Pseudolite applications in positioning and navigation: Modelling and geometric analysis

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Chris Rizos is an Associate Professor at the School of Geomatic Engineering, UNSW, and leader of the SNAP Group, which specialises in addressing precise static and kinematic applications of GPS. Chris holds a B.Surv.(Hons.) and Ph.D., both from UNSW, and has published over 150 papers, as well as having authored and co-authored several books relating to GPS and positioning technologies.

ABSTRACT

Pseudolites are an exciting technology whose potential can be explored for a wide range of positioning and navigation applications, either as a significant augmentation of space-based systems, or as an independent system for indoor positioning. Compared with satellites in space, pseudolites usually have a lower elevation, which can significantly improve the geometric strength of positioning solutions, particularly for the height component. However, due to the comparatively small separation between pseudolites and receivers/users, there are some challenging issues in modelling and geometry design that need to be addressed. In this paper, modelling strategies to deal with a variety of error sources, such as non-linearity, tropospheric delays, multipath and pseudolite location errors, are discussed. In addition, based on use of the appropriate quality indicators, the impact of the pseudolite-user geometry in ambiguity resolution and final positioning solutions is analysed. Optimal geometric designs for various positioning scenarios are proposed.

INTRODUCTION

Over the last decade or so GPS positioning has been playing an increasing role in both surveying and navigation, and has become an indispensable tool for precise relative positioning. However, in some situations, such as in urban canyons, positioning in valleys and in deep open-cut mines, the number of visible satellites may not be sufficient to reliably determine precise coordinates. Furthermore, it is impossible to use GPS for precise indoor positioning.

These problems can be addressed by the inclusion of additional ranging signals transmitted from ground-based "pseudo-satellites" (pseudolites). The use of pseudolites can be traced back as early as 1976 during the initial GPS user equipment tests at the U.S. Army Yuma Proving Ground, Arizona (Harrington & Dolloff, 1976). In the mid 1980s, the RTCM committee SC-104 ('Recommended Standards for Differential Navstar GPS Service') designated the Type 8 Message for the pseudolite almanac, containing the location, code and health information of

pseudolites (Kalafus et al., 1986). During the last decade, pseudolites have been tested for aviation, marine and land navigation and positioning applications (for example, Bartone, 1996; Choi et al., 2000; Dai et al., 2001a,b,c; Cobb et al., 1995; Ford et al., 1996; Hein et al., 1997; Morley, 1997; Stone & Powell, 1998; Wang et al., 2000, 2001; Zimmerman & Cannon, 1996).

Compared with satellites in space, pseudolites usually have a lower elevation angle, which can significantly improve the geometric strength of positioning solutions, particularly for the height component. However, due to the comparatively small separation between pseudolites and receivers/users, there are some challenging issues in modelling and geometry design that need to be addressed, such as non-linearity, tropospheric delays, multipath and pseudolite location errors.

MODELLING ISSUES IN PSEUDOLITE MEASUREMENTS

The single-differenced pseudolite observables between two receivers can be expressed in a similar form to GPS satelite observations:

Pseudo-range:

$$\Delta R = \Delta r - c \cdot \Delta dt_R + \Delta d_{orb} + \Delta d_{trop} + \Delta d_{m_R} + \Delta e_R \qquad (1)$$

Carrier phase:

$$\Delta j.l = \Delta r + \Delta N - c \cdot \Delta dt_R + \Delta d_{orb} + \Delta d_{trop} + \Delta d_{mj} + \Delta e_j \qquad (2)$$

Where ΔR and Δj are single-differenced code and carrier phase observables respectively; Δr is the single-differenced geometric range between two receivers; Δdt_R, Δd_{orb} and Δd_{trop} are single-differenced receiver clock bias, pseudolite-location error and tropospheric delay respectively; Δd_{mj} and Δd_{m_R} are multipath error for pseudo-range and carrier phase respectively; l and ΔN are the wavelength and integer ambiguity; c is the speed of light; and Δe_R and Δe_j are the pseudo-range and carrier phase observation noises respectively.

Because there is the opportunity to optimize the selection of pseudolite signals, a promising approach is to expand on the principles employed by dual-frequency GPS receivers and to develop a multi-frequency system that can instantaneously resolve the ambiguities. A four-frequency pseudolite system which uses two frequencies in the 900MHz ISM band and two in the 2.4GHz ISM band (S-band) has been suggested by Zimmerman et al. (2000). Undoubtedly, multi-frequency pseudolite development will make it more feasible to implement a pseudolite-based positioning and navigation system.

It should be emphasized that no terms need to be introduced to account for ionospheric delay for the ground-based pseudolites (unlike the GPS/GLONASS satellites transmitting signals through space). Though the pseudolite equations for carrier phase and pseudo-range are similar to the GPS observation equations, errors such as the effects of non-linearity $\Delta\rho$, the pseudolite-location bias, multipath and tropospheric delay have to be considered carefully in a different way to the GPS observables.

Effects of Non-Linearity

In positioning and navigation applications, the key geometric information from the measurements is 'distance' or 'range' between two points, which are generally represented through 'coordinates' defined in some reference frame. The relationship between the measurements (distances) and the unknown parameters (coordinates) is of course non-linear. Because the estimation techniques for the linear models have nice statistical properties, the non-linear measurement models are usually linearized using a Taylor series expansion.

In GPS data processing, different selection of parameters may have different effects on non-linearity. For example, if the baseline vector is selected as the unknown parameter in data processing (Stone & Powell, 1998; Lawrence, 1996) then:

$$-\bar{e}\Delta\bar{X} = (\Delta f + Nl) + |\bar{P}|(1-\cos(q)) \qquad (3)$$

where $\bar{e}$ is line-of-sight vector from user to transmitter; $\Delta\bar{X}$ is the baseline vector from user to reference station; Δf is single-differenced carrier phase measurements; N is the ambiguity; $\bar{P}$ is the distance between pseudolite transmitter and reference station; and q is intersectional angle between pseudolite and two receivers.

Because the wavefronts are planar, a non-linear correction term $|\bar{P}|(1-\cos(q))$ needs to be accounted for as shown in Figure 1. The approxomate error for GPS satellite due to linearization is:

$$|\bar{P}|(1-\cos(q)) = 2\sin^2(q/2)|\bar{P}| \cong \frac{|\Delta\bar{X}|^2}{2|\bar{P}|} \quad \text{where} \left(\sin(q/2) \cong \frac{|\Delta\bar{X}|}{2|\bar{P}|}\right) \qquad (4)$$

For a five kilometre GPS baseline, this error is approxomately half a metre (Lawrence, 1996). Due to uncertainty in the exact position of the user, the corrected phase will also be in error. It should be noted that Eq. 4 is not suitable for pseudolite measurment because q could be very large. It is obvious for pseudolite signals that the non-linearzed errors may become more serious.

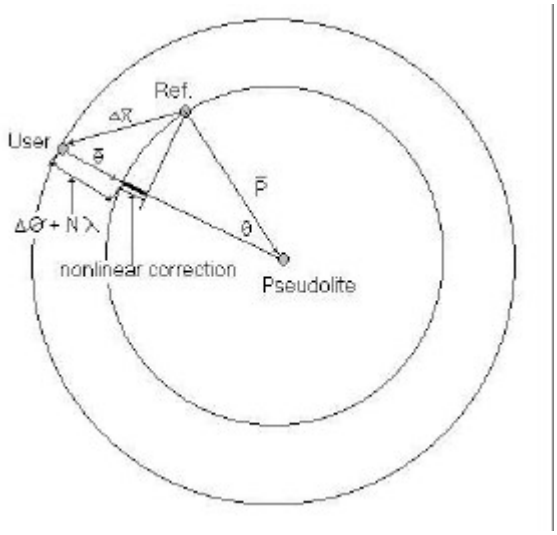


Fig. 1 Example of pseudolite non-linear correction.

When the coordinates of the user station are selected as unknown parameters, the effects of non-linearization have been analyzed in Wang et al. (2000). For distances such as between GPS satellites and users on the ground, the linearization error for a 200m error in the coordinates is just 1mm, which is clearly negligible (ibid, 2000). However, when the separation between pseudolites and users is 200m, an error of 15m in coordinates may result in a linearization error of as much as 0.6m, which is much larger than the phase measurement errors, and may lead to divergence of the computation process. Special care should therefore be taken.

Effects of Orbital Errors

In GPS relative positioning applications, the impact of the orbital errors on baseline length is approximately proportional to the ratio of baseline length between the user/reference stations to the satellite range (Bauersima, 1983). Due to the long distance from satellite to receivers, orbit errors can be ignored for short baseline positioning. However, the influence of pseudolite-location error must be considered in a different way to that of GPS orbit bias because a pseudolite is essentially a satellite-on-the-ground.

A detailed theoretical anaylsis on the impact of orbital errors and the errors in reference coordinates on the measurement models, and final positioning, can be found in Dai et al. (2000), and Wang et al. (2000). A numberical analysis is presented here. In some situations, the geometric relationship between pseudolite transmitter and users is quite different from that for the satellite transmitters and users. Hein et al. (1997) and Morely (1997) discuss two special set-ups for the pseudolite and users, indicated in Figure 2.

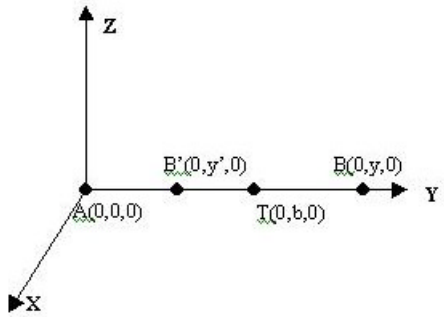


Fig. 2 Special set-ups for the pseudolite and baselines.

In Figure 2, A and B indicate the user and reference stations respectively, and C' and C indicate the locations of the pseudolite trnsmitters in the worst and best configuration respectively. Figures 3 and 4 show the effects of pseudolite location biases (5cm constant errors) on the single-difference. It can be seen clearly from Figure 3 that the influence of the orbit errors is different in different elevation and azimuth. In the worst case, the single-differencing procedure doubles the size of the pseudolite-location error in the measurements. Therefore, the pseudolite-location errors can bias significantly the precise carrier phase observation even though they are only of the order of a few centimetres in magnitude.

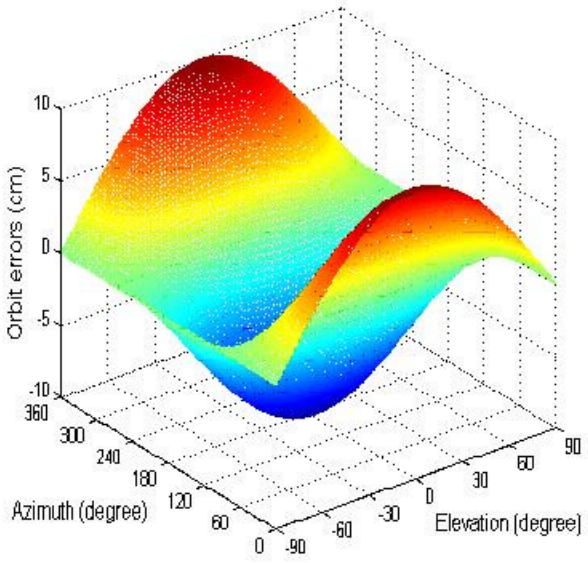


Fig. 3 The influence of pseudolite location bias in the worst configuration.

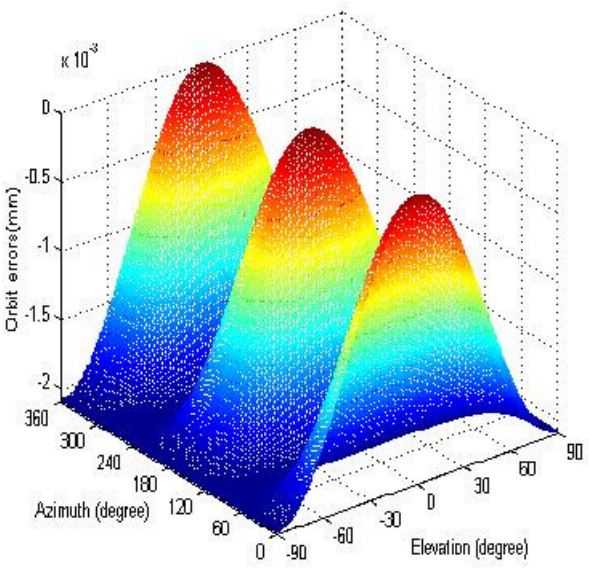


Fig. 4 The influence of pseudolite location bias in the best configuration.

It can also be seen from Figure 4 that in the best configuration the influence of pseudolite location biases are so small (less than 2μm) after single-differencing that they can be ignored.

Due to the pseudolite being stationary (unlike the moving GPS satellites) the pseudolite-location bias will be a constant. If the reference and mobile receiver are both stationary, orbit error will contribute an invarant bias to the differenced observables. The constant (or very near invariant) bias can be predicted and removed for some applications such as deformation monitoring. It should be emphasised that for kinematic applications, the pseudolite location should be precisely determined beforehand, using GPS surveying, 'total station' or other traditional surveying techniques.

Pseudolite Multipath

If one or more reflected signals arrive at the receiver antenna in addition to the direct signal, multipath will be present in both the code and carrier measurements. The effect of multipath on code observations is two orders of magnitude larger than on the carrier phase observations. The theoretical maximum multipath bias that can occur in pseudo-range data is approximately half a chip length of the code, that is, 150m for C/A code ranges and 15m for the P(Y) code ranges. Typical errors are much lower (generally <10m). The carrier phase multipath for one way measurements does not exceed about one-quarter of the wavelength (5-6cm for L1 or L2).

The multipath from pseudolites is not only due to reflected signals from the surface, but also from the pseudolite transmitter itself (Ford et al., 1996). Bartone (1999) has shown that the standing-wave multipath in an airport pseudolite ground-to-ground link can essentially be eliminated by the use of a Multipath-Limiting-Antenna for both the pseudolite transmission and reception antennas. If the pseudolite and receiver are both stationary, the multipath bias will be a constant. Hence, the influence of multipath from pseudolites cannot be mitigated and reduced to the same extent over time as in the case of GPS. Therefore the multipath will significantly increase the noise level of the measurement in a dynamic environment. The experimental results of pseudolite multipath in a static environment for one case are shown in Figures 5 and 6. The mean value and standard deviation for the pseudo-range data are -1.25m and 0.21m, and for the carrier phase are -0.105 cycles and 0.008 cycles respectively. It can be clearly seen that the influence of multipath remains at significant levels. Furthermore, it is very hard to avoid, even though careful precautions may have been taken. However, because of the constant characteristics of the multipath from a pseudolite transmitter in a static environment, it is relatively easy to calibrate it in advance. The constant (or very near invariant) bias can be predicted and removed during data processing, and pseudolite signals can, in principle, make a contribution to improving the performance for some static applications.

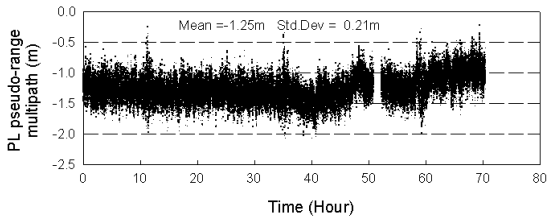


Fig. 5 Multipath influence on the double-differenced pseudo-range.

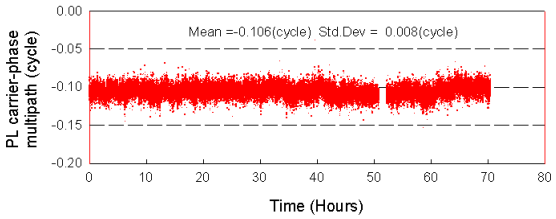


Fig. 6 Multipath influence on the double-differenced carrier phase.

Pseudolite multipath is a challenging issue that needs to be solved for kinematic applications. Good hardware design, including receivers, receiver antennas and pseudolite transmitter antennas, as well as software-based multipath mitigation techniques will be needed.

Pseudolite Tropospheric Delay

For GPS signals, a simple way to compensate for the tropospheric delay is to apply a model to estimate the delay, such as the Saastamoinen, Hopfield, or Black models. The delay derived from all of these models is highly dependent on the satellite elevation angle. Figure 7 shows the single-differenced tropospheric delay between

the receivers if the difference between the satellite elevation angles from both stations to the satellite is one degree. For the pseudolite case it is possible that a small difference in height can lead to a few degrees difference in the elevation angle. Obviously, the standard tropospheric models can not be used to compensate for pseudolite tropospheric delay. This is because the model parameters are designed for signals from GPS satellites, more than 20,000km away. Hein et al. (1997) suggest that a simple troposphere model should be used to compensate for pseudolite tropospheric delay, where the refractivity n at the base of the atmosphere is described as a function of the meteorological parameters:

$$N = (n-1)*10^6 = 77.6\frac{P-e}{T} + 71.98\frac{e}{T} + 3.75\cdot 10^5 \frac{e}{T^2} \quad (5)$$

Where P is the air pressure in hectopascals, e is partial pressure of the water vapour in hectopascals, T is the absolute temperature in degrees Kelvin. The partial pressure of the water vapour can be calculated via the relative humidity (RH):

$$e = RH*\exp(-37.2465+0.2133T-2.569*10^{-4}T^2) \quad (6)$$

If the meteorological parameters can be assumed the same, the tropospheric delay after between-receivers single-differencing can be represented by (Dai et al., 2000):

$$\Delta d_{trop} = (77.6\frac{P}{T} + 5.62\frac{e}{T} + 375000\frac{e}{T^2})10^{-6}\Delta r \quad (7)$$

Where Δr is the difference in geometric ranges between the pseudolite transmitter and the two receivers. For the standard meteorological parameters (P=1013mPa, T=20°, RH=50%), from Eq. (6) the tropospheric delay correction can reach 320.5ppm (32.05cm per km). The influence of the tropospheric delay is shown in Figure 7. It can be seen that the pseudolite tropospheric delay can reach up to 600ppm in some specified weather conditions. Similar conclusions can be found in the Hein et al. (1997) investigation. It is obvious that local weather conditions have a significant effect on the correction. Barltrop et al. (1996) suggests that the local refractivity should be estimated as a slowly varying parameter using the pseudolite measurements. If the pseudolite site can be located with the difference Δr as small as possible, the tropospheric error can be significantly mitigated.

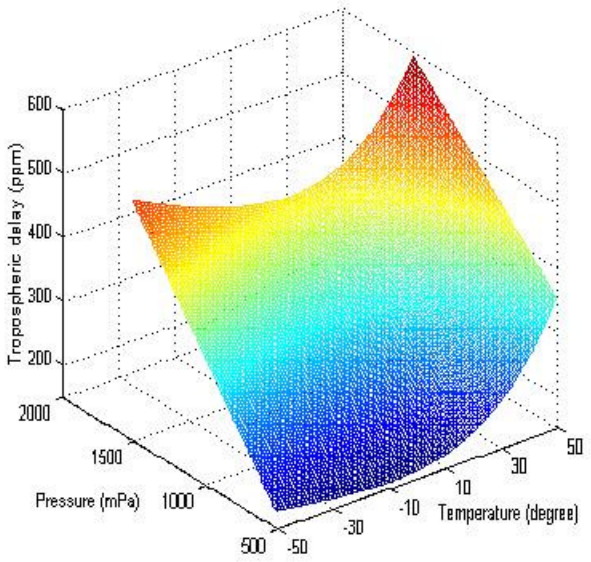


Fig. 7 Pseudolite tropospheric delay with 50% RH.

GEOMETRIC ANALYSIS

It is well known that pseudolites can be used to improve the geometric strength of positioning solutions, particularly for the height component. Pseudolite location with respect to the mobile receiver will be critical. In practice, constraints that GPS satellite signals may be blocked need to be considered. Optimization of the pseudolite location is therefore necessary. 'Geometric optimization' refers to the need to find locations for the pseudolite transmitters that will minimise the Position Dilution of Precision (PDOP), Relative Position Dilution of Precision (RDOP) or other similar factors (in this paper, RDOP is used).

Two cases of geometric optimization are investigated below, which include pseudolite location optimization for GPS augmentation by pseudolite, and receiver array optimization for pseudolite inverted positioning.

Augmentation of GPS with Pseudolites

To analyze pseudolite location optimization, a simulation with respect to pseudolite location has been carried out. Cut-off angle 15 degree, 10 degree pseudolite elevation angle with respect to mobile receiver and the constraint that all the satellites ly in the azimuth range from 100 to 150 degree, and elevation angles less 25 degree will be rejected have been used.

Figure 8 shows the 24-hour the RDOP values at UNSW, on 24 April 2000, without a pseudolite. It can be seen that RDOP values are larger than 2 most of the time, and sometime up to 6. Figure 9 is a plot of the 24-hour RDOP values where one pseudolite was located, but with varying azimuth from 0 to 360 degrees. It can be seen from the Figure 10 that RDOP values are still very large if the pseudolite was located in the azimuth band 240 to 360, or

from 0 to 60 degrees. However, very good RDOP (less than 2) values can be achieved if the pseudolite was located in the azimuth band 60 to 240 degrees. It is obvious that different pseudolite locations change the geometry significantly. It should be emphasised that the constraints rejecting all the satellites with azimuth between 100 and 150 degrees and elevation angle less 25 degrees have been used. Intuitively, pseudolites should be located in azimuth sectors where GPS satellite signals are blocked.

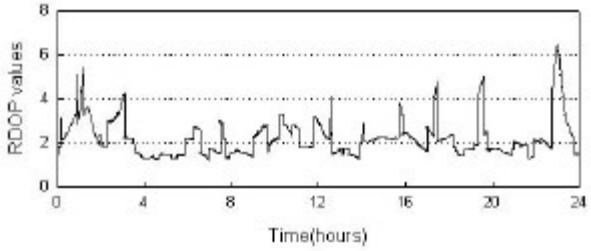


Fig. 8 24-hour RDOP values at UNSW, 24 April 2000, without pseudolite.

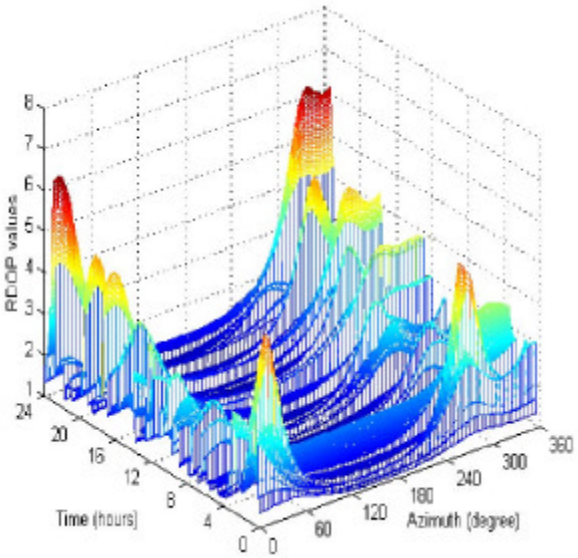


Fig. 9 24-hour RDOP values at UNSW, 24 April 2000. Cut-off angle 15^0 and one pseudolite have been used.

Pseudolite Inverted Positioning

In pseudolite inverted positioning, 'geometric optimization' refers to the need to find locations for the receiver array and the pseudolite transmitter that will minimise the RDOP (Dai et al., 2001c).

The results of a computer simulation showing the minimum RDOP values as a function of the number of receivers are plotted in Figure 10 (after the constraint that the receiver elevation angle related to the mobile pseudolite cannot be less than 0 degrees is applied). It can be seen that the RDOP values will reduce when the number of receivers increases. For a four-receiver array the minimum RDOP values can still reach 1.63. The simulation also shows that if the receivers are equally spaced in the azimuthal plane, and at a zero elevation angle relative to the mobile receivers, and one receiver is at the zenith, the minimum RDOP value is obtained. Figure 11 shows the optimal configuration in the case of a four-receiver array. Figure 12 shows the minimum RDOP values as a function of the elevation cut-off angle for a four-receiver array configuration. It should be emphasized that very good geometry can still be obtained (RDOP value less than 3) even though the cut-off angle is up to 30 degrees. This fact means that there is considerable flexibility when considering receiver array optimization.

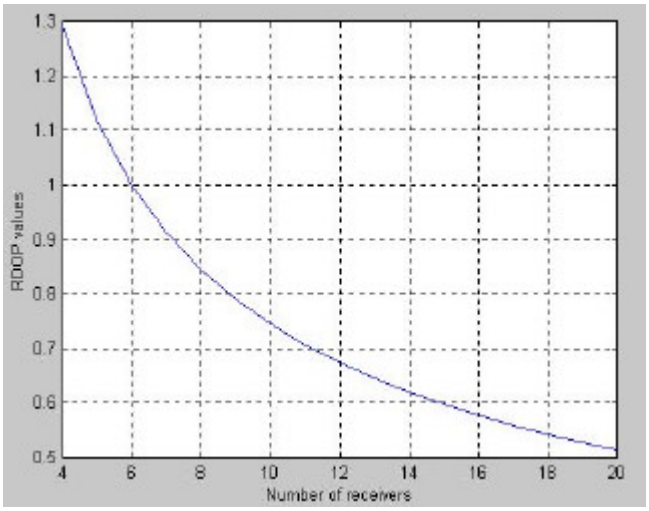


Fig. 10 Minimum RDOP values.

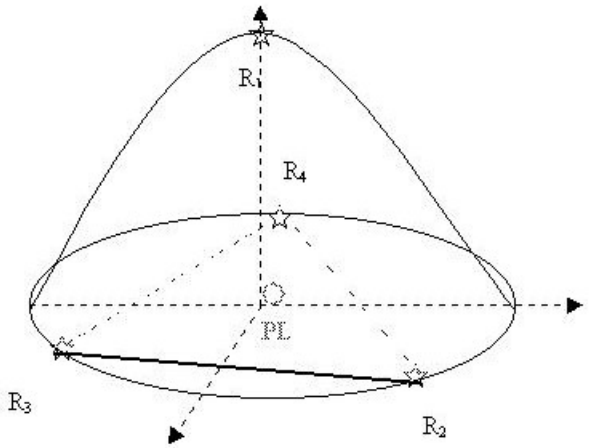


Fig. 11 Optimum four-receiver array to minimise RDOP value. R1-R4 indicates the location of the 4 receivers and the mobile pseudolite is indicated as PL.

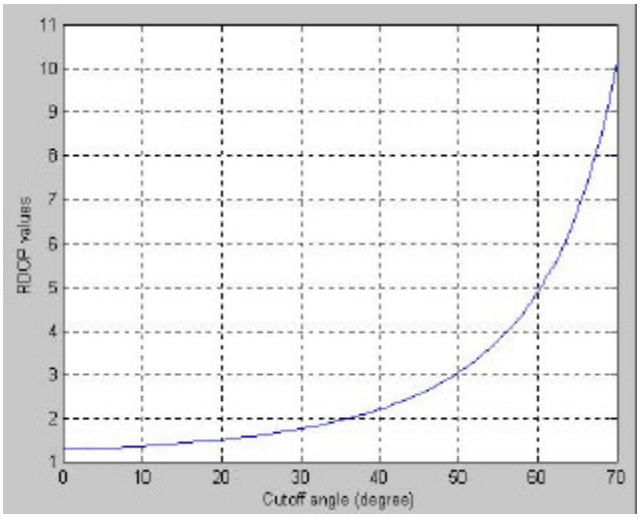


Fig. 12 Minimum RDOP as a function of cut-off angle for four receivers.

CONCLUDING REMARKS

In this paper modelling strategies to deal with a variety of error sources, such as non-linearity, tropospheric delays, multipath and pseudolite location errors, have been discussed. In addition, based on use of the appropriate quality indicators, such as RDOP, the impact of the pseudolite-user geometry on final positioning solutions is analysed. Optimal geometric designs for GPS/pseudolite integration and pseudolite inverted positioning scenarios are proposed.

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