Positioning Satellite System Using Intersatellite Communication

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A new concept for a positioning system using satellites is presented in this paper. A proposed constellation, consisting of four satellites injected into geosynchronous altitude (GEA) with a high inclination, is connected with intersatellite communication (ISC). Range differences data between satellites measured by an observer are input to the positioning algorithm. First the measurement principle of the system is explained, then the feasibility studies are performed. The system uses a relative time for the measurements, and therefore does not need the degree of accuracy required in the Global Positioning System (GPS). According to the studies performed here, any observer in an area lower than around 60 deg of latitude can, using a 10-satellite constellation, find his or her position with an accuracy of 176.5–499.8 m in case of the system error of 30.8 m. The positioning errors of some cases are evaluated; however, a detailed estimation is left for another paper.

Nomenclature

A, B, C, D	= satellite name and position
A_o, B_o, C_o, D_o	= satellite position at equator plane
a_1, a_2	= constant of hyperbolic equation
b_1, b_2	= constant of hyperbolic equation
c	= speed of light
C/N	= carrier-to-noise ratio, dB
C/N_o	= carrier-to-noise density ratio, dB · Hz
D_{AB}	= range difference
e	= eccentricity
f	= focus
FL_{AG}	= feeder link route
P	= observer's position
P_H	= hypothetical observer's position
R_{AB}	= range
RT_{AB}	= route
T_{AB}	= propagation time
TC_{BG}	= telemetry, tracking, and command link route
x, y, z	= Cartesian coordinate for satellites A and B
x_A, y_A, z_A	= satellite A's position
x_k, y_k, z_k	= observer's intermediate position until solution
x_T, y_T, z_T	= observer's true position
x_o, y_o, z_o	= observer's initial position
x', y', z'	= Cartesian coordinates for satellite B and C

Subscripts

α, β	= two satellite combinations out of A, B, C, and D

I. Introduction

RADIO navigation systems such as Decca, Omega, and Loran[1] have been used for location of ships and are limited to surface use only. Alternatively, the Navy Navigation Satellite System (NNSS)[2] and the Global Positioning System (GPS), which expand positioning capability to the space sector, have been developed. Because of its low-altitude orbits, the NNSS requires numerous satellites to cover any observer on the Earth's surface at any time. The GPS uses a minimum of 18 satellites to cover the Earth's surface and requires extremely accurate atomic clocks to keep synchronous time among satellites operating independently. The ground control station (GCS) must maintain strict control of time and only short periods of visibility are available.

The positioning satellite system described in this paper is called the method of positioning satellite system (MEPSS). The MEPSS distributes 10 satellites to cover the Earth's surface excluding in the two polar regions. The minimum number of satellites needed for positioning is four, which is the same number needed for GPS. Satellites are linked by intersatellite communication (ISC).

II. Principle of Navigation

A general principle of positioning used by satellites is that the position of an observer will be found at the crossing point of the three circular surfaces whose radii are the ranges between the observer's location and the three satellites' locations, which are already known by orbit determination. This primitive method needs to measure the range between the observer and the satellite, requiring the observer to carry a transmitter, which may be a heavy burden for him.

Another method applicable for low altitudes is that the observer can find his or her position when an assumed trajectory, based upon the observed Doppler shift history, is drawn so that it coincides with the actual trajectory. The ARGOS[3] and the DCS[4] of MOS-1 (Marine Observation Satellite-1) of NASDA have used the Doppler navigation system (DCS, ARGOS).

The GPS uses a measurement of time instead of range to avoid the transmitter. An unknown clock bias existing in the satellite is eliminated by installation of atomic clocks and another bias in the observer's clock is eliminated by one additional satellite. The triangular geodesic principle is common to the GPS and the MEPSS; however, a different measurement method is proposed here. The observer receives two range signals from the two satellites arrayed sequentially and can find the range difference between them without a transmitter. The signal flow is such that one satellite generates the original signal for the observer and for the adjacent satellite, which relays the received signal to the observer through ISC. A combination of three range differences among four satellites is used as input to an algorithm to find the observer's position.

A. Geometrical Scheme

1. Range Difference Measurement of Two Satellites

Figure 1a shows a coordinate system where two satellites, A and B, are located on the x axis and symmetrically positioned about the y axis. When position P satisfies the condition, "distance AP minus BP is constant," the point P exists on the surface of a hyperbolic curve. This means that the range difference measurement defines a surface on which the ob-

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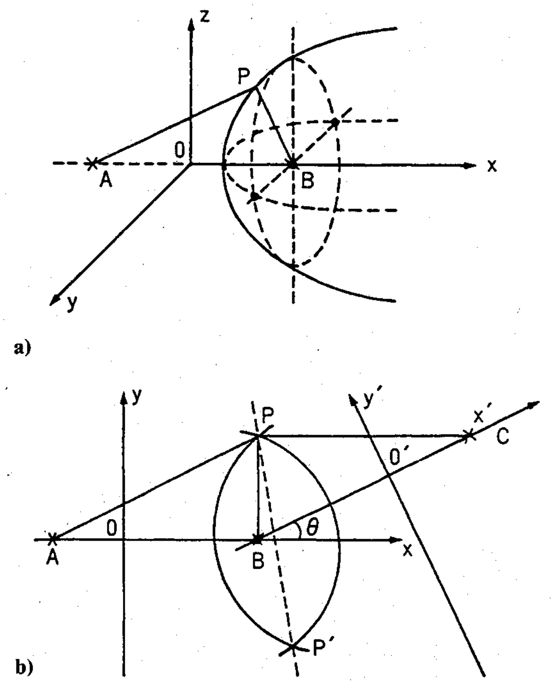

Fig. 1 Two Cartesian coordinate systems, with satellites located at the focus points, showing hyperbolic surface and curves having a constant range difference in a) two-satellite case and b) three-satellite case.

server exists. Equation (1) defining the relationship as drawn in Fig. 1a is shown below:

$$\frac{x^2}{a_1^2} - \frac{y^2 + z^2}{b_1^2} = 1 \tag{1}$$

where $f = \pm a_1 e$ is the focus,

$$e = \frac{\sqrt{a_1^2 + b_1^2}}{a_1}$$

is the eccentricity, and $AP - BP$ is the difference.

2. Range Difference Measurement of Three Satellites

Three satellites, A, B, and C, are considered here. A and B are located as shown in Fig. 1a. C is located on an x' axis such that a line $\overline{BC}$ intersects the x axis with angle θ. The y' axis is drawn in the xx' plane. The new z' axis is drawn in the plane perpendicular to the xx' plane. In the xyz coordinate plane, two hyperbolic surfaces are drawn. One has a constant difference between AP and BP and the other has a constant difference between BP and CP.

The observer P exists on a curve made by the intersection of two hyperbolic surfaces that are drawn in the plane perpendicular to the xy and $x'y'$ planes. The hyperbolic surfaces are axial symmetric to the x and x' axes, respectively, and plane symmetric to the xy and $x'y'$ planes. Figure 1b shows the three-dimensional structure cut by the xy and $x'y'$ plane. If the observer's altitude data are equivalent to the distance to the xy and $x'y'$ plane, his or her position will be determined at the crossing point of the hyperbolic curve. The second hyperbolic curve is shown by Eq. (2):

$$\frac{x'^2}{a_2^2} - \frac{y'^2 + z'^2}{b_2^2} = 1 \tag{2}$$

3. Range Difference Measurement of Four Satellites

Four satellites, A, B, C, and D, are considered. Three hyperbolic surfaces are drawn by AB, BC, and CD. A schematic drawing for the four-satellite case can be shown; however, the geometrical scheme of a simple case is already shown in Fig. 1b. Therefore, the similar but more complex four-satellite case is not shown here. The observer exists at the point where the three surfaces intersect.

B. Numerical Calculation for Positioning

There are two typical methods to determine position. One is an algebraic method in which a system of second-degree algebraic equations with three unknowns must be solved. The second one consists of some numerical calculations, one of which is a steepest descent method; a method of getting the solution is described in the following paragraph.

Satellite position is defined as (x_A, y_A, z_A) for satellite A. The same system is applicable when defining satellites B, C, and D. A hypothetical observer's position P_H near the true one is assumed to be as (x_τ, y_τ, z_τ). We can find a range difference between the ranges AP and BP. The same method is applicable when finding range differences for BC and CD. Data acquired from actual measurement is defined in Eq. (3):

$$D_{AB} = AP - BP \tag{3}$$

where D_{AB} is the range difference among A, B, and P. At first, P does not coincide with the hypothetical observer's position P_H, and therefore the calculated range difference would not coincide with the measured figure. The difference between the two range figures is described by Eq. (4)

$$f(x,y,z) = \sum_{\alpha,\beta} \{\sqrt{(x - x_\alpha)^2 + (y - y_\alpha)^2 + (z - z_\alpha)^2} - \sqrt{(x - x_\beta)^2 + (y - y_\beta)^2 + (z - z_\beta)^2} - D_{\alpha\beta}\}^2 \tag{4}$$

where α and β are combinations of A, B, C, and D. If the hypothetical observer's position is swept around the true position, and if the two points coincide with the actual position, then Eq. (4) has a minimum value toward which the slope is decreasing. Therefore, an initial point P_H given near the true point will converge into the true position through the computation of the steepest descent method algorithm shown in Fig. 2.

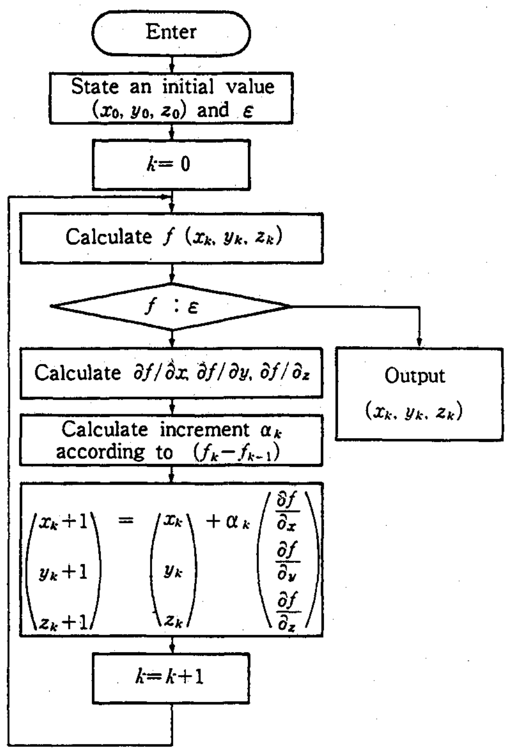

Fig. 2 An algorithm for positioning.

III. Constellation

The constellation configuration design defines a fundamental structure of the MEPSS. Figure 3 shows an apparent Earth trajectory of the typical four satellites. The figure-eight orbit crosses the equator plane at A_o, B_o, C_o, and D_o, which are located every 36 deg on longitude. The inclination defines a coverage of two hemispheres and 6.5 deg is adopted here.

The rationale for the design is as follows: The figure-eight orbits provide a widely distributed constellation by which good triangular geodesic conditions are satisfied, i.e., a long baseline and a wide triangle area made by three apexes at the satellite position. Even if three sequential satellites are on a straight line, the fourth satellite will make a triangle with the first and third satellites of the sequence. To keep this condition constant, the relation between the sequential two satellite's position in the orbits is equivalent to 120-deg separation in mean anomaly. The 36-deg separation satisfies the four satellites' visibility above a 5-deg elevation to an observer located at the equator, and introduces global coverage by 10 satellites. Figure 4 shows the relationship between the inclination and the upper limit of latitude at which the four satellites are available. A higher inclination brings a better triangular geodesic condition and a lower latitude limit: therefore, a compromise is needed. Table 1 shows the calculated results of some cases. A case with 70-deg latitude, 5-deg elevation limit and 6.5-deg inclination would give almost all equal coverage for the two hemispheres. Based upon those conditions, the global coverage is shown in Figs. 5. The inside of the convex curve shows the available visibility above the 5-deg elevation. Almost all areas lower than 60-deg latitude are covered, excluding the areas that lie outside the hatched edges of the coverage. Figs. 5a and 5b show two global coverage maps having a 6-h interval.

IV. Measurement Method

A. Measurement of Range Difference

The simplified model shown in Fig. 1a is assumed to explain the measurement principle. The range difference is *ABP* minus *AP*, which is acquired from a comparison of two range signals received by the observer. An adoption of a pulse signal as the range signal is simple way, but since a large peak power and a tremendous range ambiguity make the measurement system difficult, the pulse signal should not be adopted. A method of pseudonoise (PN) code, identical to the one used by the GPS,[5] is suitable. Furthermore, a combination of simple shift registers easily produces a long code having a range span significantly larger than GEA range, without ambiguity. The range difference is defined by Eq. (5)

$$D_{AB} = c(T_{ABP} - T_{AP}) - R_{AB} \tag{5}$$

where T_{AP} is the propagation time between *A* and *B*, and R_{AB} is the range between satellites *A* and *B*. When the observer receives the PN code, the correlator synchronizes the received codes with the phase of the shift registers of the local codes. Then a comparison between the phases of the two shift registers shows the time difference, $T_{ABP} - T_{AP}$ in Eq. (5), if the clock rate of the shift register is used as a time signal. These basic principles should be applied to the sequential four out of 10 satellites. The code characteristics are defined by the satellite constellation and clock frequency. A code length is defined by a maximum range, which is calculated under the following conditions: two satellites are shifted 8500 km from the equator plane, the observer is at 65-deg latitude, and for the inclination, a value larger than 6.5 deg is assumed. At this time, the maximum range *ABP* is around 80,000 km. If a PN code of 1-MHz clock rate is used for coding, then a 0.267×10^6 cycle is necessary to code the maximum length. A 20-stage shift register can code this range and has $2^{20} - 1 = 1{,}048{,}575$ bits in a cycle. When the 1-MHz clock is slightly shifted to 0.9536752 MHz, the shift register recycles every second. If the integral second is synchronized with the start of this sequence, the observer can determine the precise second from the code. The time can also be calculated precisely by counting the bits from the start of one bit level and then, using a high-speed counter, counting the wave-forms within one bit. Indications of larger time intervals, such as minutes, hours, and days, are also included in the telemetry. This time is equal to the satellite position through the orbit prediction data. The 20-stage shift register is equivalent to a Gold code[6] with two shift registers of 10 stages each.

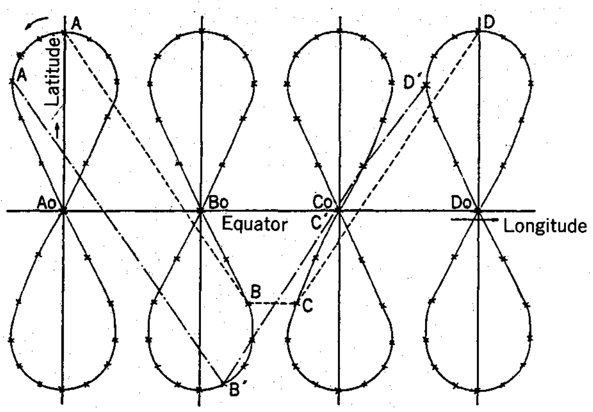

Fig. 3 Satellite constellation for four-satellite case: Satellite position in each figure-eight trajectory has 120-deg mean anomaly difference, and the *A B C D* and *A′ B′ C′ D′* cases have 6 h difference.

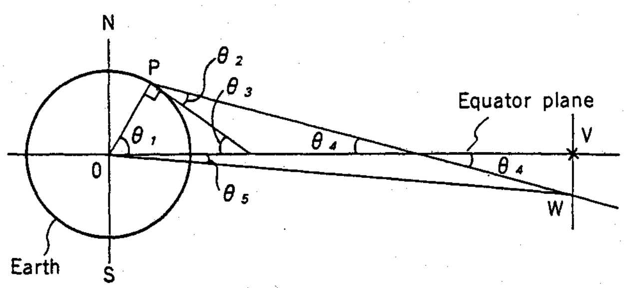

Fig. 4 Relationship between the observer point *P* and the inclination θ_5. θ_1 is latitude and θ_2 is look angle.

Table 1 Relationship between the upper limit of latitude for the observer and the orbit inclination. θ_1, θ_2, θ_5, and *VW* correspond with Fig. 4

Latitude, deg θ_1	Elevation, deg θ_2	Shifted range[a], km *VW*	Orbit inclination, deg θ_5
75	0	3,062	4.2
70	5	4,684	6.5
65	5	8,523	11.5
65	7	6,999	9.5
60	5	12,583	16.7
60	7	10,959	14.6

[a] *VW* shows the shifted range from the equator plane to the north or south direction.

B. Time Standard

The time standard generated by a quartz crystal is used as the source for both the range signal and the time information. The quartz crystal's performance is determined by stabilities of the aging effect and the temperature environment. In the MEPSS, it is assumed that the satellites move in a figure-eight ground trajectory and the maximum deviation from the equator plane is 8500 km. The satellite movement per day is approximately 34,000 km. If 1-m accuracy per day is required, the stability requirement is 1.16×10^{-8} per day. In the case of TIMATION (Time Navigation),[2] the aging rate was observed

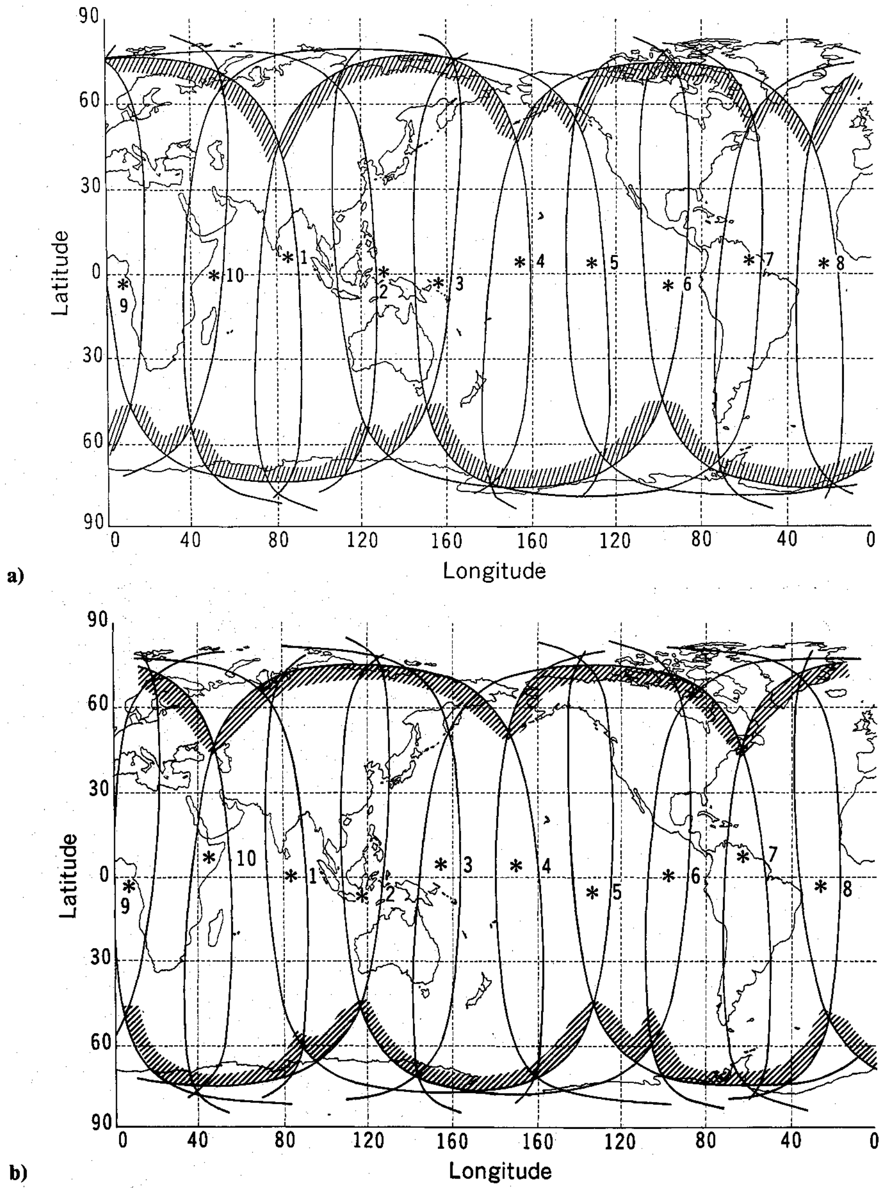

Fig. 5 Earth coverage of 10 satellites: 108-deg mean anomaly differences are given to 10 satellites and the contours show the look angle above zero elevation angle from the observer, and 4 or 5 satellites are visible within the hatched area; a) and b) are 6 h different.

as 2 parts per 10^{12} per day, which is much lower than the requirement. In the MEPSS, the GCS can always monitor the satellites. Therefore, a present frequency and a frequency drift coefficient based upon observed data are recognized and transmitted to the satellites for the latest telemetry word. The observer can use them immediately for positioning. The continuous visibility is a superior characteristic of the MEPSS as compared to the GPS. This is one of the reasons that the MEPSS satisfies its system performance by adopting a simple quartz crystal rather than the complex atomic clock required for the GPS. Another stability factor, a short-term drift, may be caused by the thermal environment. It is well known that very stable situations have been obtained in the past. In the case of TIMATION,[2] even though the temperature environment changed from -2 to 24°C, the crystal temperature was maintained at 24 ± 0.1°C. The temperature coefficient is 1 or 2 parts in 10^{12} per 1°C. Such stability is easily realized by an oven under temperature control. The long-term stability performance depends on the characteristics of the crystal element itself. Stability levels sufficient to satisfy the above requirements are easily obtainable with a commercial-use quartz crystal.

C. Measurement Signal

Figure 6 shows a signal structure. The signal consists of a range signal and telemetry data. The range signal is assumed to use Gold code,[6] which is composed of more than two PN codes driven by the clock, and the telemetry data include navigation aids, satellite status data, quartz crystal compensation data, etc. The time in the satellite can be very accurately maintained by the GCS based upon the national standard. The two signals originally generated from the common quartz crystal, range, and telemetry are modulated on the same frequency carrier to unify the signal into the quadrature phase modulation scheme and both signals are kept in a very accurately synchronized relation.

For the GPS, the telemetry data has a frame of 1500 bits and a data speed of 50 Hz. Data is updated every 30 s. This same scheme would be applicable to the MEPSS system; Fig. 7 shows signal routes among the four satellites, the observer, and the GCS.

When the signal (3) in Fig. 6 is received by the observer, the content of the signal shows the time of satellite A, which can be used to find satellite A's position through orbit determination and prediction computation. This means that the observer

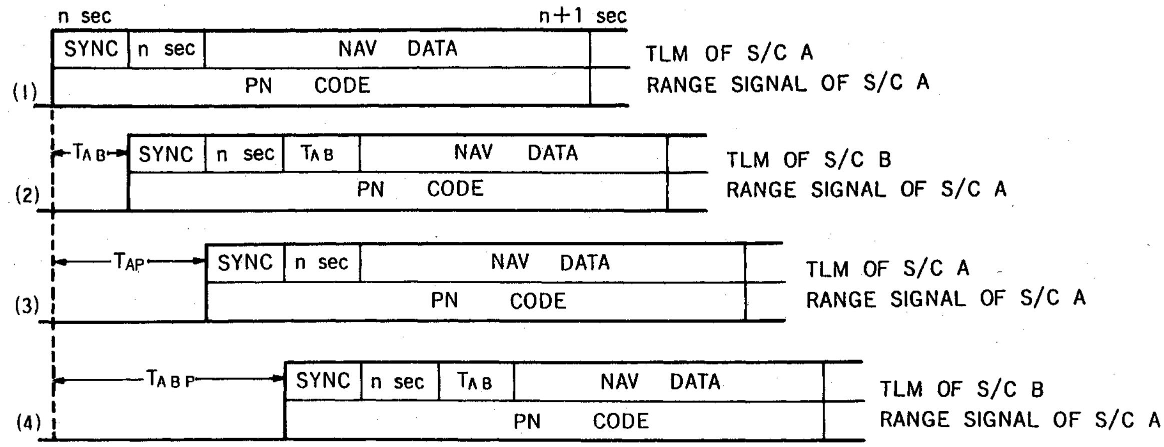

Fig. 6 The direct and relayed signal structures and timing chart for an observer: (1) in original signal, (2) in transmitted signal from satellite *B*, (3) in the direct received signal, and (4) in relayed and received signal. SYNC: synchronization; S/C: spacecraft.

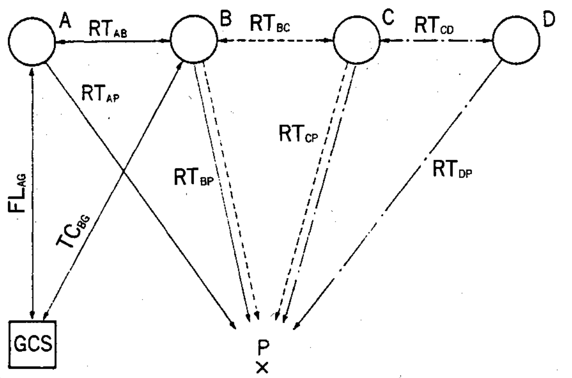

Fig. 7 Signal routes among four satellites *A*, *B*, *C*, and *D*, the observer *P*, and the ground control station.

understands that the signal (3) in Fig. 6 is generated from the fixed point. The original signal is relayed to the observer through the route RT_{AB} and satellite *B*. Then the observer receives both signals (3) and (4) in Fig. 6 and finds the range difference $c(T_{ABP} - T_{AP})$ in Eq. (5) from a comparison of the two received signals. R_{AB} in Eq. (5) and satellite *B*'s position when the signal is passed must be known. The signal (1) in Fig. 6 is received in satellite *B*, where it is demodulated and decoded. Then a part of the demodulated, decoded data is returned to satellite *A* through the route RT_{AB} in Fig. 7. Satellite *A* transmits both the returned and the original signals to the GCS through the feeder link FL_{AG} in Fig. 7, where the range difference R_{AB} in Eq. (5) is detected by comparisons of the two signals. The calculated R_{AB} is transmitted to satellite *B* through telemetry, tracking, and command link TC_{BG} and edited as T_{AB} in the updated telemetry word. The observer can find satellite *B*'s position by the time T_{AB} that *B*'s time lags satellite *A*'s time and the range difference R_{AB} in Eq. (5). Therefore, the observer can draw the hyperbolic curves from the two fixed points as shown in Fig. 1a. The same method will be applicable to *BC* and *CD*; the observer can then find his or her position.

V. Link Design

A. Link Design for Observer

Major factors of the downlink to the observers are dependent upon the characteristics of the satellite antennas, the observer antenna, the transmission power, and the receiver noise figure (NF). In the MEPSS, attitude control is assumed to be a three-axis stabilized type and the orbit is at GEA with high inclination. Under such conditions, even considering relative movement between the satellite and the observer, the satellite yaw plane is always perpendicular to the orbit plane, and the yaw axis is always pointing to the center of the Earth. Therefore, the satellite should be designed such that when the satellite antenna axis is aligned to the yaw axis, the main lobe points to the center of the Earth without any angle control. A beam width to cover the Earth is around 19 deg, which could be provided by a 19-dB gain reflector type antenna fixed to the satellite body. The GPS uses L-band frequencies (1.575 and 1.227 GHz) with the main one being 1.575 GHz. Therefore, the link analysis considered here will also use this frequency (1.575 GHz). To avoid complex antenna direction control, the observer must use a wide beam antenna, with a 70-deg beam width and 7.9-dB gain. The link budget based upon these parameters is shown in Table 2. C/N_o here is 39.7 dB · Hz if the bandwidth of the navigation data is 200 Hz. The required C/N at BER 10^{-6} is 10.5 dB, with an expected margin of 6 dB. C/N_o of 38.6 dB · Hz was obtained under similar conditions.[5] Acquisition time of the range signal is dependent upon C/N_o and the correlator mechanism. C/N_o cannot define the time, but 39.7 dB · Hz is a reasonable figure for PN code acquisition.

B. Link Budget for Intersatellite Communication

Assume that the maximum range between the satellites is 31,400 km and 26 GHz of Ka-band frequency for this link. The Tracking and Data Relay Satellite (TDRS)[7] has been equipped with a narrow beam antenna to obtain a high-bit-rate information transmission, and the angle acquisition mechanism posed an engineering challenge.

The MEPSS, however, needs only a specific PN code transmission, so the required bandwidth is the correlator loop band, which could be 200 Hz for acquisition and narrower after that. A medium gain of 30 dB and a 5-deg beamwidth antenna is enough to satisfy the requirement of the marginal link condition. Such a wide beam antenna could eliminate the necessity of the closed-loop control of the antenna. Angle uncertainties for the antenna pointing originate from the receiving and transmitting sides of the satellites. A position uncertainty of around 1 km on the part of the receiving satellite divided by the range of 31,400 km between the satellites gives an angle uncertainty as seen from the transmission side. The attitude control of around a tenth of a degree is an angle uncertainty of the reception side. Both uncertainties are smaller than the beamwidth. This type of antenna, under such conditions, would not need the closed-loop control, because the angle uncertainty is in the vicinity of the line of sight. Therefore, angle acquisition is achievable by command control based upon the computed prediction without a search mode.

A small-size phased array antenna consisting of 19×19 patch antenna elements is a reasonable candidate. The an-

Table 2 Link budget, case A: link between a satellite and an observer; case B: link between the satellites; k in item 8 is Boltzmann's constant

Item	Case A	Case B	Remarks
Transmit power	3 BW	0 dBW	Case A: 2 W, Case B: 1 W
Feeder loss	3 dB	3 dB	Nominal value
Tx[a] ant. gain	19 dB	30 dB	Case A: $BW^b = 19$ deg and $D^c = \phi0.66$ m, Case B: $BW = 5$ deg and $D = \phi0.15$ m
EIRP[d]	19 dBW	27 dBW	(4) = (1) − (2) + (3)
Span loss	189.5 dB	210.7 dB	Case A: R = 36,000 km and f = 1.575 GHz, Case B: R = 31,400 km and 26 GHz
Incident power	− 168.5 dBW	− 183.7 dBW	
Rx[e] G/T^f	− 20.4 dB	− 2.3 dB	Case A: ant. gain = 7.9 dB and NF = 1.5 dB, Case B: ant. gain = 36 dB and NF = 5 dB
C/N_o	39.7 dB · Hz	42.6 dB · Hz	(8) = (6) + (7) + (k), K = 228.6 dB

[a]Transmit. [b]Beamwidth. [c]Diameter. [d]Equivalent isotropically radiated power. [e]Receive. [f]Gain-to-noise temperature ratio.

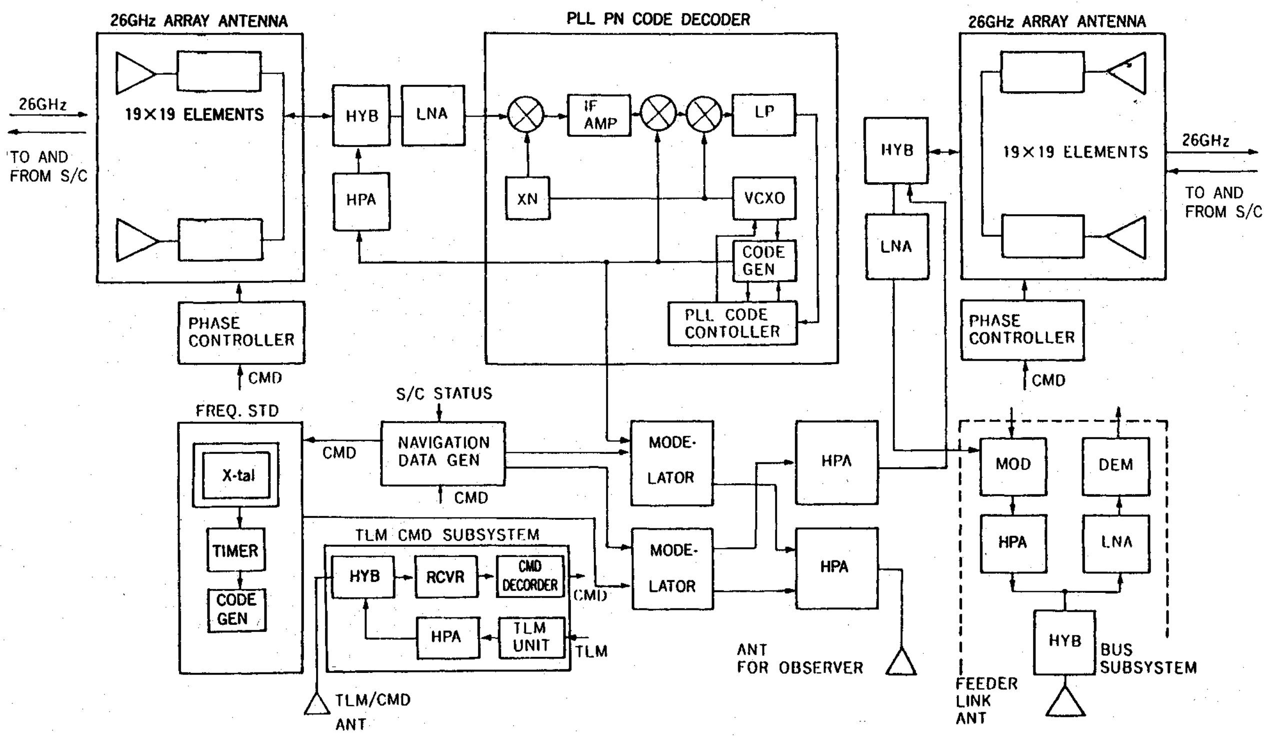

Fig. 8 Block diagram of the positioning satellite C^3 subsystem.

tenna aperture is a flat plate and should be attached to the roll/pitch plane of the satellite.

The link budget, based upon the above parameters, is shown in Table 2. Once the satellites are injected into their orbit, the group of satellites are continuously connected by the ISC link. The tedious acquisition of the PN code occurs only once; after that, synchronized code transmission and reception can be maintained unless an abrupt link breakdown occurs. If the Doppler effect makes the initial acquisition difficult, the Doppler compensation[7] technique used by TDRS is an effective alternate method.

VI. Equipment Installed in Satellite

A. Mission Equipment Configuration

The mission payload configuration is shown in Fig. 8. The original signal is generated by a quartz crystal oscillator, which is kept within a very constant temperature environment by an oven, and the clock, which is used by the range signal and all equipment. The ISC uses a phase-array antenna consisting of patch elements with a beam steerable range of ± 35 deg in the roll/pitch plane and a constant beam pointing in the roll/yaw plane. The patch elements are placed in a 19 × 19 square array on the flat plate. The 19 elements in the roll/yaw plane array are fixed-phase synthesized type, and the 19 elements in the roll/pitch plane array are variable array-phase synthesized type. This antenna is used on both receiving and transmitting satellites. Their beams are controlled by commands from the GCS according to the predicted satellite movement.

When a satellite is illuminated by an adjacent one, the signal passes through the low noise amplifier (LNA), where the frequency is converted to the intermediate frequency (IF). The signal is then fed to the code and carrier tracking loop, where the local code is correlated with the received signal by a sweep function based upon the expected code phase and carrier frequency. Both are then synchronized through the acquisition process. The decoded data are fed to a modulator and then to the observer as the relayed signal, and also fed to the high-power amplifier (HPA) for return to the previous satellite to provide a counting range between the satellites. The original signal is generated at the frequency standard unit. It is then fed to the modulator, then to the observer as the direct signal, and finally fed to HPA for the adjacent satellite. The telemetry (TLM) and command (CMD) subsystem can receive a great deal of processed data from the GCS, including the range difference between satellites through telemetry, tracking, and command (TT & C) link. The subsystem then feeds this data to the navigation data generator to update. The latest navigation data is provided to the observer with the range data. The feeder link could also transmit the source data for the range difference between satellites from the GCS.

B. Satellite Configuration

Now that the outer configuration of the satellite has been explained by the three-axis stabilized type, the weight and power specifications further clarify the satellites' concept. The weight and power are summarized in Table 3, the elements of which are included in Fig. 8. Those figures are based on estimations of past payloads. According to a rough estimate to find the satellite's scale, the mission payload configuration is similar to KIKU-5,[8] which is the Experimental Test Satellite V of NASDA and was launched in 1985. The estimated weight of the mission payload of the MEPSS satellite is 114 vs 100 kg of KIKU-5. The power is 135 vs 120 W. The two satellites can therefore be considered in the same category. KIKU-5 is a geostationary satellite used for aeronautical control experiments, and weighed 550 kg at the beginning of its life.

VII. Calculation

A. Positioning Error Budget

The positioning error sources come from the uncertainty of the satellite position, fluctuation of the original signal, and the measuring capability of the observer's receiver. The telemetry word that the observer can read in his or her signal should include the latest six orbital elements, by which the observer can determine an accurate satellite position when a time is designated. The time in the satellite is controlled by the GCS and the accuracy is kept within the national standard, 1 μs. This is equivalent to 0.39×10^{-9} m, which is considered negligible.

Table 3 Weight and power summary of mission payload

Item	Quantity	Weight, kg	Power, W
26 GHz array antenna	2	64	—
Phase controller	4	16	40
LNA	4	4	30
PLL[a] PN code decoder	2	5	5
Frequency standard	2	3	2
Navigation data generator	2	4	15
Modulator	2	6	3
L-band HPA	4	6	30
Ka-band HPA	2	4	10
L-band antenna	1	2	—
Total	—	114	135

[a]Phase lock loop.

Table 4 System error budget

Item	Error, m	Remarks
Ephemeris prediction	7.03	GPS case study[9]
Range code fluctuation	≃ 0	Negligible small
Code loop at satellite	21.2	Regeneration at $C/N_0 = 40$ dB · Hz and $BW^a = 50$ Hz
Code loop at observer	21.2	Same
Propagation error	0.5	Nominal value
Range counter resolution	1.5	100 MHz clock
Total	30.8	rms

[a]Bandwidth.

The uncertainty of the six elements calculated at GCS depends on error factors in the location of ground stations, its measurement hardware performance, the orbit determination algorithm, data bases of the Earth model, etc. The error estimation to be used here could not be performed without a fixed condition. Therefore, the GPS error estimation is used here; that is, 7.03 m accuracy.[9] The next factor to be considered is fluctuation of the range signal, which is equivalent to that of the quartz crystal. As already discussed in Sec. IV.B, its long- and short-term drifts are negligibly small.

Code lock loops of the range signal are located at the observer's receiver and the ISC receiver of the satellite. When code regeneration is performed, the phase uncertainty of the clock is caused by noise components of the signal. This means that it is a function of the receiving power and the loop bandwidth. A wide-band loop is used for the acquisition phase, even though less accuracy is expected. However, longer integral times compensate for it, and a narrow-band loop is used in the nominal tracking phase and contributes to better accuracy. The system error budget is shown in Table 4.

When the signal propagates into the ionospheric layer, a range error due to diffraction occurs. This is small[5] when it is compared to the other errors, and could be compensated for by computation based upon the layer model and its elevation angle. Figures used in GPS in Table 4 are also used here. To find the range difference, a high-speed counter will be used. The range resolution depends upon the maximum frequency, i.e., the quantization level of the measurement.

B. System Error Evaluation

Based upon the error sources discussed in the previous section, positioning errors are estimated using a simple model in which the errors in Table 4 are put in a geometrical model consisting of the satellite positions and the range differences. Case A in Table 5 shows a three-satellite case where the observer is at elevation zero, i.e., his or her altitude is given, and five cases of the observer positions at the same longitude and at five different latitudes. Case B shows a four-satellite case under the same longitude and latitude conditions as case A.

VIII. Conclusion

The possibility of a new positioning satellite system concept using 10 satellites is compared to the 18-satellite system of the GPS. The MEPSS utilizes relative time for the range difference measurement and absolute time for the apparent satellite position finding. The reason that a less-severe requirement for the time is sufficient has been explained in Sec. IV.B. The NASA TDRS is the only ISC system in use today. However, many new applications may be enabled with this proposed system because the satellite constellation could overcome visibility over the horizon limits that the geostationary satellite without ISC cannot achieve. The specific Ka-band and optical region without attenuation of atmosphere absorption will be the subject of future technical discussion. Using satellites as ISC and a platform for remote sensing is becoming popular; however, little has been written about using satellites for triangulation. A multisatellite system and ISC could provide the basis for a triangulation network, and this paper contributes to this concept.

Table 5 Position error, X is direction to 135-deg longitude from the center of Earth, Y makes right-hand coordinate with X and Z axes, and Z is north direction

Observer position	Case A			Case B min/max			
Latitude/Longitude, deg	X, m	Y, m	Total, rms	X, m	Y, m	Z, m	Total, rms
0/135	39.1	109.6	116.4	78.1/274.3	48.5/48.7	143.5/406.6	170.3/486.3
15/135	39.1	109.1	116.0	78.8/268.2	48.5/48.5	144.0/402.7	171.1/485.9
30/135	39.1	110.4	117.1	80.7/278.3	48.7/48.7	146.8/403.9	174.3/493.1
45/135	39.6	112.8	119.7	83.9/292.1	49.4/49.1	151.2/412.0	180.0/507.4
60/135	40.2	116.7	123.7	88.2/309.0	50.1/50.1	157.0/422.7	186.8/526.1

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References

[1]Tsuchiya, T., *GPS: A Precision Positioning System by Satellite*, 1st ed., Institute of Japan Geodesy, Tokyo, 1986, pp. 13–34.

[2]Bartholomew, C. A., "Satellite Frequency Standards," *Navigation*, Vol. 25, No. 2, 1978, pp. 113–120.

[3]Levanon, N., and Ben-Zaken, M., "Random Error in ARGOS and SARSAT Satellite Positioning System," *IEEE Transaction on Aerospace and Electronics Systems*, Vol. AES-21, No. 6, 1985, pp. 783–790.

[4]Shimada, M., Ogawa, E., and Nagayama, H., "DCS Data Processing of MOS-1," *Study Report of Space, Aeronautical and Navigation, Electronics*, Institute of Electronics, Information, and Communication of Japan SANE, Tokyo, Dec. 11, 1987.

[5]Spilker, J. J., Jr., "GPS Signal Structure and Performance Charactristics," *Navigation*, Vol. 25, No. 2, 1978, pp. 121–146.

[6]Anon., "Tracking and Data Relay Satellite System (TDRSS) User's Guide," NASA Goddard Space Flight Center, Rev. STDN 101,2, Sept. 1984, pp. 3-1-3-138.

[7]Flanklin, S. B., "TDRSS-User Satellite Acquisition and Tracking," *Proceedings of the International Telemetring Conference*, Vol. 14, 1978, pp. 671–682.

[8]Murayama, H., Yamada, S., Kasai, R., Ohmura, M., and Yamaguchi, T., "ETS-V System," 12th AIAA Communication Satellite Conf., AIAA Paper 86-0723, San Diego, CA, March 1986.

[9]Russel, S. S., and Schaiby, J. H., "Control Segment and User Performance," *Navigation*, Vol. 25, No. 2, 1978, pp. 166–172.

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