A NEW TIMING DEVICE OF SATELLITE TRACKING CAMERA WITH GEODETIC PURPOSE

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Abstract

For the photographic observations of an artificial satellite in geodesy, it generally needs to use cameras equipped with precise timing devices. Various timing devices being designed by some authors, they have not necessarily been satisfactory in handling facility, simplicity, high effeciency, and their price.

Thus, the new timing device has been designed in view of the use of a simple equatorial camera. This device, in brief, is based on the following principle.

A satellite trail is chopped by narrow metal slits passing by a photographic plate, while the serial position marks of the same slits are photographed by multiple flashing lights of a discharging flashlamp. The times when the satellite trail was chopped by the slits are determined through the relative positions between the chopped satellite images and the position marks of the slit plate corresponding to each flash time, while the flash times are read by a recording oscillograph with standard time signals. Using this device, the timing accuracy of 1 msec. will be expected.

In this paper, detailes of the timing device are described and its error estimations are discussed with preliminary experiment.

1. Introduction

Until recently the dimension and figure of the earth have been derived from triangulation and gravimetric observation made only on limited areas of the earth. For wider ranges, i. e., for geodetic connection of two continents or distant islands to a continent, Solar Eclips or star's occultations by the Moon, have been applied, of which observing chances are, considerably limited. However, by launching of artificial satellites, new possibility for the long range geodesy was opened.

In the use of the satellites for the geodesy, it is necessary to fix the motion of the satellites in the sky, since the satellites are regarded as triangulation stations floating in the sky. To attain this purpose following methods are thought out :

1) to use flash lights provided for the satellite,
2) to use synchronized cameras at different stations,
3) to use a precise timing device equipped for a camera.

With regard to the first method the geodetic satellites such as ANNA and GEOS are planned in practice, and are subjecting to the tests at present. In this case, however, it needs to use a powerful telescope for photographing these faint satellites. Accordingly, this method is not applied effectively for the observations at isolated islands, where the transportation of large instruments is difficult.

In the second method it is possible to use a relatively small camera for the bright satellites such as Echo. Also the experiments of the camera shutter synchronization within at least 1 msec. at each station is in progress, using the very low frequency (VLF) time signals. However, this synchronizing demands very complicated electronic system, and the cost of the observing system perhaps will come quite expensive.

Comparing the above three, it seems that the third method is most effective, since, which the use of a simple cameras is possible.

In order to determine geodetic positions within the error ± 5 m, assuming that the altitude and the topocentric angular velocity of the satellite is 1000 km and $1000''$/sec respectively, an accuracy of ± 1 msec. are required for the timing device. As satellite cameras having these timing accuracy, Baker Nunn Camera (Smithonian in USA), BMK Camera (Zeiss Co.) and BC-4 Camera (Wild Co.) etc. are well known at present.

Among these cameras, B. N. Camera, developed by the Smithonian Astrophysical Observatory for the precision optical satellite tracking net, was designed as a super Schmidt F/1 of 50 cm focal length in order to photograph satellites to the 12 th magnitude. In this camera, a barrel shutter rotating with a highly precise angular velocity breaks the trails of stars and satellites. Since the focal field is spherical, we must use a film instead of a glass plate. Therefore, the accuracies of measurement of the images compare unfavorably with that of glass plates. On the other hand, BMK and BC-4 Cameras have been developed with the object of the Ballistic Missile. Their timing devices are mounted portable cameras, and also based on mechanical shutters. To keep always the precise timing accuracy, the manufacturing the devices requires higher techniques and they are obliged to come expensive.

Instead of these mechanical shutters Tsubokawa (1963) has designed a photoelectric timing device consisting of a series of knife-edges, and proved its excellency, when it was mounted to a portable camera.

Thus several mechanics for the precise timing device has been developed hitherto. However, for the use of the bright satellites such as ECHO, we cannot pass the problem untouched, which arises from the differences of the brightness between a satellite and comparison stars causing a systematic error in measurements of position of the satellite trail on a plate. Only for reducing the brightness, it is possible by means of F-stopping or using lower sensitivity plates. In this case, however, a guiding error comes into question, especially by a simple equatorial camera. Accordingly, it is highly desirable that the camera for bright satellites has the function to reduce the brightness of the satellite to that of the comparison stars.

Based on the foregoing view a new timing device has been designed to meet the demands of convenience of handling, easiness of setting and reducing the brightness of the satellite.

2. The Principle of The Timing Device

In order to chop a satellite trail on the photographic plate, moving slits are used in the new timing device.

If a plate having several slits passes in front of the photographic plate when the satellite transits the camera field, the trail of satellits will be chopped as shown in Fig. 1. During the slit plate is moving, a series of flash lights is emitted onto the photographic plate through time mark slits bored in top and bottom of the slit plate. Thus the time marks which represent the positions of the moving slit plate corresponding to each flash time are photographed on the photographic plate with the breaks of satellite trail. The standard time signals and time of each flash are recorded in a suitable recording instrument as explained in the later paragraph. Accordingly, the time marks are connected to the standard times, and the times when the satellite trail is chopped by the slits are determined through this connection.

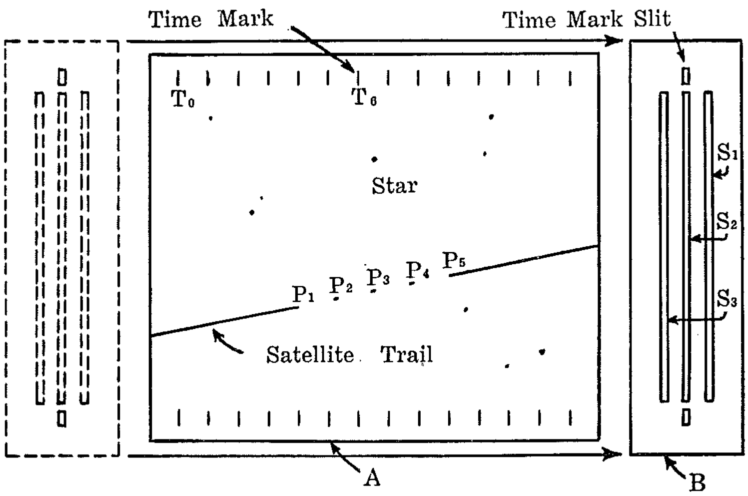

Fig. 1. Schematic diagram of new timing device

Now, In Fig. 1 A and B are the photographic plate, and the slit plate which have three slits and a pare of time mark slits, respectively. The image of satellite traverses on the photographic plate from left to right. At the start of trail, the slit plate is situated at the left side of the photographic plate, as shown by broken diagram. After a while, the slit plate will begin to moved towerds right when the satellite approaches to the optical center of camera, where the start time of the slit motion may easily be obtained through the finder. The motion of the slit plate has to be faster than the image of satellite. (As regards the speed of the slit plate, it will be discussed in the third paragraph). Subsequently, the right side edge of slit plate will catch up with the image of satellite at point P_1, and cut off the light beam from the satellite. At point P_2, similarly slits will catch up with the image, and the photographic plate will be exposed to the light beam again in a short time interval. If the width of slits S_1 is narrow, the chopped trail will be photographed as a point like image. Similarly, when the slit plate arrives at the right side of the photographic plate, three chopped image at P_2, P_3, and P_4, have been printed by slits S_1, S_2, and S_3 respectively.

During motion of the slit plate, the time marks are printed to the photographic plate by a series of flash lights as the marks denoted by T_1, T_2, ... T_n as shown in Fig. 1, while the times (t_1, t_2, ...) referred to these marks are determined in the preceding way. From these data any position of slit plate will be obtained as a function of the flashing times. Even if the motion of the slit plate is not linear, the nonlinearity will be eliminated by increasing a number of the flash. If the shape of slit plate is well known, the timing of (P_2, P_3, P_4 ....) can be interpolated from analyzed motion of the slit plate.

The practical process of the timing of (P_2, P_3, P_4 ....) is described below in more detail. (See Fig. 2.)

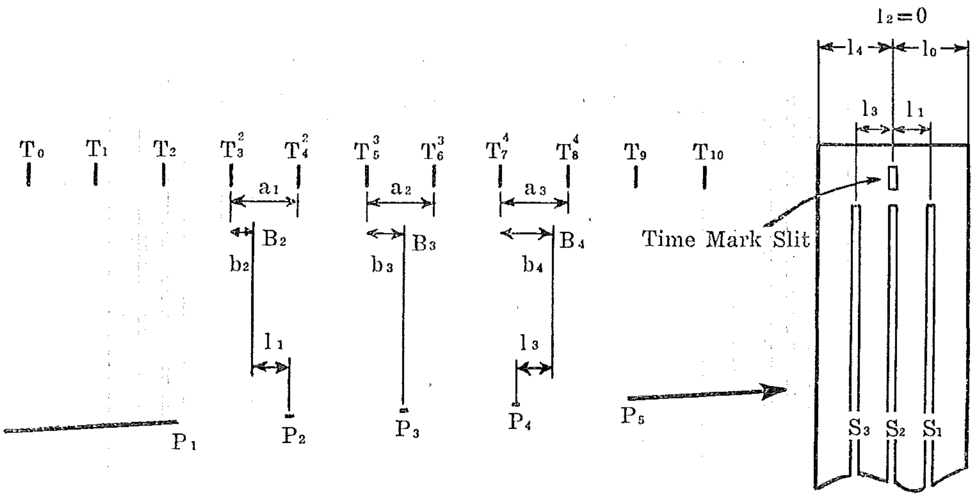

Fig. 2. Principle of time determination of the satellite images

In Fig. 2, provided that the shape of the slit plate is known, the positions B_2, B_3, B_4 ....of the time mark slits at the moment when the trail was chopped will be yielded as the positions situated at the distance of l_1, l_2 l_3 .... from P_2, P_3, P_4 ...., where l_1, l_2, l_3 ... are slit intervals as shown in Fig. 2.

Assuming that for the sake of brevity the movement of the slit plate is linear, we can determine the times (t_{p2}, t_{p3}, t_{p4} ....) when the trail are chopped at (P_2, P_3, P_4 ...), by the following formulae :

$$t_{pj}=t_i^j+\frac{b_j}{a_{j-1}}\Delta t_i^j \quad (i=1,\ 2,\ 3, \cdots\cdots,\quad j=2,\ 3,\ 4, \cdots\cdots)$$

where, suffix i means the order of the time marks and is counted from zero point of the time marks, and j means the order of the chopped images of satellite trail and is counted from the first image ($j=2$). Also t_i^j represents the flash time corresponding to time mark T_i^j which is most closely situated to the left hand side of B_j, and a_{j-1}, b_j, and Δt_i^j are definded as :

$a_{j-1}=$ the distance between T_{i+1}^j and T_i^j on the photographic plate,

$b_j=$ the distance between B_j and T_i^j,

$\Delta t_i^j=t_{i+1}^j-t_i^j$.

In the foregoing we have described the time determination process using the time marks on one side only of the photographic plate. Actual movement of the slit plate has naturally slight vibration in vertical compornent. Therefore, it may be necessary to consider two dimensional analysis of the position of time marks printed both in top and bottom on the photographic plate. However, in practice, by using time marks enough in a short time interval, it seems to be possible to eliminate the quadratic terms in the change of the driving speed of the slit plate.

3. Specification of The Device

1) Slit plate

The width of each slit is not so important for the timing accuracy concerend. By narrowing the slit, however, it becomes possible to reduce the exposure. Accordingly, the accuracy of image of the bright satellite such as ECHO will be improved. This is one of the advantages of the present device.

In general, the more number of the slits, the better the observational accuracy becomes the better. On the other hand, however, we must also take into account the strength and moving speed of the slit plate, and the velocity of the satellite image etc. Hence the number of the slits and slit intervals have to be determined by their balance.

To investigate the images, which are to be photographed by this device provides the following data :

topocentric angular velocity of the satellite	:	$\omega=1000''/\text{sec}$,
focal length of camera	:	$f=1000\text{mm}$
moving speed of slit plate	:	$v=30\text{mm/sec}$,
slit width	:	$d=0.1\text{mm}$,
slit interval	:	$D=6.7\text{mm}$.

The relative-velocity between the focal image of the satellite and the slit plate varies with the direction of each movement, same or not. In our case the both velocities are 25 mm/sec and 35 mm/sec, respectively.

As regards chopped intervals of the satellite trail, we have,

$D\times f_\omega/(f_\omega-v)=1.3$ (mm) for the rel. vel. of 25 mm/sec,

$D\times f_\omega/(f_\omega+v)=1.0$ (mm) for the rel. vel. of 35 mm/sec.

On the other hand, corresponding to each relative-velocities, we get the following exposures allowed for the satellite.

$d/(f_\omega-v)=1/250$ (sec) for the rel. vel. of 25 mm/sec,

$d/(f_\omega+v)=1/350$ (sec) for the rel. vel. of 35 mm/sec.

Therefore, the sizes of photographic image of satellite on the focal plane are estimated as follows :

$$40+5/250=60\ (\mu),$$
$$40+5/350=54\ (\mu),$$

that the size proper to the satellite image being supposed to be $40\,\mu$. In general, the sizes of satellite images photographed in practice will become smaller than the above ones for the short exposures than given above.

The circumstance described above can be explained in the Fig. 3.

In so far as only the measuring accuracy of time marks is concerned, it is possible to increase the accuracy over required one by increasing the speed of the moving slit plate. Provided that the measuring accuracy of the time marks is 10 μ this corresponds to 0.33 msec. in the timing accuracy. Accordingly, if the equipment are designed by the data described above, it will

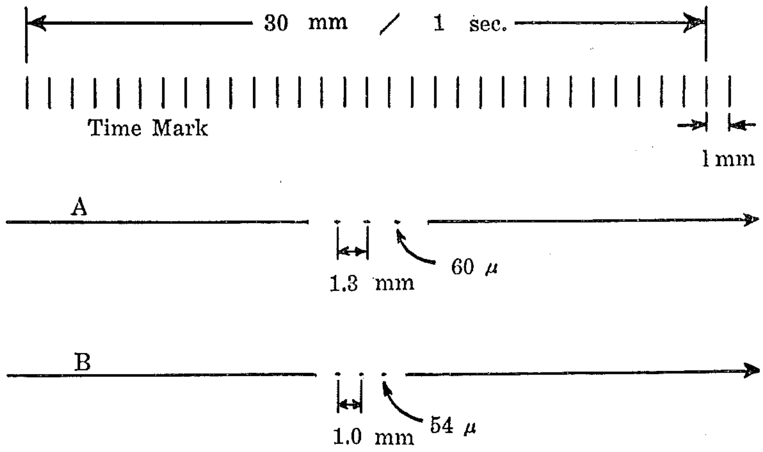

Fig. 3. An Schematic diagram of the photographic images taken with the new timing device.
Case A) The direction of movement of the satellite is equal to that of the slit plate.
Case B) The direction of movement of the satellite is in opposite to that of the slit plate

be enough to obtain the timing accuracy of 1 msec. except the error caused by the ambiguity of photographic image of the satellite. As regards the latter, we can expect the same accuracy in time judging from the experimental results that the measuring accuracy of chopped satellite images in general was within $\pm 5\,\mu$ on the plate (corresponds to $1''$ in second of arc in this case).

As the speed of the moving slit plate, 30 mm/sec. has been supposed in the preceding. In practice, the driving mechanism of the slit plate should be so designed that the speed is changeable in corresponding with topocentric angular velocities of the satellites, in order to keep always the uniformity of photographic images. In such case, the timing accuracy is affected by the velocities to a certain extent. However, this effect will be negligible in the concerned accuracy, except for the extremely lower velocities.

2) Flashing lamp

As described in the foregoing paragraph the timing accuracy depends partially on the accuracy of measurement of time marks by flashing lights. Accordingly, it is desirable to make short the duration of the flash lights as possible to produce sharp time marks. If the duration and speed of the slit plate are supposed to be 10 μ sec and 30 mm/sec, respectively, then the slip of the time mark image becomes 0.3 μ. Accordingly, for the timing accuracy concerned above, it will be out of the question. Hitherto, the fluctuation of the speed of the slit has been disregarded. If the speed is perfectly equal, only the first time mark is needed. In practice, it is improbable, and is subject to some fluctuation. In such case, we have to take larger number of the flash in unit time in proportion to the fluctuation. The present flashing lamp has duration of its flash shorter than 10 μ sec and lamps of over 30 flashes per second are already available. However, even if a considerable fluctuation is contained in the slit motion, it will be practically sufficient to take the number of flash to about 30/sec in order to keep timing accuracy of $\pm$ 1 msec.

3) Recording instrument

In order to record times of the flashing, we may use the strong pulses of electro-magnetic wave, which is generated around a lead-wire by a flash current in flashing tube. As the recording instrument employed, an electromagnetic oscillograph will be suitable. Moreover, it will be possible to use a magnetic tape-recorder. In this case, recording will be made more simply, since the time signals can be directly recorded without amplifier.

4) Situation of slit plate

It is most desirable that the slit plate will be put on the focal plane of the camera. However, this place is occupied by a photographic plate. Accordingly, the location of the slit plate should be designed as closely as possible to the focal plane, so long as the motion of the slit is not disturbed.

In practice the interval between the glass plate and the slit plate can be taken at least within 0.3mm. Therefore, the unclearness of the photographic images of satellite and time marks caused by above interval will not come into question.

4. Block Diagram of Observing Equipments

The brock diagram of observing equipments is shown in Fig. 4.

5. Results of Experiments

Based on the principle described in the foregoing paragraph, the first timing device has been constructed for trial. The experiments and tests of the device have been carried out in October 1965 at the Simosato Observatory belong to Hydrographic Office of Japan, located at the middle part of Japan. In these experiments a simple equatorial camera F/5 of 60 cm focal length, was used equipted with above device.

The general view of the timing device is shown in Fig. 5 a. Fig. 5 b shows a flashing light generator. In Fig. 5 a the mark A shows a Xenon multiple flash tube. The light from the flash tube is guided to two fixed small prisms B (size 3 mm $\times$ 3mm) through a condenser lens attached to the top of the tube A. Then the light is sent to the two second prisms C (same size with B), which are attached to the upper and lower sides of the central one of the three slits E in the slit plate D. The slit plate D is moved parallel to the photographic plate by a driving motor F. The slits E have the size

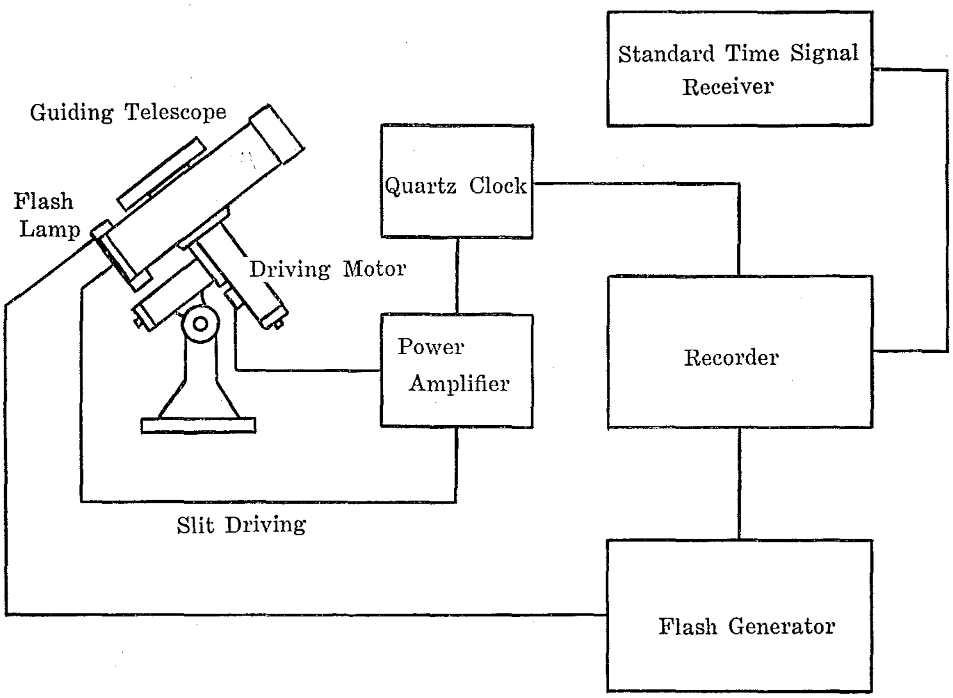

Fig. 4. Block diagram of observing equipments.

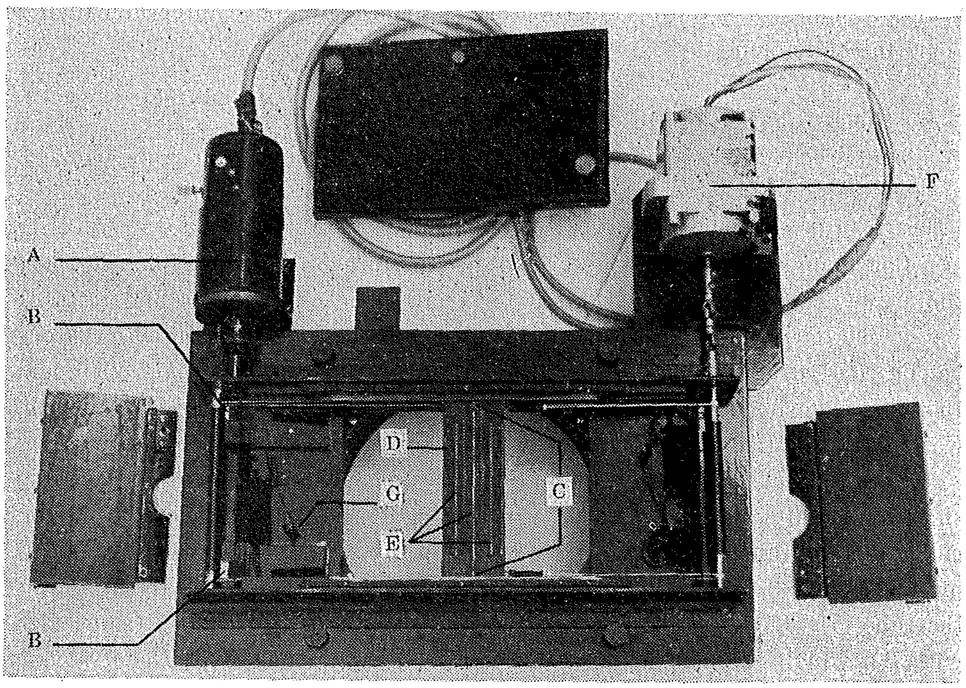

Fig. 5a. Timing device

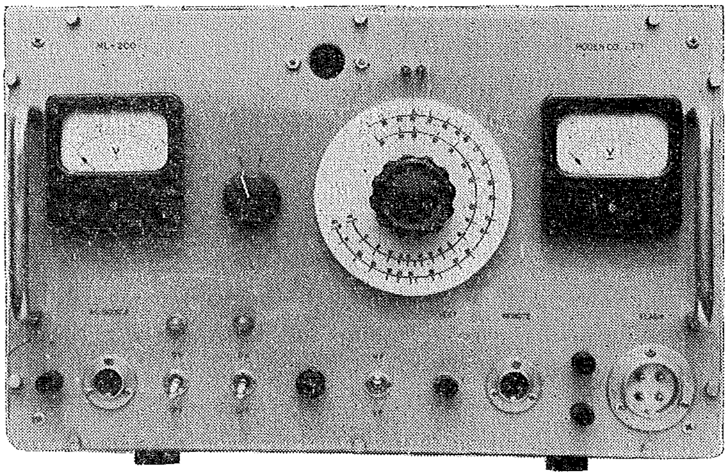

Fig. 5b. Flashing light generator

of 0.1 mm $\times$ 80 mm and their mutual distances are 11 mm. After passing through the prisms C time marks are photographed by the flashing lights. The marks G show electric switches, by which the slit plate D is moved in advance of the operation of the flashing. This makes possible to determine the zero point of time marks. In these experiments, the driving speed of the slit plate was fixed to 40 mm/sec, and the sequence of the flash lights was preferred to 30 flashes/sec.

Although the details of the analysis on these experiment are in progress, their preliminary results are given in the following.

1) The timing may be accomplished in accuracies of $\pm$ 1 msec. in spite of disregarding the quadratic term of the speed change of the slit plate.
2) The vibrations of the slit plate are negligible.
3) The sizes of the Echo Satellite images chopped by the moving slit plate are smaller about 40 μ, and their photographic densities are comparable to 9 th magnitude (with the Oriental SS glass plates and the exposure in two minutes).
4) The measuring accuracies of the time marks are within 2~3 μ.

6. Summary

The following items provide a summary of the relative advantages of this new timing device.

1) A stability of the timing is expected in a long period, because the driving mechanism of the slit plate is very simple.
2) It is possible to attach to a portable camera.
3) Vibration of the slit plate is very small, compared with the ones of a focal plane shutter and a lens shutter.
4) It is possible to bring the slit plate close to the photographic plate, and to improve the clearness of the satellite images in comparison with

the usual satellite cameras.

5) Since the satellite images obtained with this device are point-like, the measurement of the images is very easy and its accuracy is very good, compared with those of the break-like images photographed with the usual one.

6) It is possible to reduce the systematic measuring errors of the satellite positions on the photographic plate caused by the difference in the brightness between the satellite and comparison stars, because this device allows us to reduce only the brightness of satellite.

7) As a wide field is easily obtained for the long slit, the observations of satellites such as ECHO can be made easily, of which predictions are uncertain at present.

8) By using signals of flashing lights instead of a mechanical switch, it will be expected the higher precise timing accuracies.

9) This method does not require special expensive equipments.

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