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SELECTION OF GPS SATELLITE CONSTELLATIONS FOR
SPACECRAFT ORBIT DETERMINATION

by

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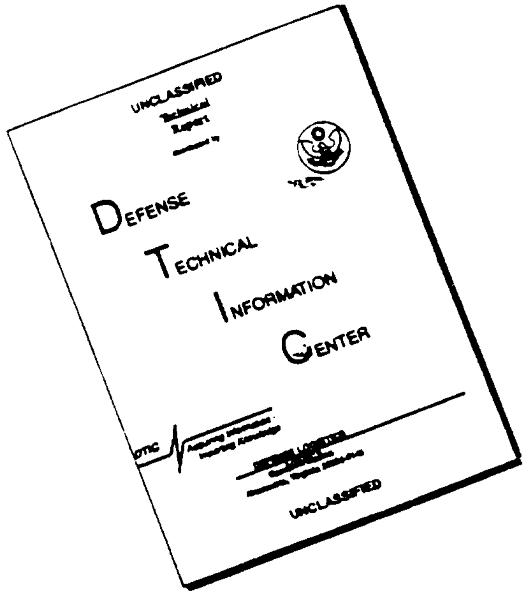

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ABSTRACT

As far as global positioning systems (GPS) being used in the determination of spacecraft orbits is concerned, they will increase the autonomous navigation capabilities of spacecraft, reducing equipment carried on board satellites, and saving on ground stations. In conjunction with this, it will be possible to increase precision and reliability. However--different from ground utilization environments--it is necessary to reanalyze and solve such problems as satellite selection, error calibration, high dynamics, antenna set ups, and so on, associated with the use of GPS in determining spacecraft orbits. This article considers such things as atmospheric interference, signal propogation paths, relativity theory effects, satellite window stability, and so on, putting forward principles of satellite selection based on the requirements of different tasks as well as a different type of method associated with opting for the use of weighted least square methods, causing all visible satellites to participate in positioning calculations.

I INTRODUCTION

The proliferation and complexification of astronavigational missions require spacecraft to possess highly autonomous navigation and guidance functions. Satellite positioning technology is capable of supplying these. Acting as a satellite based navigation system, global positioning systems (GPS) possess such characteristics as all weather, accurate, close to continuous coverage of the surface of the earth as well as medium and low earth orbits. User equipment is simple and inexpensive. It is capable of carrying out positioning, speed measurements, time service, and even attitude determination. In such areas as aviation, maritime navigation, land navigation, map making, and so on, it has already achieved satisfactory applications.

As far as the use of GPS in orbital determinations associated with such spacecraft as space shuttle medium and low orbit satellites, space stations, spaceships, and so on, is concerned, it possesses a good number of unique advantages--for example, it is possible to reduce and simplify earth observation stations, lower monitoring costs, make orbital corrections in close to real time, eliminate delays associated with information going back and forth between satellites and earth, save on ground data processing, increase spacecraft operating efficiencies, and reduce many types of errors associated with traditional telemetry and control systems, such as, electric wave propogations errors, the spin of the earth, polar movements, gravity fields, telemetry station positions, and so on. Since 1982, the U.S. has test flow a type of two channel GPS receiver on Landsat-4, Landsat-5, space shuttles, as well as the Navy's two satellites for military use, clearly showing its superior efficiency compared to other telemetry and control systems.

GPS was designed for medium and low dynamics users close to the surface of the earth. When it is used for spacecraft positioning, cases of "environmental inappropriateness" will appear. First of all, changes in error sources make reciever positioning models partially inappropriate for use any more. High dynamics movements not only produce effects on receiver tracking circuits. Due to relativity effects, they lead to relatively large errors. In particular, changes in satellite reception windows and frequent replacements will give rise to increases in positioning errors as well as fluctuations, and so on. Taking GPS and successfully using it for spacecraft, that is--with the presumption of maintaining appropriate positioning accuracy--using it on moving space subscribers over wide ranges with high dynamics, requires solving such problems as are set out in the discussion above. This article, first of all, considers all the various factors in satellite selection when using GPS for spacecraft orbit determinations as well as indices of satellite selection, in the end, putting forward a method opting for the use of least square methods by all satellites which can be used for positioning.

II. SATELLITE CONSTELLATION SELECTION

In general situations, GPS positioning requires the use of measurement signals from 4 GPS satellites. Moreover, in the majority of situations, the number of visible satellites is greater than 4. This then requires the selection, among the visible satellites, of 4 satellites which are, in a certain sense "optimum", to use in positioning.

GPS three dimensional positioning errors are normally expressed as [1]

$$m_p = PDOP \cdot \sigma_0 \qquad (1)$$

In this, mp is three dimensional positioning error.
PDOP is positioning accuracy factor (Position Dilution of Accuracy).

σo is error in psuedo range measurements.

In a similar way, it is possible to define planar position accuracy factor HDOP, elevation accuracy factor VDOP, receiver clock error accuracy factor TDOP, and geometric accuracy factor GDOP. Equation (1) clearly shows that GPS positioning errors are composed of two parts--ranging errors and satellite geometric set up. As a result, users are capable of going through selection of satellite constallations to make DOP factors minimal, causing GPS positioning errors to be minimal. Up to the present time, GPS satellite constellation selection has all been based on this principle. Moreover--in map making, navigation, and positioning close to the ground--very good applications have been achieved. Speaking in terms of medium and low orbit spacecraft, their visibility to GPS satellites is very, very much better than ground users (see Fig.1). However, "satellite constellations that make DOP minimal among all visible satellites" are certainly not optimal satellite constellations. In the vicinity of the ground, satellite angles of elevation must be greater than zero. However, with regard to space users, angles of elevation can be negative, even to the point of most visible satellites possessing negative angles of elevation. At this time--among all visible satellites--satellite constellations that make DOP minimal are not necessarily the optimum ones. We consider the several types of cases below.

1. Among all sources of errors, errors given rise to by atmospheric interference (for example, ionosphere delay and troposphere delay) account for the major part, sometimes reaching 40-50 meters. Research [2] clearly shows that troposphere delay is basically generated below 100 km. Moreover, 80% of errors are generated under 10 km. This then does not produce influences with regard to spacecraft positioning. Ionosphere delay is basically generated below 700 km. Moreover, 60% of errors are generated below 350 km. If GPS satellites are chosen on the

boundary of visible satellites, the signals will then penetrate the ionosphere twice. If angles of elevation are chosen somewhat larger, it is possible to basically keep clear of atmospheric interference. As a result, when selecting a certain satellite, it is not only necessary to consider its geometrical set up with respect to the structure of the satellite constellation as a whole, it is also necessary to consider the errors it brings with it. Besides this, in navigation texts, calibration parameters related to atmospheric interference as well as receiver calibration models associated with atmospheric interference are no longer suitable for use.

2. Satellite Signal Attenuation Factors. When satellite signal propogation paths increase in length, signal attenuation is then severe. Limits associated with reception powers are -163dBW[3]. Based on this, it is possible to precisely specify an interval which cannot be use in association with GPS satellites.

Assume that GPS satellites are at heights H above the ground, spacecraft are at heights h (h<H) above the ground, and the earth is a sphere with radius R.

Then, the closest distance of spacecraft from GPS satellites is (H-h). The farthest distance is $(\sqrt{H^2+2RH}+\sqrt{h^2+2hR})$

3. Relativity Theory Effects. When designing GPS systems, adequate consideration has already been made of the influences of relativity theory on medium and low dynamic users in the vicinity of the ground. This not only meant adjusting a frequency deviation associated with GPS satellite clock frequencies. Moreover, in positioning calculations, consideration was given to calibration quantities and necessary parameters distributed by satellites.

When GPS satellites are seen as circular orbit satellites, based on relativity theory, the frequency drift is:

General relativity theory frequency drift: $\Delta f_1=\frac{\mu}{C^2}\left(\frac{1}{r_u}-\frac{1}{R_s}\right)\cdot f$ (2)

Special relativity theory frequency drift: $\Delta f_2=\frac{1}{2C^2}(Vu^2-Vs^2)\cdot f$

In this: μ is the earth's gravitational constant
C is the speed of light
ru is the user (spacecraft) position vector
Vs is GPS satellite (SV) movement velocity
Vu is user (spacecraft) movement velocity
Rs is GPS satellite (SV) position vector /3
f is frequency

GPS satellite clock frequency deviation is calculated on the basis of formula (2) with respect to a relatively stationary user positioned on the equator of the earth's surface. With regard to precise determinations associated with spacecraft, there is a need to do new calculations.

4. Satellite Window Stability. So called satellite windows refer to a set of precisely determined satellites participating in positioning. Due to GPS satellites and user spacecraft both being located in high speed dynamic states, the range of changes in usable time periods associated with each window (that is, a set of 4 satellites) is very large. It is primarily determined by:

- Changes in satellite visibility as a function of user height. Reference [4] marks out time periods of visibility associated with GPS satellites at different altitudes (Fig.2).

- When spacecraft and GPS satellites are moving in the same directions or opposite directions, this type of period of visibility must also enlarge or diminish.

- Among visible satellites, selection of the optimum 4 satellites to act as positioning satellites. Due to the fact that spacecraft heights and speeds are much larger than users on the ground, satellite window replacement is then quite frequent. Moreover, each iteration of satellite replacement will give rise to DOP value fluctuations.

As a result, when selecting a set of satellites to use doing positioning, it is not only necessary to consider the optimum geometrical positions. It is also necessary to consider the time periods of continuous usability.

III. GEOMETRICAL FACTORS

Here, we put forward a type of variable, weighted comprehensive geometrical factor. With regard to medium and low dynamic users in the vicinity of the earth's surface--in particular, stationary users--satellite constellations associated with extremely small GDOP or PDOP are capable of achieving the best positioning results. However, the variability and variety of astronavigational missions as well as spacecraft being far, far larger than ordinary users in both space domain and time domain, simple minimal DOP is no longer appropriate.

As far as the different stages in different astronavigational missions are concerned, requirements with regard to GPS positioning are different--for example, NASA's gravity probe GP-B[3] has positioning accuracy requirements 3-4 orders of magnitude higher than GPS satellites. Direction finding accuracies are 5 orders of magnitude higher. Time determinations are still the same. During rendezvous processes between spaceships and space stations, normal accuracy requirements are far, far higher than axial direction accuracy requirements. Moreover, during docking--in the same way--there is a requirement for very high axial direction accuracies. Weather satellites and natural resource satellites require having high vertical positioning accuracies. Space shuttles, by contrast, have different requirements for positioning accuracies in various different directions during different flight phases.

In order to satisfy requirements in the various areas above, a linear combination of HDOP and VDOP is constructed:

$$WDOP = a_1 \cdot HDOP + a_2 VDOP \quad (3)$$

In this, weighting parameters a1 and a2 are not negative. Due to the fact that DOP values are only one type of relative measurement, option is made for the use of the restrictions below:

$$a_1 + a_2 = 1, \qquad a_1 \geq 0, \ a_2 \geq 0 \quad (4)$$

Calculating from a1 = 0 to a1 = 1, as far as WDOP curves for changes as a function of time for each interval of 0.1 as well as corresponding satellite constellation diagrams are concerned, several examples are given in Fig.3 to Fig.8. a1 is determined on the basis of respective horizontal and vertical accuracy requirements associated with spacecraft missions. It is capable of being a constant. It can also vary in accordance with different flight stages.

In the diagrams, it is possible to see that satellite geometrical accuracy factors and satellites used are different in accordance with different weighting parameters selected. At the same time, in the diagrams, it is clearly shown that, as far as extremely small DOP is concerned, it is very difficult to maintain satellite window stability. In Fig.4, despite the fact that WDOP values are maintained around 1.5, within 1000 seconds, however, satellite changes surpass 70 iterations. As a result, only selecting satellites with extremely small DOP is very unrealistic. It is necessary to add constraints with regard to satellite changes.

IV. LARGE WINDOW POSITIONING

In order to eliminate perturbations given rise to by satellite changes during positioning processes, option is made for the use of all usable satellites and not only for the use of 4 satellites, that is, taking positioning satellite windows and changing them from small to large. In this, the authors considered the following factors.

1. Selection of Usable Satellites. Following along with increases in spacecraft altitude, the number of GPS satellites that can be seen is far, far greater than for ground users. During positioning, usable satellites are, first of all, selected from among visible satellites. /4

2. Positioning Equation Linearization. When option is made for the use of large window positioning, simultaneous equations can be increased to 5-10. In the majority of cases, there are 7. In order to reduce the amount of calculations, positioning equations are linearized.

3. Option is made for the use of least square methods to solve for positioning results.

4. In order to make different GPS satellites play different roles during positioning processes, option is made for the use of weighted least square methods. Weighting parameters are capable of considering GPS satellite geometrical set ups and quality (for example, errors given rise to by various factors). Weighting is also capable of guaranteeing that satellite enter and exit window times are gradual, avoiding perturbations.

Acting as sample calculations, the authors opt for the use of weighed least square methods. At the same time, use is made of data associated with 6 GPS satellites to carry out positioning. Weighting parameters in examples temporarily only consider satellite elevation angles ei . Using ai to represent weighting numbers corresponding to satellites i participating in positioning, calculations are done of 3 types of weighting cases. Final positioning errors are primarily given rise to by ranging errors.

(1) 情况 1 $\alpha_i = 2.5\sin e_i$	(1) 情况 2 $\alpha_i = e_i$	(1) 情况 3 $\alpha_i = \sin 2e_i$
$\alpha_2 = 0.746$	$\alpha_2 = 0.303$	$\alpha_2 = 0.570$
$\alpha_4 = 0.564$	$\alpha_4 = 0.227$	$\alpha_4 = 0.440$
$\alpha_5 = 1.564$	$\alpha_6 = 0.676$	$\alpha_6 = 0.976$
$\alpha_6 = 0.244$	$\alpha_6 = 0.098$	$\alpha_6 = 0.194$
$\alpha_{27} = 0.933$	$\alpha_{27} = 0.383$	$\alpha_{27} = 0.693$
$\alpha_{31} = 1.415$	$\alpha_{31} = 0.602$	$\alpha_{31} = 0.933$
(2) 误差: 77.5m	77.22m	78.78m

(1) Case (2) Error

V. CONCLUDING REMARKS

GPS used in spacecraft orbit determination will bring with it a good number of direct and indirect advantages. It also brings a series of problems that await solution. This article primarily analyzes the problem of satellite constellation selection, giving consideration to atmospheric interference, signal propogation paths, relativity theory effects, and satellite window stability. A type of new geometrical precision factor is constructed as well as least square methods associated with all usable satellites to do positioning. Further research is in the midst of being carried out.

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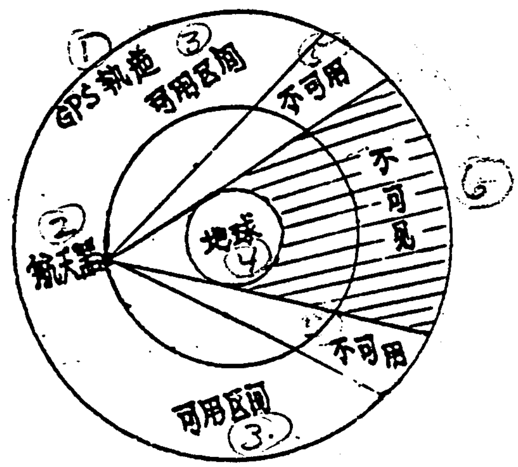

Fig.1 Usable Area Divisions

Key: (1) GPS Orbit (2) Spacecraft (3) Usable Interval (4) Earth (5) Not Usable (6) Invisible

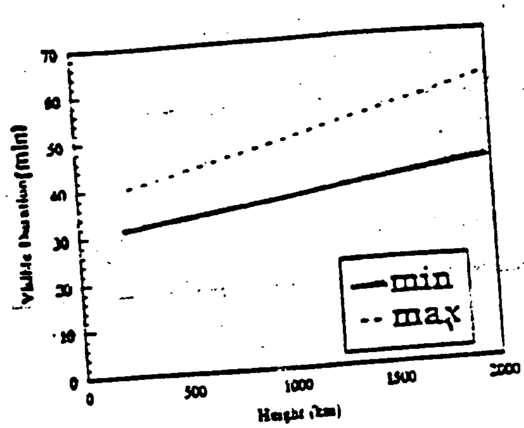

Fig.2 Possible Periods of Continuous Spacecraft SV Observation

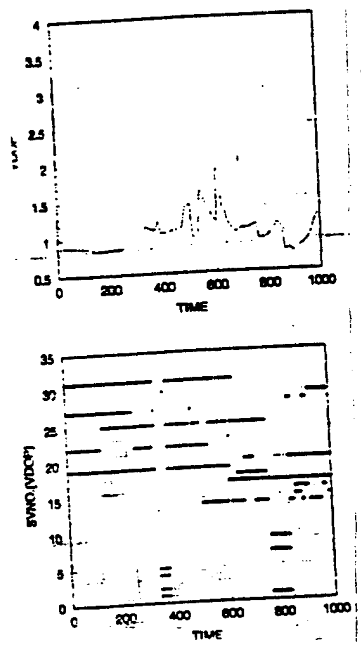

Fig.3 WDOP (a1 = 0) and Satellite Windows

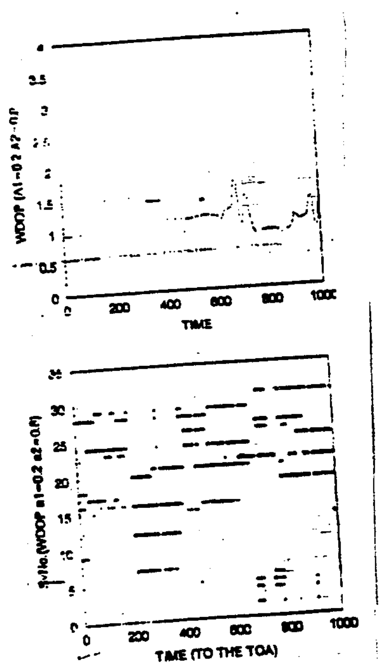

Fig.4 WDOP (a1 = 0.2) and Satellite Windows

/6

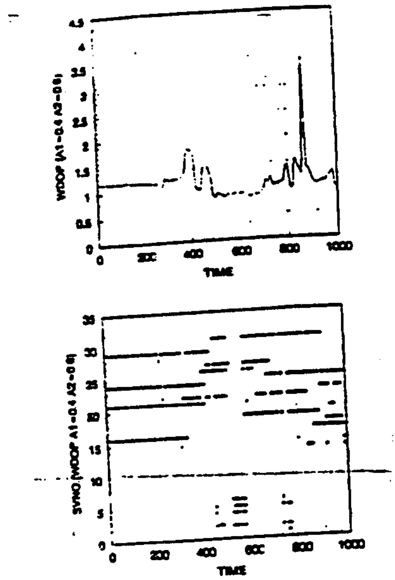

Fig.5 WDOP (a1 = 0.4) and Satellite Windows

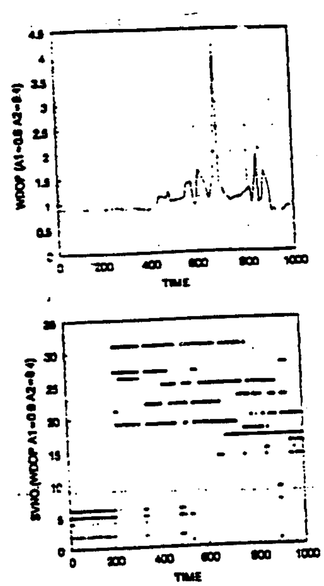

Fig.6 WDOP (a1 = 0.6) and Satellite Windows

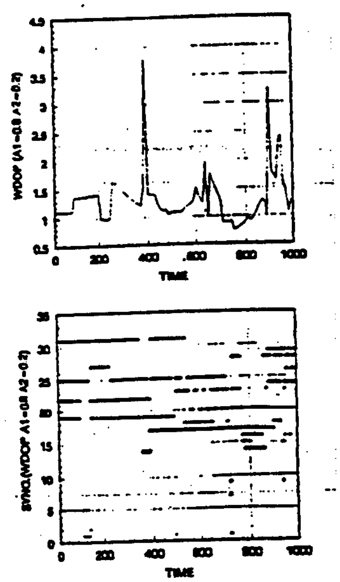

Fig.7 WDOP (a1 = 0.8) and Satellite Windows

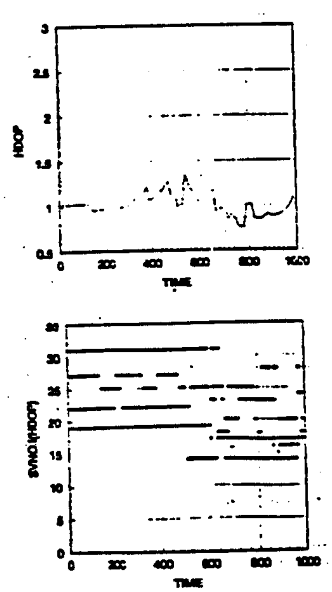

Fig.8 WDOP (a1 = 1.0) and Satellite Window

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