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Kinematic GPS solutions for aircraft trajectories: Identifying and minimizing systematic height errors associated with atmospheric propagation delays

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[1] When kinematic GPS processing software is used to estimate the trajectory of an aircraft, unless the delays imposed on the GPS signals by the atmosphere are either estimated or calibrated via external observations, then vertical height errors of decimeters can occur. This problem is clearly manifested when the aircraft is positioned against multiple base stations in areas of pronounced topography because the aircraft height solutions obtained using different base stations will tend to be mutually offset, or biased, in proportion to the elevation differences between the base stations. When performing kinematic surveys in areas with significant topography it should be standard procedure to use multiple base stations, and to separate them vertically to the maximum extent possible, since it will then be much easier to detect mis-modeling of the atmosphere. **Citation:** Shan, S., M. Bevis, E. Kendrick, G. L. Mader, D. Raleigh, K. Hudnut, M. Sartori, and D. Phillips (2007), Kinematic GPS solutions for aircraft trajectories: Identifying and minimizing systematic height errors associated with atmospheric propagation delays, *Geophys. Res. Lett.*, *34*, L23S07, doi:10.1029/2007GL030889.

1. Introduction

[2] In airborne laser swath mapping (ALSM) also known as airborne LIDAR, vectors measured by a scanning LASER ranging instrument are added to the position of the aircraft to obtain the coordinates of features or objects of the terrain along the flight path of the aircraft. The primary sources of error are scanning pointing errors, range errors, aircraft orientation errors, and aircraft position errors. In this paper we focus on the errors associated with kinematic GPS positioning of the aircraft. Project B4 mounted a large ALSM survey in May 2005 in order to image the near-field of the San Andreas and San Jacinto fault systems in Central and Southern California (www.earthsciences.osu.edu/b4). Our goal was to create a 'geodetic-grade' digital elevation model (DEM) for the near-field of these faults, so that in the event that a great earthquake occurs on one of them in the future, we could mount a second ALSM survey, difference the 'before' and 'after' DEMs, and so determine near-field crustal deformation with unprecedented resolution. Because we suspected that GPS positioning errors might be one of the largest sources of error affecting the LIDAR point clouds and DEMs, we used more than 120 GPS base stations during the ALSM survey, about 100 of which were survey stations occupied only when the associated fault section was being surveyed. As a result of this 'GPS Heavy' approach, the survey aircraft could be positioned relative to at least 5 and as many as 16 different GPS base stations during each of its flights. In most ALSM surveys only one or two base stations are used to control the aircraft trajectory during each flight segment. Nearly all of the base stations used in the B4 survey were located within 1 km of the faults and the flight lines, with a fault-parallel spacing that rarely exceeded ~10 km.

[3] Our plan was to use kinematic GPS software to position the aircraft relative to each base station in turn, and then 'blend' these individual solutions so as to produce a weighted mean trajectory solution. We initially assumed that the aircraft positioning errors were dominantly random errors whose amplitudes were influenced mainly by the instantaneous distance between the aircraft and the base station. However, it did not take long to realize that this was not true, and while the individual solutions usually agreed to within ~3 cm in the horizontal, the vertical solutions often differed by amounts of order 10–20 cm, or even more, and these vertical deviations tended to be systematic. We also noticed that vertical offsets or height biases between the individual trajectory solutions tended to be larger when the plane was flying over pronounced topography. This led us to understand that the problem was the way in which our software was modeling the delays imposed on the GPS signals by the atmosphere. Later we realized that this problem has been known and studied for some time [*Collins and Langley*, 1997], although many people working in ALSM, and in other kinematic surveying applications, seem to be unaware of it, or are using data processing techniques that essentially ignore the problem. In retrospect, it was very fortunate that we used so many base stations during the B4 survey, and that they were usually distributed over a wide range of elevations, because this made it almost impossible not to recognize that a serious problem was occurring with the modeling of atmospheric propagation delay. For this reason we will discuss our early difficulties and their subsequent diagnosis in some detail, since the techniques we used to identify the problem should be of use to other workers in this field. The underlying problem can be solved in two ways: by estimating tropospheric delay parameters or

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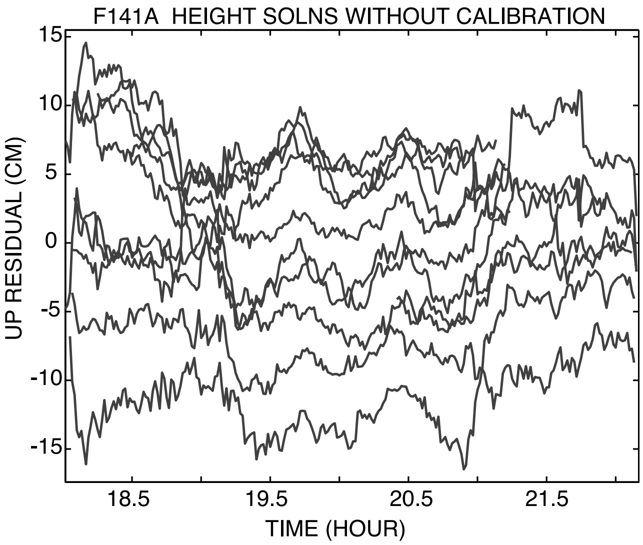

Figure 1. The height residual time series associated with each of the aircraft trajectory solutions obtained using 11 different base stations. The average of the eleven trajectory solutions was removed from each single base station solution to form the residual time series for that base station.

corrections during the course of the kinematic analysis [*Collins and Langley*, 1997], or by calibrating these delays through external measurements, which is the approach described here.

[4] In this paper we illustrate and analyze the delay problem using data obtained during flight 141A of the main B4 survey. This flight took place on day 141 of year 2005 over the northwestern Coachella Valley through the San Gorgonio Wilderness segments of the San Andreas Fault. (Using the terminology developed by the B4 project, this flight was used to acquire all five swaths over survey segment SAF02 as well as three of the five swaths collected for segment SAF03.) Similar results were obtained during other flight segments, but few additional insights are obtained from a review of these additional results.

2. Initial Data Analysis

[5] In order to impose a well defined reference frame on the LIDAR point clouds and DEMs, all GPS base stations used to control the aircraft trajectory were positioned using GAMIT/GLOBK software [*Herring et al.*, 2006] along with about 30 continuous GPS (or CGPS) stations associated with the SCIGN (now PBO) network. These CGPS stations were constrained to their coordinates (for the particular day) within the reference frame of the California Spatial Reference Center (http://csrc.ucsd.edu). Most of the new survey stations were positioned on more than one day, and typically repeatabilities of $\sim$3 mm and $\sim$8 mm were obtained in the horizontal and vertical components, respectively.

[6] The geodetic GPS receivers deployed at the base stations and the GPS receiver on the aircraft were dual frequency devices operated at a sample rate of 1 Hz. We analyzed the trajectory of the aircraft relative to each of the base stations using KINPOS software developed at the National Geodetic Survey [*Mader*, 1995]. During flight 141A a total of 11 base stations were used - nine of which were survey GPS stations established by us, while the other two were CGPS stations. The eleven trajectory solutions agreed to within a few cm in the horizontal. But as mentioned above, the individual height solutions deviated by as much as 20 cm or more, and these offsets were in large part biases. Figure 1 shows the residual time series associated with each base station: these were obtained by averaging the individual solutions, and removing this mean solution from each single base station solution. The mean value of each residual height time series is referred to as the height bias associated with that base station.

[7] When the trajectory height bias associated with each base station is plotted against the ellipsoidal height of the base station, the two quantities are found to be linearly correlated (Figure 2a). The slope of the best fitting line is -8.54 ± 0.67 cm/km. The strong influence of the height or elevation of the base station on the height bias associated with the trajectory solution obtained using that base station immediately suggested a possible role for the atmosphere. Past versions of KINPOS in use at the National Geodetic Survey, including the version that we were using, did not provide for estimation of atmospheric propagation delays as does most scientific-grade static GPS analysis software. Instead these delays were predicted by KINPOS using a model. But like 99% of all practitioners of kinematic GPS positioning, we simply allowed the parameters of the atmospheric delay module to remain at their default values. Since the latitude dependence of the delay model was not significant given the limited aperture of a single flight, we can evaluate the zenith neutral delay (ZND) predicted by KINPOS as a function of height, and this curve is plotted in Figure 2b (it is the dashed curve on the left). During the static analysis of our ground control network previously performed using GAMIT/GLOBK software, we estimated the ZND above each station, using a solution interval of one hour. Accordingly for every base station subject to a static analysis during the time interval of flight 141A we can compare the observed values of ZND (the circles in Figure 2b) with the curve predicted by KINPOS operating with its default parameters. Not only are the directly estimated values of ZND inconsistent with the default model employed by KINPOS, but the discrepancy varies roughly linearly with height. It is well known that ZND errors trade-off with height errors in static positioning [*Beutler et al.*, 1989; *Santerre*, 1991], and so this seemed a very likely explanation of what was producing the height biases in the trajectory solutions.

3. Calibrating the KINPOS Delay Model

[8] In order to test this hypothesis we used a least squares adjustment procedure to modify the parameters of the KINPOS delay model until its prediction for ZND as a function of height closely matched the ZND measurements produced by GAMIT. This calibrated model prediction is represented by the right hand (solid) curve in Figure 2b. Having externally 'calibrated' the KINPOS delay model in this way, we then repeated our kinematic analysis for the aircraft trajectory using each base station in turn. These individual solutions were averaged, and this blended solu-

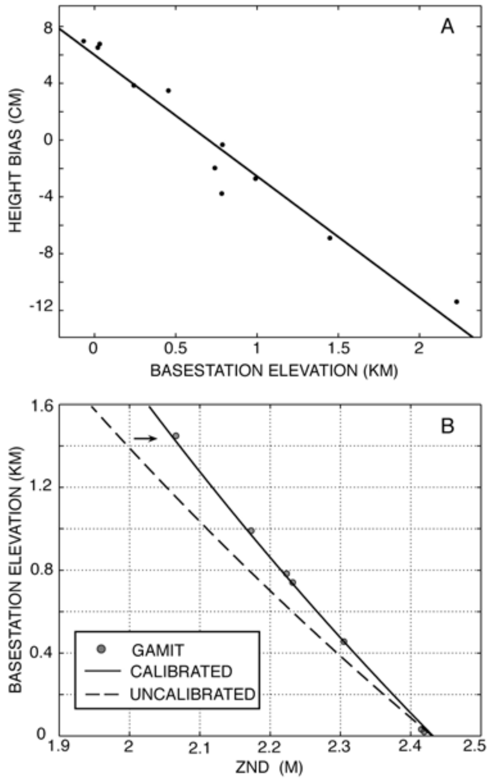

Figure 2. (a) The height bias associated with each single base station solution plotted against the elevation (ellipsoidal height) of the base station. The height bias for a given solution is defined as the average value of its residual time series (shown in Figure 1). The best linear fit has a gradient of −8.54 ± 0.67 cm/km. (b) Zenith neutral delay (ZND) versus elevation. The direct measurements of ZND at seven base stations (made using GAMIT software) are plotted against the height of those stations (circles). The height variation of ZND computed using the delay modeling module with KINPOS software, when its parameters are left to their default values, is that indicated by the dashed curve. The solid curve indicates the ZND predicted by this model as a function of height, when the model parameters have been adjusted so as to force a good agreement with the GAMIT measurements.

tion was subtracted from the eleven original solutions (obtained using an uncalibrated delay model) as well as each of the eleven new solutions. These residual times series are shown in Figure 3. Note that the large height biases associated with the original trajectory solutions (blue or grey curves) have almost completely disappeared. The 'spread' in the new height solutions (red or black curves) is about a fifth or sixth of its previous value. Note also that the solutions were very little affected in the horizontal. The average of the eleven original height solutions is clearly biased or offset relative to the average of the eleven new solutions. Clearly one cannot suppress systematic errors through a process of averaging.

[9] The eleven original solutions are not only differentially or relatively biased. The original residual height time series are oscillating in time (and in phase with the other residual time series) relative to the final solution. Part of the bias affecting each of the original solutions is varying systematically with time, and therefore is not controlled by the (constant) height of the associated base station. We now demonstrate that this behavior is controlled by the varying height of the aircraft. In Figure 4 we removed the mean value of each of the original residual time series (i.e. we subtracted the constant bias associated with each base station), and then plotted the remaining component of height bias against the instantaneous height of the aircraft. These quantities are linearly related, with the slope being + 8.29 ± 0.01 cm/km, which is statistically indistinguishable from the slope of the line in Figure 2a, except for the reversal of sign. The explanation is fairly obvious: systematic ZND errors at both the base station and the aircraft lead to systematic height errors in the estimated trajectory for the aircraft. The difference in sign is due to a reversal of reference or point of view. In Figure 2a we are relating the height solution error for the aircraft and the elevation of the base station: the ZND prediction error at antenna B produces a height estimation error at antenna A. In Figure 4, we are relating the height solution error for the aircraft and the elevation of the aircraft: the ZND prediction error at antenna A produces a height estimation error at antenna A. This sign reversal means that the height bias is ultimately driven by the height difference between the aircraft and the base station.

4. Analysis and Discussion

[10] In retrospect, we should not have been surprised that performing kinematic GPS analysis of an aircraft trajectory without paying due attention to the spatial structure of atmospheric propagation delay leads to significant systematic errors in our height solutions. This lesson was absorbed long ago in the realm of high-accuracy static GPS position-

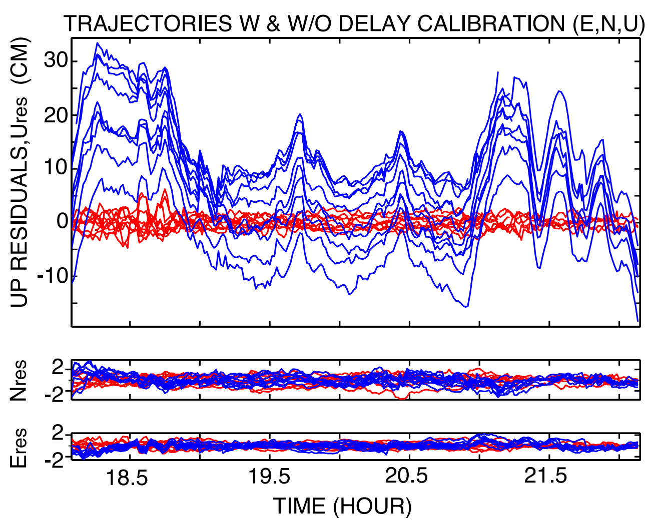

Figure 3. The up, north, and east residual time series associated with the eleven initial solutions derived using the default delay model (blue curves) and those associated with the refined solutions derived using the externally calibrated delay model (red curves). The residuals are defined relative to the mean of the refined solutions.

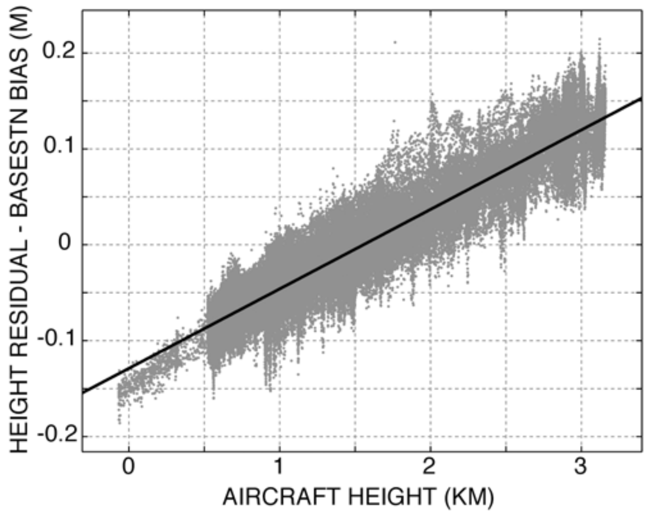

Figure 4. The non-steady component of height error in the original height solutions, defined as the residual height time series (blue curves in Figure 3) minus the mean value of that series for each base station, plotted against the instantaneous height of the aircraft. The data for all 11 solutions are plotted together. The best fitting straight line has a gradient of 8.29 ± 0.01 cm/km.

ing [*Beutler et al.*, 1989; *Santerre*, 1991]. For short baselines the relative height solution is sensitive only to the differential value of ZND above the two GPS antennas (ΔZ), and *Beutler et al.* [1989] demonstrated that the height error is very nearly proportional to the error in ΔZ. In our case study the ZND prediction error prior to external calibration (i.e. the distance between the curves in Figure 2b) was roughly linear in height, and therefore the error in ΔZ was roughly proportional to the height difference, ΔH, between base station and aircraft. In combination these two nearly linear relationships imply that the height error (or bias) should be roughly proportional to the elevation difference between aircraft and base station, which is what we found. Of course, the specific rate at which ZND prediction error and therefore GPS height bias depends on the elevation difference will vary with location, season and weather.

[11] We are not the first group to recognize the impact that delay modeling errors have on kinematic height estimates [*Collins and Langley*, 1997]. In the static context one can simply estimate zenith delay parameters for each GPS station, since delay structure changes only very slowly over time. In routine static positioning applications using GAMIT, for example, we estimate a zenith delay parameter for each GPS station every two hours. Estimating delays in a kinematic context is significantly more difficult because the mobile GPS antenna is often changing its height during the course of the survey, in which case the zenith delay above that antenna may be rapidly changing as a function of time. This is a fairly serious complication. As a result few kinematic GPS analysis software packages estimate zenith delay parameters, but instead use an internal model to predict zenith delay parameters based on the latitude and elevation of each GPS antenna, or based on atmospheric parameters such as surface pressure and humidity and scale heights for the wet and dry components of the neutral atmosphere. The great majority of scientists and engineers that use software of this kind make no serious effort to tune the parameters of these internal delay models so as to make them more realistic for a given location and time. Instead, they allow any adjustable parameters associated with the atmospheric delay model to default to the 'factory settings' of the software. As we have seen this can lead to 20 cm height errors, or even greater errors.

[12] The use of multiple base stations will manifest this problem in areas with significant topography, because the various solutions will be subject to different biases, and will thus disagree. In an area with very little topography the biases associated with different base stations will be nearly equal and so the trajectory solutions will not disagree. Nevertheless height biases will usually remain, just in a more insidious (covert) form. However, if the aircraft flies very low, say $\leq$600 m, over level ground, the prediction error for differential ZND will be smaller just because the total elevation range is smaller, and height bias levels may be acceptable.

[13] While this study was made in the context of ALSM, our finding applies equally to any kind of kinematic GPS survey in which there are large vertical offsets between the base station and the roving antenna. The first step towards the solution of a technical problem is knowing that you have one. In areas with significant topography, using base stations established with large height differences is the surest means of detecting atmospheric biases in kinematic height solutions. Maximizing the distance between the lowest and highest base station is more important than having a lot of base stations.

[14] There are two possible solutions to the bias problem. One approach, demonstrated here, is to calibrate the delay model using zenith delay parameters derived from a static analysis of the base stations. We refer to this as the external calibration technique. It has the obvious limitation that it is only applicable in the presence of significant topography (say >1 km). The second and more practical approach is to directly estimate delay parameters in the kinematic GPS analysis software - *Collins and Langley* [1997] modified KINPOS software to implement this approach. A similar capability has been incorporated in MIT's kinematic GPS software called TRACK, which we are now using. We are also modifying KINPOS to add this capability, using algorithms that differ from those used in TRACK or by *Collins and Langley* [1997]. We shall discuss our experience with the direct estimation of delay in a future paper. Our initial focus has been on the external comparison and calibration approach because we believe that it most clearly illuminates the fundamental problem, and therefore both motivates and informs our work on direct estimation.

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