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RANGING OF MEDIUM AND LOW ORBIT SATELLITES

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ABSTRACT This article first of all introduces principles and methods associated with various types of satellite ranging methods. Mutual comparisons are made between various types of methods. After that, an exposition is made of current trends in medium and low orbit satellite ranging.

KEY TERMS Ranging Tracking Satellite

GRAPHICS DISCLAIMER

I. INTRODUCTION

In order to calibrate and operate useful loads, it is necessary to accurately know satellite positions. We know that, with the aid of digital models of orbits, it is possible to calculate satellite positions. However, orbit models are determined by a few parameters (for example, orbital plane orientation, perigee amplitude angle, major hemiaxis, eccentricity, as well as final mean anomoly, and so on). Due to the fact that satellites in space are subject to various types of forces, the various parameters discussed above, therefore, vary as a function of time. It is necessary to make periodic updates. Because understanding of certain forces is not very complete, as a result, opting for the use of theoretical methods in order to update orbit parameters is not sufficiently accurate. There is a need to make use of ground stations to do supplementation of actual tracking data with regard to satellites.

As far as satellite observaton and measuring data which it is possible to obtain on the ground is concerned, there is ranging from ground stations to satellites, displays of satellite direction and azimuth angles, pitch angles, as well as their rates of change. Methods for directly and indirectly measuring these data include Doppler methods, angular measurement methods, as well as range and approach speed measurement methods.

When spacecraft did not pose high requirements for accurately making precise determinations of orbits, it was only necessary to go through Doppler and angle measurement methods, and it was possible to obtain adequate tracking data. However, a new generation of medium and low orbit satellites begins to pose requirements on orbital accuracies. For example, such satellites as GEOS-3, SEASAT, LAGEOS, STARLETTE, ERS-1, POPSAT, TOPEX, and so on, all require precise determinations of their orbits. In this type of case, methods for ranging and measuring approach speeds with relatively high accuracies are able to satisfy this type of requirement. The explanation which follows is a unified explanation of the designation medium and low orbit which has not occured in the literature. This article opts for the use of the formulation method in the article "Three Axis Stabilized Ground Observation Satellites and Their Attitude /135 Control" (Control Engineering, 1987, No.5, P1-9). This defines low orbit as 500km or less. Medium orbit is defined as 500km ~ geosynchronous orbit.

Methods for measuring ranges between two points which are very distant from each other are measuring the times required for electric waves to go and come back between the two points (transmission delay time). The methods for precisely determining transmission delay times include side tone ranging, PN code ranging, as well as laser ranging, and so on.

II. SIDE TONE RANGING

This type of method for precisely determining distances between satellites and ground stations lies in measuring the propogation time between sine wave signals sent from the ground to satellites reaching satellites, and, in conjunction with that, being retransmited through the satellite back to the ground station.

Assuming that the ranging tone of the transmiting terminal is

$$S(t) = A\sin\omega t \qquad (1)$$

the ranging echo received by the ground station is

$$S'(t) = A'\sin\omega(t+\tau) \qquad (2)$$

In the equations, A and A' are, respectively, transmiting terminal and receiving terminal ranging signal amplitudes. ω is ranging tone angular frequency. τ is the propogation time associated with electromagnetic waves from transmiting terminals arriving at targets and then, from targets, arriving at receiving stations. If it is possible to precisely measure delay τ, it is then possible to calculate range R from target to receiving station in accordance with the equation below

$$R = \frac{1}{2} C\tau \tag{3}$$

In equations, C is the speed of light. The condition for setting up the equation above is transmiting stations and receiving stations using the same antenna. Equation (2) can also be written as

$$S'(t) = A'\sin(\omega t + \varphi) \tag{4}$$

φ is the phase difference of receiving terminal signals with regard to transmiting terminal signals

$$\varphi = \omega\tau = \omega 2R / C \tag{5}$$

therefore,

$$R = \frac{C}{2\omega}\varphi \tag{6}$$

From (6), it is possible to know that, if the phase difference φ between receiving and transmiting terminal ranging tones is measured, it is also possible to solve for distance /136 R.

Transmiting terminal signals passing the zero point in the positive direction form an open gate pulse, opening up counter gate circuits to carry out counting of clock pulses. Receiving terminal ranging echo signals passing the zero point in a positive direction forms a close gate pulse, causing counter gate circuits to close. At this time, the clock pulses which registers have counted are K. Then,

$$\tau = K / \underset{\text{clock}}{f_{时钟}} = K \underset{\text{clock}}{t_{时钟}} \qquad (7)$$

In equations, fclock and tclock are, respectively, clock pulse frequency and period. tclock is the resolution for time measurements. If use is made of phase meter readings in order to measure ranges, one then has

$$\varphi = \omega\tau = K\left(\frac{2\pi f_m}{\underset{\text{clock}}{f_{时钟}}}\right) = K\varphi_0 \qquad (8)$$

In equations, φ_0 = 2πfm / fclock represents phase resolution. fm is range tone frequency.

Maximum delay τmax must be smaller than range tone period T. If not, within τmax, ranging echoes will show the appearance of multiple zero point crossings in the positive direction. However, counters form close gate pulses on the first echo crossing the zero point in the positive direction. As a result, one has the appearance of errors associated with whole cycle numbers. This type of phenomenon is called range fuzziness.

However, ranging errors include ranging instrument errors added to receiver input terminal thermal noise effects. Thermal noise errors are determined by the equation below

$$\sigma_R = \frac{C}{4\pi f_m}\sqrt{Bn} / \sqrt{S/\varphi} \qquad (9)$$

In equations, Bn = tracking ambient noise band width (single sideband).

S/φ = S/N power density (for received ranging tone).

When echo signal to noise ratios S/N are fixed values, σR and ranging tone frequencies form a direct proportion. That is nothing else than to say that if one wants to increase ranging accuracy, it is necessary to raise ranging tone frequencies. However, this leads to maximum time delays τmax or a lack of blurred range reductions.

In order to resolve the contradiction between ranging accuracy and lack of blurred ranges, it is possible to go through a sequential transmission of a set of ranging tones in order to resolve it. This set of side tones is composed of a main side tone (high frequency) and several secondary side tones (low frequency) . These low frequency signals, between themselves as well as with the main side tone, have a common origin point. /137 After that, on the receiving side, going through a distinguishing of common origin points in order to achieve a conincidence between transmited main side tones and received main side tones, it will have a delay of τ relative to the transmiting side.

In this system, option is made for the use of narrow band locked phase rings to lock on tracking with regard to each side tone component. The lowest frequency secondary side tones guarantee the maximum lack of blurred ranges Rmax . Using the highest frequency main side tone guarantees the required range accuracy σR . Located between the highest side tone and lowest side tone are matching tones. Each matching tone is used in order to resolve one by one phase blurrings or range blurrings associated with adjacent high side tones.

As far as the frequencies used in side tone ranging systems are concerned, according to NASA standards, they are set as 500kHz, 100kHz, 20kHz, 4kHz, 800Hz, 160Hz, 32Hz, and 8Hz. Main side tones are selected from among 500kHz, 100kHz, and 20kHz. The reason is that each side tone is obtained through a simple division of the side tone frequency before it. Therefore, 8Hz side tone frequencies are used to make time base datums associated with other side tones. As a result, 8Hz side tones are also called "datum side tones".

Side tone ranging systems developed by the European space agency are limited by modulation frequency spectra associated with transmission. In actuality, transmission frequencies are 100kHz (main side tone), and 20kHz, 16kHz, 16.8kHz, 16.16kHz 16.032kHz, as well as 16.008kHz (secondary side tones).

The transmitted side tone series which is shown in Fig.1 is a function of time.

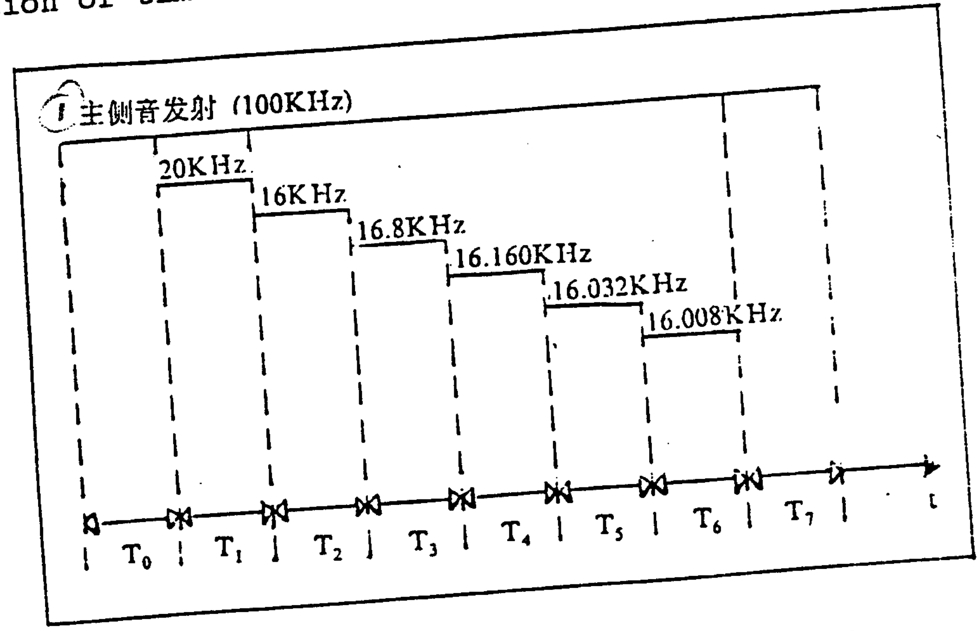
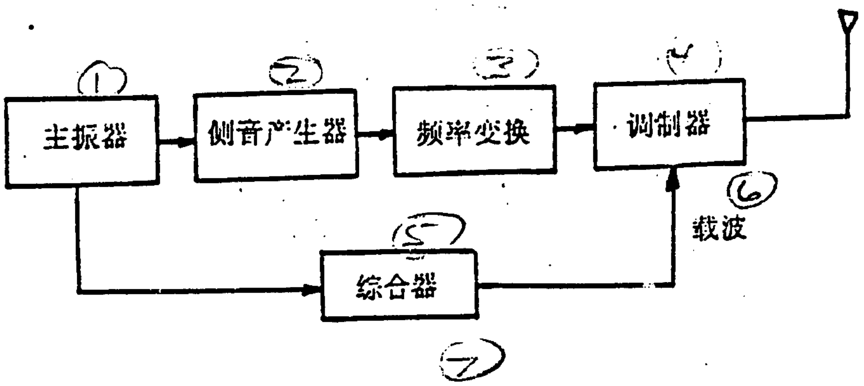


Fig.1 Returning Side Tone Series Time Relationships

Key: (1) Main Side Tone Transmission

Time To is the time required to lock ground station receivers onto received carrier waves and to lock range demodulators onto transmited main side tones. T1 - T6 are times required to resolve fuzziness. During this period, 8Hz side tones obtained possess the time accuracies of main side tones and are reconstructed. At time T7 , measurements of time delays between datum 8Hz side tones and reconstructed 8HZ side tones are gone through in order to carry out ranging. A schematic diagram of the principles associated with side tone ranging systems is as shown in Fig.2.



a.发射机

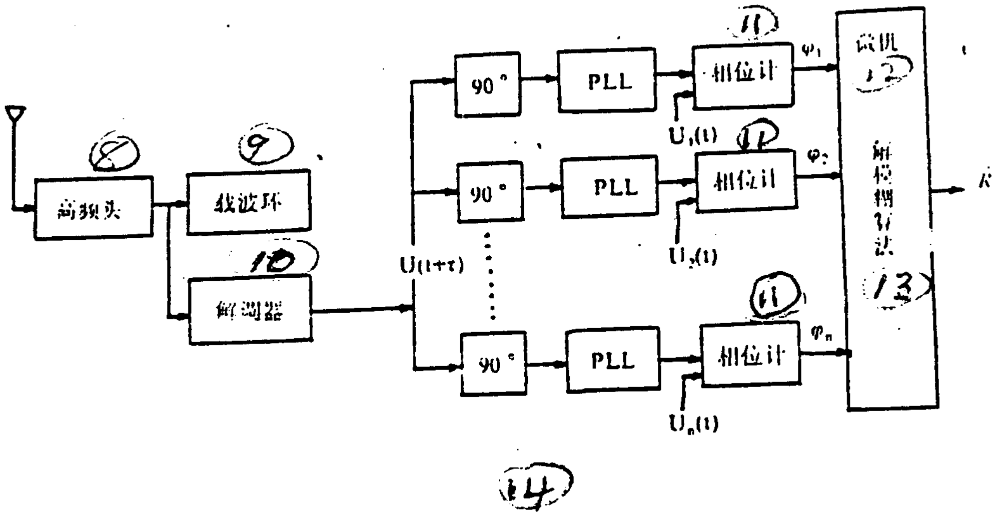


Fig.2 Side Tone Ranging System Schematic

Key: (1) Master Oscillator (2) Side Tone Generator
(3) Frequency Convertor (4) Modulator (5) Synthesizer
(6) Carrier Wave (7) Transmiter (8) High Frequency Head
(9) Carrier Wave Loop (10) Demodulator (11) Phase Meter
(12) Microcomputer (illegible) (13) Deblurring Algorithm
(illegible) (14) Receiver

At the present time, use of side tone ranging systems is relatively wide. For example, there are applications in the U.S. Goddard space center, the European space operation center, India's ISAC center, West Germany's Weihayimu (phonetic) ground station, and so on.

With the relative positions of satellites and earth stations already known, it is thus possible to calculate time delays given rise to by atmospheric refraction. Before ranging and before transmissions on spacecraft, respective calibrations are done for time delays created by ground station equipment and transmiters on satellites. After corrections of the supplementary factors discussed above, measurement result accuracies can reach a few meters. For example, the U.S. Goddard ranging system S wave band ranging accuracy is 2 meters. The ranging accuracy of low orbit satellite side tone ranging equipment developed by Portugal is 4 meters.

III. PN Code Ranging

In cases where continous tracking is the objective, use is often made of PN code ranging methods.

PN code ranging methods are methods which make use of PN series modulated carrier waves to carry out electric wave ranging. The structure of PN code ranging methods is as shown in Fig.3.

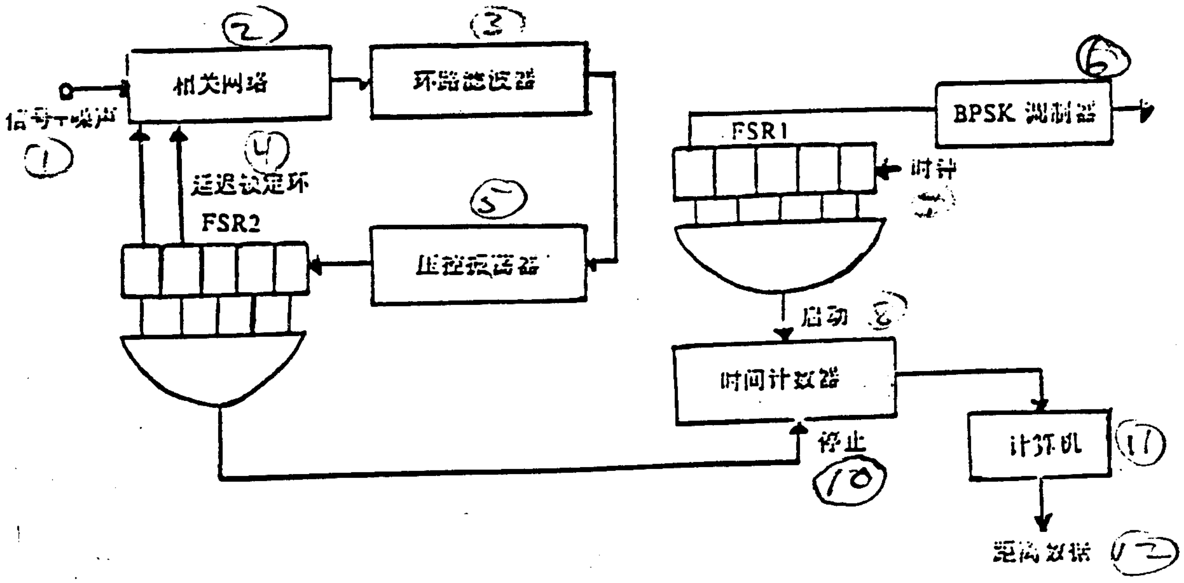


Fig.3 PN Code Ranging

Key: (1) Signal (illegible) Noise (2) Correlation Network (3) Loop Circuit Filter (4) Delay Lock On Loop (5) Voltage Control Oscillator (6) Modulator (7) Clock (8) Start (9) Time Counter (10) Stop (11) Calculator (12) Distance Data

PN series are generated by n stage feedback shift registers (FSR). The period is shown by using the formula below

$$T_s = (2^n - 1)\Delta \qquad \overset{\text{second}}{(\text{秒})} \qquad (10)$$

In the formula, Δ is chip duration.

n stage FSR are n stage shift registers corresponding to shunt output feedback associated with n order original multiple term forms. As a result, considered in terms of structure, the aggregate of the contents of n registers (internal status) will not be the same again right up to Ts seconds. PN code ranging methods make use of nothing else than this property.

In Fig.3, on FSR#1 associated with the production of PN series, n inputs and gates are connected. After going through detection of specially designated internal states (for example, all 1 states), pulses are produced. Time counters start up. PN series generated in FSR are modulated on carrier waves and sent out. After return signals are picked up by receivers, they enter DLL (delay lock phase loop). If DLL is in a locked on state, then FSR#2 makes reception series phases synchronous. After using the same kind of methods to detect FSR#2 interior states, time counters are made to cease operation. Then, it is possible to obtain delay time τ, thereby obtaining the distance from target to ground station receiver.

However, in PN code ranging methods shown in Fig.3, if delay times exceed Ts seconds, then, there is a Ts whole number multiple of fuzziness between precisely specified values obtained from time counters and actual delay periods. As a result, the largest delay period which it is possible to measure is Ts . This corresponds to the maximum range associated with the formula below

$$R_{max} = CT_s / 2 = C\triangle(2^n - 1) / 2 \tag{11}$$

Based on differences in methods of constructing correlation networks, DLL associated with determining PN code ranging method precisions has such methods as lock phase demodulation + video frequency correlation methods as well as envelope correlation methods, and so on. Among these, lock phase demodulation + video frequency correlation methods have the best characteristics. Tracking errors given rise to by the added noise are shown by the equation below:

$$\sigma_n / \triangle = \sqrt{0.53 P_0 N_0 / 2P_s} \tag{12}$$

In the equation: Po = loop circuit filter constant (rad/sec)
No = single sideband noise power frequency spectrum density (watts/hertz)
Ps = reception signal power (watts)

In equation (12), Po is a parameter determining loop circuit band widths. The smaller this value is, the narrower loop circuit band widths then are.

If one takes the phase difference between reception series and datum series and defines it as ε , then, in a case where |ε| < 3△ / 2 , DLL will not produce error signals. In order to lock on loop circuits, it is necessary to explore the phases of datum series. To this end, the maximum time required (maximum acquisition time) is shown by the formula below:

$$T_{amax} = (2^n - 1) / 1.8 P_0 \tag{13}$$

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Maximum measurable range Rmax , tracking precision σn / $\triangle$, and maximum acquisition time Tamax are three large factors associated with surrounding effects given rise to in PN code ranging methods.

PN code ranging methods are primarily used in continuous tracking. Its precision is also on the meter order of magnitude. For example, PN code ranging systems developed by Japan's electric wave research institute have resolutions which reach 1.5 meters. As far as the PN code ranging system developed by the Japan Electric Company (NEC) for use in tracking the "swan" science satellite, launched in 1975, is concerned, ranging precisions at ultra high frequencies and S wave bands, respectively, are 100 meters and 1.5 meters.

IV. LASER RANGING

In the area of precision satellite ranging, lasers have even more clearly demonstrated their potential. Laser ranging technology is advancing very fast. In 1965, U.S. and French artificial satellite laser ranging precisions still did not exceed around 10 meters. However, today, 0.2 millimicrosecond pulse lasers are capable of giving 2-3 centimeter ranging precisions.

At the present time, in the world, there are over 20 nations in the process of operating laser ranging stations. Use is primarily made of pulse outputs that are 0.2 - 5 Joule ruby lasers. However, the newest systems, which possess ranging precisions of a few centimeters, opt for the use of laser systems associated with second higher harmonics (green color) of YAG lasers. At high quantum yield wave lengths, this type of laser makes use of photoelectric cells exposed to light and short transmission intervals to obtain extremely narrow pulse widths. This is the main development direction for laser systems from now on.

Ranging precisions almost form an inverse proportion with pulse widths. Ruby laser pulse widths in the early period were approximately 20 millimicroseconds. Even if one opts for the use of shaping systems, it is still only possible to reach the level of a few millimicroseconds. However, opting for the use of wave form lock in YAG lasers, it is possible to realize 0.2 millimicrosecond pulses.

In situations with ruby lasers, laser beam angles of spread are generally a few milliradians. In order to narrow light beams, there is, normally, a retransmission following the interposition of several power reverse telescope systems.

As far as determinations of received optical luminous flux requirements are concerned--besides distance and light beam spread angle--there are also scattering angles and effective surface areas of back reflectors (satellite borne), effective light gathering surfaces of receiving telescopes, as well as atmospheric and optical system penetration rates. With regard to LAGEOS satellites--in situations composed of 50 centimeter aperture receiving telescopes and typical ruby lasers--the received luminous flux attenuates to 10-17 in association with transmission time. There are only a few tens of photons. In order to reliably detect this type of weak light--besides using photoelectric multiplier tubes--it is necessary to adopt certain measures. First of all, it is necessary to do the utmost to narrow telescope fields of vision through the adding of filters with wave length widths of around 10Å in order to reduce background light static. During satellite ranging, one wants, before the fact, to understand quite precisely satellite orbits and observation point positions. Taking this as a given, it is possible to relatively easily make precise determinations for the instants of reflected light reception. Before this instant, if photoelectric tube signal circuits are cut, it is then /142 possible in a big way to reduce the influences associated with randomly generated static photons.

By 1982, there were already 14 satellites carrying laser back reflection devices--for example, LAGEOS satellites, STARLETTE satellites, "painting" (danqing) satellites, and so on. With regard to laser ranging associated with these satellites, it is primarily used in order to study geodynamics (dynamics of the earth's crust, geopositioning, study of the tides) as well as precise determinations of models for the gravitational field of the earth. Besides this, laser ranging is a method with prospects for monitoring of active geological faults as well as checking on continental drift. Of course, with regard to the marine observation satellite No.1 (MOS-1), launched by Japan on 5 March 1987, the precision ranging belongs, by contrast, to another type. The MOS-1, which acts as the start for a series of Japanese earth observation satellites, is synchronous with the sun. It has opted for a regressive orbit which is capable of crisscrossing observed surfaces of the earth. The apogee altitude is 917 kilometers. The perigee altitude is 903 kilometers. The angle of inclination is 99.1°. It goes around the earth once in 103 minutes. Each day, it goes around the earth 14 times. Due to the earth's rotation, the orbit around the earth on the second day is shifted toward the west 169 kilometers along the equator. In 17 days, after circling 237 times, the satellite returns to the initial orbit on the 18th day. With regard to this type of orbit, the number of times domestic Japanese ground stations are capable of seeing it each day are limited to 4 - 5. Each instance is 10 - 15 minutes. Therefore, there is a need to make precise use of it during short periods of time. At the same time, due to requirements associated with satellite borne instruments (visible light and infrared spectrum earth observation instruments), there is a need to measure with high precision satellite positions relative to the surface of the earth. Japan opts for the use of laser ranging. Accuracy is around 10 centimeters.

Besides fixed laser stations, in order to economize on costs, mobile type laser ranging equipment was also developed outside the country. For example, in 1978, Contraves-Goerz Corp developed--for NASA's Goddard space flight center--five precision mobile optics mounting systems (MOMS) to carry out laser ranging against satellites carrying back reflectors. MOMS is a precision servo mounting. On the mounts, there are installed one 30 inch aperture receiving telescope and one 4 inch aperture Kude (phonetic) mirror transmiting optics system. The whole system is mounted on a 45 foot long trailer. Main laser devices are placed in a clean room on the trailer.

V. COMPARISONS OF SEVERAL TYPES OF RANGING METHODS

The three types of ranging methods discussed above each have advantages and disadvantages. We now make a brief discussion of these below.

As far as the highest laser ranging precisions are concerned, they generally reach the centimeter level. Recently, according to reports (Acquisition tracking and pointing Proceedings of the meeting.Orlando,FL.Apr.2 4.1986.P77-83), high precision laser stations have already been set up outside China. Accuracies are capable of reaching a few millimeters. This type of laser ranging system has a 15 ton weight level and is a pitch telescope precision pointing system. Tracking is under open loop computer control. The algorithms used in the earliest detection data and orbital calculations are accurate enough to maintain satellites inside the width of narrow laser beams. Systems /143 at the present time are being utilized to track LAGEOS and STARLETTE satellites. However, the manufacturing costs and operating expenses associated with laser ranging systems are all very expensive. In conjunction with this, there is also a requirement not to have any cloud cover. Therefore, they are not all weather.

Sine wave side tone ranging and PN code ranging each possess special features. Sine wave side tone resolutions are high. Acquisition times are short. They occupy narrow frequency bands. They are capable of obtaining high precision ranging signals. However, nonfuzzy ranges are subject to limitations associated with the lowest frequency side tones. PN code sequences possess nonfuzzy ranges that are long. Resolutions are high. They have counter jamming capabilities and security. However, they occupy wide frequency bands, and acquisition times are a little long.

In view of this type of situation, the tendency abroad is to take the two and combine them, forming tone code composite ranging signals. These possess the advantages of side tones and

PN codes and are one type of comparatively good signal form. The typical applications introduce into side tone signals a low frequency false random code in order to distinguish range fuzziness or introducing into false random codes a high freqency side tone in order to provide ranging precision. For example, the first generation of the U.S. Goddard ranging system is pure side tone ranging. However, around 1965, option was then made for the use of composite forms of ranging--that is, during tracking in near earth orbits, operations were done in accordance with pure side tone forms. During long distance tracking, operations were carried out in accordance with composite modulation forms.

VI. PRESENT TRENDS IN SATELLITE RANGING

With regard to satellite ranging, there have already been 30 years of history up to now. Following along with unceasing advancement in technology, ranging precisions have not only greatly increased, but system volumes have continuously decreased. For example, in the early 1960's, the U.S. space ground link system (SGLS) ranging unit accounted for a whole plane full of hardware. By 1982, however, the volume of ranging hardware had been reduced to one machinery cabinet.

In recent years, there have been trends in various nations associated with two areas in regard to satellite ranging--that is, unceasing improvements in ranging technology itself and the evolution from ground based to space based.

(I) Improvements in Ranging Technology

1. Just as was discussed above, taking side tones and PN codes and combining them, adopting the advantages of both, to construct composite model ranging methods.

2. The newest side tone ranging is as shown in Fig.4. In the system in question, locked in phase loops and phase meters are combined into one--not only respectively locking onto various

side tone echoes but also respectively giving phase differences from the original side tones. What is worth paying attention to is that side tone transmissions opt for the use of time series sending, however, side tone echo receiving and phase comparisions can also opt for the reuse of the time. Therefore, it is possible to very greatly reduce the entire volume. /144

The European space agency's new generation of side tone ranging systems opt for the use of middle frequency correlation demodulation devices to avoid adopting the use of narrow band filters in ranging demodulators, thereby satisfying tracking system delay stability requirements. Besides this, systems include standard connection ports (for example, IEEE standard 488-1978) and users are able, on the basis of special task requirements, to regulate the phases of side tones transmited, thus making this type of new generation side tone ranging system capable of application to any ground station environment and possessing high flexibility.

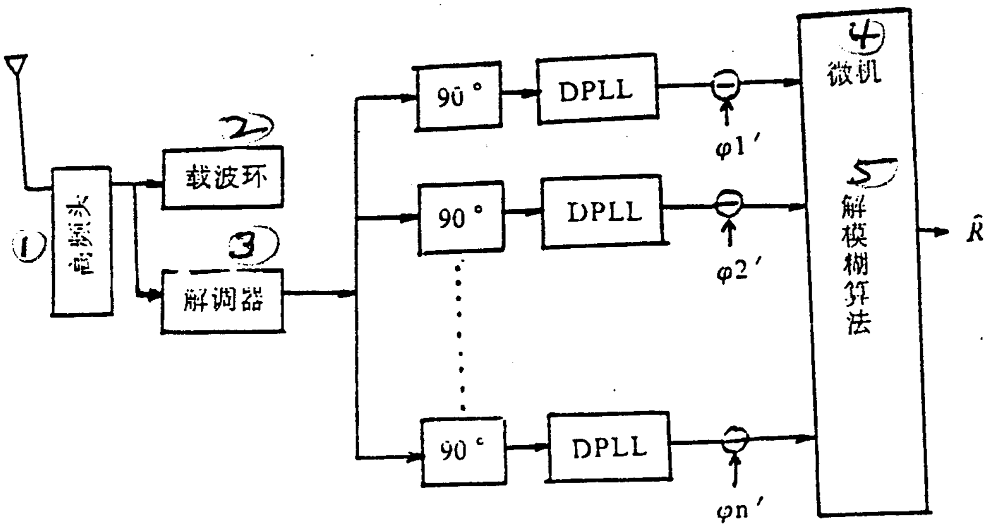

Fig.4 Newest Side Tone Ranging System
Key: (1) High Frequency Head (2) Carrier Wave Loop
(3) Demodulation Device (4)
Microcomputer (5) Deblurring Algorithm

3. Just as was introduced before, in PN code ranging methods, maximum nonfuzzy ranging distance Rmax, tracking precision $\sigma n/\triangle$ and maximum acquisition time Tamax are determining factors. However, these three are mutually interacting. First of all, in order to increase precision--according to equation (12)--Po and $\triangle$ values ought to be as small as possible. When Po values are small, in order to maintain maximum acquisition times invariable, it is necessary--on the basis of equation (13)--to reduce n values. Under conditions where n values are reduced and $\triangle$ values drop, it will necessarily lead to Rmax values being greatly reduced. Therefore, in PN code ranging methods, option is generally made for the use of compromises.

In regard to the contradictions discussed above, on 19-23 May 1986, at the fifth session of the international space technology and science conference, which was held in Tokyo, Japan, Tokyo University put forward one type of dual speed PN ranging system (before this, an article had already been published in magazines). The authors made use of PSK/PSK dual speed communication forms. PSK/PSK dual speed communications methods are a special four phase PSK associated with the combining of high speed BPSK and low speed BPSK. It possesses the characteristics below. /145

(1) Low speed modulation channels (low speed communications) are capable of making use of the low group error rate achieved at low speeds.

(2) Through resolution results associated with low speed communications feedback, high speed communications achieve roughly the same error rates as BPSK before conversion to dual speeds.

(3) Band widths are invariable after dual speeds.

Dual speed PN ranging methods possess two channels associated with PSK/PSK dual speed communications forms with the characteristics above. PN sequences with two different periods are transmited at the same time, causing simultaneous DLL operation corresponding to the various sequences.

PN sequences transmited by high speed communications channels and low speed communications channels are respectively represented by the use of PNhigh and PNlow . FSK series generating these PN sequences are respectively represented by the use of nhigh and nlow . In PSK/PSK dual speed communications methods, if one takes the 1 place length associated with high speed communications and defines it as $\triangle$, then the 1 place length associated with low speed communications is $N\triangle$(N:place speed ratio). Thus, PNhigh and PNlow periods are, respectively:

$$\underset{\text{high}}{T_{高}} = (2^{\overset{\text{high}}{n_{高}}} - 1)\Delta$$

$$\underset{\text{low}}{T_{低}} = (2^{\overset{\text{low}}{n_{低}}} - 1)\Delta N$$

Using logic and electric circuits to detect specially designated PNhigh FSR states, pulses are generated. With regard to PNlow use is made of the same kind of methods to generate pulses. Then, the periods of corresponding pulses are:

$$\underset{\text{high low}}{T_{高低}} = \Delta LCM[2^{\overset{\text{high}}{n_{高}}} - 1, (2^{\overset{\text{low}}{n_{低}}} - 1)N]$$

When $\underset{\text{high}}{2^{n_{高}}} - 1, \underset{\text{low}}{(2^{n_{低}}} - 1)N$ is mutual mass, one has

$$\underset{\text{high low}}{T_{高低}} = (2^{\overset{\text{high}}{n_{高}}} - 1)(2^{\overset{\text{low}}{n_{低}}} - 1)N\Delta$$

This value is very large, thus enlarging maximum nonfuzzy range values.

(II) Evolution from Gound Based to Space Based

1. Satellite Borne Measurement Systems West Germany developed a set of precise range and range rate equipment (PRARE). The equipment in question is composed of ground transmiters and components installed on the European space agency's earth resources satellite No.1 (ERS-1). This system opts for the use of PN measurement signals--in space-earth-space directions--to carry out dual direction ranging. The signals in question, under 8GHz modulation, travel on carrier waves.

Through ground transmiter transmissions and passing through /146 traveling up 7GHz carrier waves, they return to the satellite. At the same time, a second type of signal is modulated on downward traveling 2GHz carrier waves. On the ground, it is permissible to make use of interrelationships between these two types of signals in order to precisely determine ionosphere correction parameters. Correction parameters and other auxilliary data uses 7GHz carrier wave up links to be transmited to the satellite. All data is stored on the satellite and, when the satellite flies over the central ground station, is processed by it.

Due to transmiting and receiving equipment being shifted from the ground to satellites, as a result, costs of ground stations drop. In conjunction with this, multiple ground stations are served. The numbers only depend on the satellite storage capacity. Besides this, ground stations are capable of not needing to be looked after by people. This type of system is not only capable of being used with high orbit satellites, but is also able to be made use of with low orbit satellites. The accuracy estimates can reach decimeter orders of magnitude.

2. Relay Satellite Systems The number of times that ground stations are capable of observing medium and low orbit satellites each day and the time periods associated with each observation are both limited. For example, as far as the MOS-1 satellite is concerned, Japanese ground stations are only able to observe it 4-5 times each day. The time period in each instance does not exceed 15 minutes. In order to continuously track these satellites, it is then necessary to increase the number of ground stations (have a number of ground stations set up outside the country). This then increases expenditures. In order to reduce the number of ground stations, reduce costs, and increase efficiency, in the early 1970's, at the same time the U.S. was developing the space shuttles, the idea was also brought up for the tracking and data relay satellite system (TDRSS). On 4 April 1983, the first TDRS-A satellite was carried on the first

"Challenger" space shuttle flight and launched. It would become a new type of measurement system in the 1980's.

After the system was set up, it was almost capable of carrying out continuous tracking of medium and low orbit space craft. Through transmiting ranging and Doppler frequency shift information between them and measurement and control stations, it is possible to realize precise determinations of the orbits of these spacecraft.

With regard to TDRSS orbital measurement capabilities, the U.S.--in the middle 1970's--made use of 6 geosynchronous applied technology satellites, tracking 6 Yunyu and 3 geodetic satellites as well as Apollo-Soyuz spaceships. In tests, option was made for the use of dual direction ranging and range rate orbital determination technologies. From ground stations that had gone through precision surveys, ranging and range rate signals are transmited to relay satellites. They are then transmited from relay satellites to spacecraft being tracked and measured. The spacecraft take these signals and transmit them back to the relay satellites. Finally, they are transmited back to ground stations, using them to measure range totals and speed totals.

The ranging tones used are 100kHz. Carrier waves are 2GHz. Through careful calibration of response devices, it is possible to make overall measurement errors reach an order of magnitude of a few meters.

As far as ranging of space shuttles is concerned, the U.S. opted for the use of relay satellite methods discussed above. However, in cases where space shuttles are located in areas that cannot be supplied coverage by TDRSS, option is still made for the use of supplemental plans where ground stations directly do tone ranging of space shuttles. At this time, the main side tone is 500kHz. The lowest secondary side tone is 4kHz. Side tone sequences are transmited after going through 1.7GHz secondary carrier wave phase modulation.

Ever since U.S. development of tracking and data relay satellite systems--due to the fact that this type of measurement system has a series of advantages--various nations have been in competition to imitate them. Japan plans to make use of large model rockets to launch three one ton satellites, constructing a data relay satellite JTDRS system. The French space research/147 center (CNES) has also put forward a space relay type "applied and relay technology satellite (STAR) system" project. Use is made of S wave bands. Ranging precision is 30 meters. The European space agency considers that, in the 1990's, they must develop relay satellite systems.

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