies both require.

In the channel structure of an integrated GPS/Glonass receiver, the L-band low-noise amplifier, the wave filter, the intermediate-frequency amplifier, and the frequency converter employ MMIC integrated circuits, and the intermediate-frequency wave filter employs an acoustic surface wave filter. Using integrated circuits on a large scale in the data channel structure not only reduces bulk, but also increases operating reliability.

Navigation computation is basically the same for both GPS and Glonass, but they still have certain differences. Glonass uses six orbital elements to represent the ephemerides, that is, it uses the satellite's positions X , Y , and Z of the coordinate system at a right angle to the earth's core and their time derivatives \dot{X} , \dot{Y} , and \dot{Z} to represent the ephemerides. Thus, almanac values are related to choice of coordinate system. The two systems use different earth core reference coordinate systems: GPS employs the WGS-84 ellipsoid coordinate system, while Glonass uses the SGS-85 ellipsoid coordinate system. In addition, GPS and Glonass have different sub-frames, frames, and frame groups, and the meanings of the data in their ephemerides are different: Glonass uses Cartesian coordinates, while GPS uses Kepler orbital parameters.

3. Design Requirements of an Integrated GPS/Glonass Receiver

The GPS/Glonass channel portion performs the amplification, frequency conversion, and sampling functions of the GPS/Glonass signals received by the antenna. The whole channel is primarily made up of a low-noise amplifier, a downconverter combination, an intermediate-frequency amplifier, a dual converter, an AGC amplifier, an A/D converter, and other circuits.

The frequency synthesizer is composed of reference source numerical frequency division composite circuits, wave filter amplifier circuits, and frequency multiplication circuits.

Signal processing operations that have undergone A/D conversion are all performed in the numerical area, and signals input by the channel portion are sampled through f_{AD} frequency sampling.

The signal portion's circuits primarily include a three-choice switch, a carrier correlator, a code correlator, an integrating accumulator, a carrier numerical control oscillator (NCO), a code NCO, a code generator, and CPU control and interface display circuits.

The primary functions of each channel are: (1) carrying out pseudo-code range-finding, that is, pseudo-range phase measurement; (2) carrying out carrier wave Doppler velocity measurement, that is, measurement of carrier wave Doppler frequencies; (3) carrying out demodulation of PSK data, that is, code-synchronous and frame-synchronous.

The makeup of each channel is: (1) pseudo-code search and capture loop; (2) pseudo-code precise tracking loop; (3) carrier search and capture loop; (4) carrier-wave automatic frequency tracking loop (AFC loop); (5) carrier phase-locked tracking loop; (6) PCM code-synchronous loop and frame synchronizer.

The carrier wave correlator performs the numerical correlation of input signals and local carrier Doppler estimated values. Correlation is accomplished using the EPROM table look-up method.

The code correlator performs correlation computation of input C/A code and local C/A code. The code NCO has 25 positions. Its highest position is used to drive the code generator. By adjusting the NCO, it is possible to make the local code shift as required. By using a C/A code generator made from ASIC gate arrays, it is possible to control programming. By choosing GPS or Glonass code patterns from the CPU controller, integration of the two systems is achieved.

A carrier NCO, a code generator, and a code NCO are integrated on one ASIC gate array,

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A carrier NCO, a code generator, and a code NCO are integrated on one ASIC gate array, and a three-choice switch and a code correlator are integrated in another gate array.

The channel software has three main states, and each state has a status word which can be read out from the navigation computer.

A one-character 16-bit¹ master-slave response communication method is used between the channels and the navigation computer. The navigation computer transmits four kinds of commands: (1) interrogation commands; (2) control commands; (3) setup commands; (4) data commands.

The navigation software of integrated GPS/Glonass receivers uses modular design, i.e., the major functions are designed as interchangeable modules. By compiling these modules into the software library, when actually manufacturing the multichannel receiver, one has only to transfer each module and design

Page 161

a working environment for it, so that the amount of software work is decreased greatly when developing a new product. Linear derivation is primarily used in methods for solution of navigation equations. Where possible, Kalman filter algorithms are used. An excessive number of state variables cannot be selected.

4. High Dynamism Expanded-Frequency Tracking Technology

Tracking of highly dynamic expanded frequency signals means that after completing capture, the receiver tracking code and carrier wave Doppler estimated value can, within a certain range of error, track changes in the pseudo-code phase and Doppler frequency of the input signals caused by high-speed motion of spacecraft. The tracking portion is primarily composed of a code tracking loop, an AFC loop, and a digital locked loop. After capture is completed, [the signal] first enters the code loop, and after code-loop locking, enters the AFC loop. Use of the AFC loop is mainly based on the following two points: (1) there is a large error in captured Doppler frequencies, and most phase-locked loops cannot enter tracking; (2) when the dynamism of spacecraft is relatively great, it always causes a greater rate of change of Doppler frequencies, and phase-locked loops cannot deal with high-dynamism situations like these. After the AFC loop is locked, each part uses program control implementation to capture higher frequencies and

¹ Could also be "16-position."

enter the phase-locked loop. The loop frequency band-width of each loop is variable, to adapt to requirements for dynamism and accuracy.

The code tracking loop used in this paper is an early-late code tracking loop structure.

The automatic frequency control (AFC) loop uses a cross-accumulation AFC structure.

The digital phase-locked loop (DPLL) used in this paper is similar to a Costas loop. To gain greater accuracy, a narrow-band DPLL structure is used.

For the integrated GPS/Glonass receiver to be able to navigate in combination with INS in the future, it must have as small a volume as possible, so the channel part will make extensive use of integrated circuits, and the whole receiver will use digital processing. Not only will energy consumption be reduced, the use of CMOS circuits will lower energy consumption and increase the system's reliability as well.

IV. Concluding Remarks

Using GPS navigation satellites, it is possible to obtain a high degree of accuracy when using a repeater positioning system to position spacecraft. However, in recent years, because the United States has put into effect selective availability (SA) and anti-spoofing (AS) technology, positioning accuracy has greatly decreased for users of C/A code. For example, C/A code range-finding accuracy drops to approximately 100 meters (95% accuracy), altitude accuracy falls to approximately 150 meters, and speed measurement accuracy decreases to 0.3 meters per second. At the same time, the Glonass system does not yet have any technology for artificially lowering accuracy, and use of an integrated GPS/Glonass receiver is ensured to have greater positioning accuracy. Experiments by departments concerned show that 95% of Glonass horizontal positioning error is within 20 meters, altitude error is within 36 meters, and speed measurement accuracy is within 0.1 meters per second. Its accuracy is equivalent to the level of GPS without SA. Orbit measurement and shooting range monitoring of missiles and carrier rockets are two of the functions for which the American military GPS system is designed. Since the 1980s, many models of missile- and rocket-borne GPS receiving systems have been developed, and many experiments have been carried out. For example, the Texas Instruments MBRS and AMRS missile-borne receivers have been deployed on Minuteman missiles. The use of missile-borne repeater schemes has received even greater favor, because [these repeaters] have the advantages

of small volume, light weight, and low cost. They have been applied in Trident, ERIS, RAJPO, and other missile tests. At the end of the 1980s, experts in charge of GPS and Glonass expressed intentions to use the systems jointly. After several years of hard work and trials, the American corporation Honeywell produced an integrated GPS/Glonass receiver and carried out flight tests on Northwest Airlines airplanes. Applications of integrated GPS/Glonass receivers in military fields are being conducted now. Trials can also be made in flight tests of China's spacecraft.

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