Heave Determination by Stand-alone GPS and/or Inertial Sensors

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1. Introduction

In many hydrographic applications such as echo sounding care must be taken to obtain a good height reference. Readings of absolute water level can be taken from tide gauges, but it is frequently difficult and error prone to extend the information to the sounding position. Also, it is usually not possible to evaluate measurements in real time.

Therefore, there is a tendency to use differential GPS, which is on-board most surveying craft anyway, also for height determination. Whereas for positioning an accuracy in the metre range might be sufficient, the height reference should be accurate on the sub-decimetre level. Consequently application of DGPS for height reference poses more stringent demands on the proximity to the reference station and the quality of the solution.

Height variations may be categorised into long-term, with a time characteristic of hours, as they arise from tidal action and the change of meteorological parameters and short-term, caused by waves and the manoeuvring of the boat. These short-term variations, with a time characteristic of seconds, must be corrected for during the processing of echo soundings.

2. Heave from inertial sensors

As an independent way of measuring height variations heave sensors are frequently employed. Such sensors, which provide also roll and pitch angles as a by-product, are based on accelerometers and angular rate sensors. In a simplified description, the combined sensor array yields vertical acceleration which is then integrated over time to produce height.

$$h(t) = \iint a_v(t)\,dt\,dt + h_0$$

The integration is a problem which heave sensors have in common with all inertial navigation systems. An ideal measurement device produces a time series of true values plus a random noise with a normal distribution about zero. This random noise, when integrated, turns into a random walk [1], whose average excursion from zero rises without limit. *(The double integration only aggravates the problem.)* Therefore, in good navigation systems, inertial measurements are supported by absolute measurements from another sensor. Processing is usually done by a cleverly tuned Kalman filter that combines the advantages of either sensor for an optimum overall result.

For short-term height variations, if we do not want to rely on a DGPS reference station, a source for absolute height information is not available. Instead of an absolute measurement the assumption of height varying about a mean *(of zero)* must suffice. In the frequency domain this assumption is realised by a high-pass filter, i.e. low frequencies are eliminated from the result. The best choice of frequency cut-off depends on the wave frequency and vessel dynamics. If the actual height variation contains frequencies lower than the cut-off, that part of the spectrum is lost. A heave sensor yields particularly good results if the actual motion is narrow-banded well above the cut-off frequency.

Another important consideration in filtering is phase distortion [2]. Since a filter uses past information to produce an update at measurement epoch, the output is delayed by an amount of time which is frequency dependent. Such an output cannot be used for heave compensation. Commercially available heave sensors use special filters to reduce the effect of phase distortion but, even with aiding information from log and compass, the results are substantially degraded during vessel turns and accelerations. In post-processing, however, phase distortions can easily be avoided by filtering with past and "future" information.

3. Heave from stand-alone GPS

The authors have demonstrated in a previous paper [3] that epoch-to-epoch GPS carrier phase differences from a single GPS receiver can be used to estimate short-term co-ordinate variations. Under the assumption that there were no cycle slips between epochs j and j+1 the carrier phase ambiguities disappear and the epoch-to-epoch carrier phase difference for measurements to one particular satellite can be written in good approximation as

$$\phi(t_{j+1}) - \phi(t_j) = (\rho(t_{j+1}) - \rho(t_j))/\lambda + \Theta_{clock}(t_{j+1}) - \Theta_{clock}(t_j) + \varepsilon(t_{j+1}) - \varepsilon(t_j)$$

with t_j GPS time at epoch j
ϕ raw GPS carrier phase observation
ρ geometric distance between antenna and satellite
λ GPS signal wave length
Θ_{clock} receiver clock error
ε random measurement error.

If the time difference $t_{j+1}-t_j$ is sufficiently small, i.e. a few seconds, variations in satellite clock and orbit errors will be small enough to be neglected in this phase difference. Variations of the troposphere and the ionosphere over several seconds may influence the difference by more than a few centimetres. By reducing the time difference between observation epochs these influences will decrease tremendously. Tests on a permanent observation site have shown that the influence of the tropospheric and ionospheric variations are less than 5 mm if the time difference is 1 sec or less. Since the difference in geometric distance between antenna and satellite ρ contains the change of the receiver antenna position, the latter can be computed from simultaneous observations of at least four satellites, together with the influence of the receiver clock error difference $\Theta_{clock}(t_{j+1}) - \Theta_{clock}(t_j)$. The result for the change in the antenna coordinates is then only affected by random measurement errors ε.

The change in ellipsoidal height of the antenna, in relation to the epoch time difference, can be interpreted as an observed vertical velocity that must be integrated to obtain heave.

$$h(t) = \int v_v(t)dt + h_0$$

The integration includes the random measurement errors which will result in a random walk as explained in chapter 2. Additionally the neglected changes of tropospheric and ionospheric influences lead to a systematic error if integration is spanned over longer intervals. The frequency behaviour of the errors and, in particular, its dependence on the integration interval poses problems analogous to those encountered with inertial sensors. Thus the arguments regarding filtering and the unavailability of low-frequency information hold just as well as in chapter 2.

4. Test examples

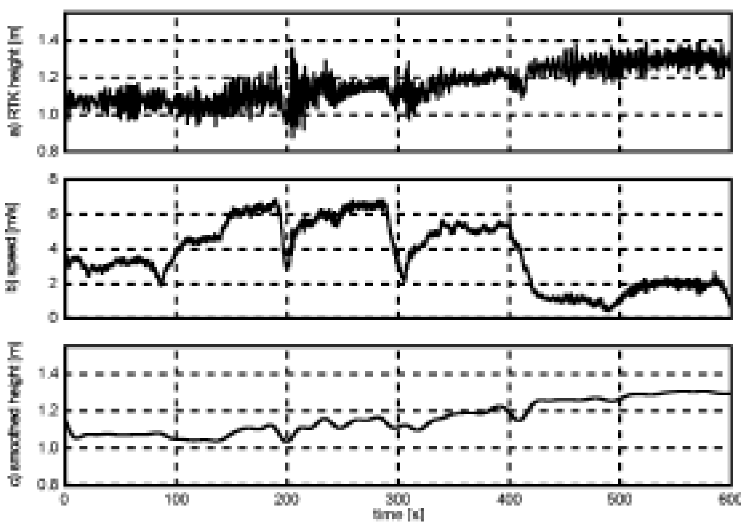
4.1 Test on a surveying boat

On 4.October 2001 a test experiment was performed on boat no. 2 of the surveying vessel "Komet" of the German hydrographic service *(BSH)*. The boat was equipped with a dynamic motion *(heave)* sensor TSS DMS-25, temporarily installed near the boat's centre of gravity in the water line, and a Leica SR 530 GPS receiver, whose antenna was almost exactly above the heave sensor. The test was done on the Jade near Wilhelmshaven, where a SAPOS reference station was available in a distance of less than 5 km. The RTK-solution, stored with a frequency of 10 Hz, can be regarded as representing the actual motion of the antenna. The receiver also stored the raw data with the same frequency of 10 Hz for later analysis.

The motion sensor was connected to a notebook computer on which was stored: heave *(as determined by the DMS in real time)*, roll and pitch angles and the "raw" data, in particular vertical acceleration. The sensor was aided by a GPS *(not however by a compass)*, which also provided the time tags for the 10 Hz data storage.

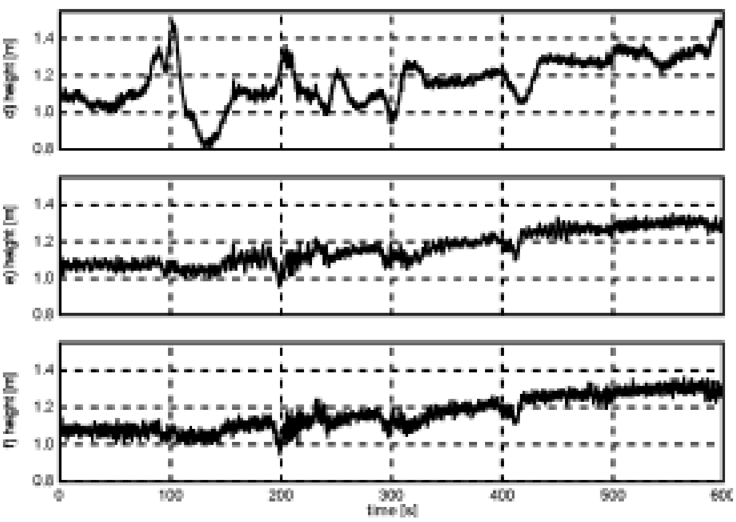
Fig. 1 shows results of the experiment over a time scale of 600 s. In part a) the height of the antenna as obtained from the RTK-solution is plotted. The long-term variation can be attributed to tidal and wind-induced water level changes as the boat is moving. The considerable short-term variation is mainly due to wave action. The test was conducted in a strong wind with short-period waves of about 0.3 m - 0.5 m height. If there was no accurate height determination available, these short-term variations would appear as a noise in the depth soundings. It is therefore desirable to obtain an independent means to correct for short-term variations.

Fig1: Test on boat #2, VS Komet on 4.Oct.2002



It is interesting to compare to fig. 1b) where the speed of the boat over ground is depicted. Obviously there is a correlation between some pronounced speed changes and antenna height variations on the scale of about 1 dm. Here, the dynamic behaviour of the boat *(independent of waves)* is observed. At speeds less than about 4 m/s the boat reacts as a displacement vessel, whereas at higher speeds *(> 5 m/s)* the dynamic lift of a planing craft is dominant. Part c) of the plot shows the RTK-height, smoothed by 20 s averaging. For comparison purposes these smoothed results could be considered as the long-term behaviour of the on-board GPS antenna.

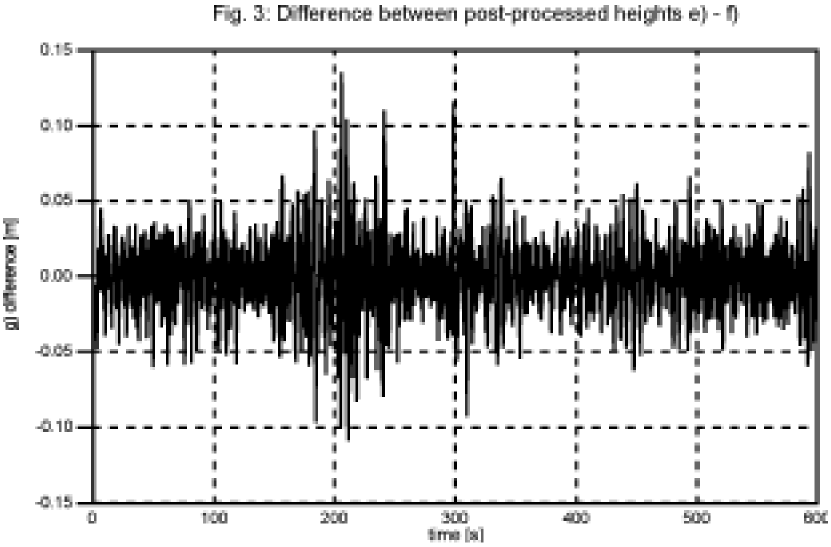
Fig. 2: Corrected heights, alternative methods see Text



In fig. 2 the heave as obtained from different methods has been subtracted from the RTK height. The graphs should therefore show the mean vertical position after heave compensation. The difference between the heave-corrected RTK-height and the smoothed result shown in graph c) of fig. 1 can be used to calculate a comparable standard deviation for the different methods. The standard deviation of the initial RTK-height in plot a) of fig. 1 is derived as 4.1 cm.

For the plot d) in fig. 2 heave has been used as determined in real time in the TSS sensor for the position of the GPS antenna *(remote heave)*. There are catastrophic excursions which, when inspected in comparison with plot b), are obviously caused by lateral accelerations. If the missing compass aid had been available, a decisive improvement would not have been reached as separate tests have shown. The TSS sensor offers the possibility to set the heave bandwidth according to the vessel dynamics and, in our experiment, "short" has been chosen. Since the dynamics of the boat are indeed very fast and the experiment was conducted in rather rough sea conditions, a still shorter bandwidth setting would haven been desirable. For this reason, on the boat's permanently installed motion sensor a specially implemented setting "very short" is used. In d) the standard deviation calculated as described above is 9.7 cm.
For the plot in e) the TSS sensor's raw data have been post-processed as explained in chapter 2 using MATLAB's signal processing toolbox. An 8th order Butterworth digital high-pass filter [4] with 0.2 Hz cut-off has been applied forward and backward such as to avoid any phase distortions. A considerable improvement seems to have been reached. The standard deviation in e) comes down to 2.2 cm.

In part f) of the plot the moving GPS receiver's *(stand-alone)* epoch-to-epoch phase differences have been used to obtain vertical velocity as described in chapter 3. After integration heave was computed using a high-pass filter with 0.1 Hz cut-off. The corrected height shows a similar quality as the one in e), the standard deviation from the smoothing result also being 2.2 cm.



Without an absolute height reference heave is the momentary height deviation from some mean and there is no unique way of determining it. Comparison of e) and f) shows that from a stand-alone GPS receiver the necessary information can be generated with a similar quality as from an inertial system. The difference between the alternative methods is shown in fig. 3. Using these differences, the standard deviation of the corrected heights derived from GPS or heave sensor is calculated as 1.7 cm. In both cases filtering problems are avoided by post-processing.

4.2 Test on a land vehicle

To more thoroughly investigate these methods of heave determination another experiment has been done on a land vehicle on 29.Oct.2001. The same TSS DMS-25 motion sensor was installed, together with a Trimble 4700 series GPS receiver recording at 5 Hz, on a hand-pulled cart. As a venue a BMX bicycle course was chosen so as to be able to rerun the test with a *(nearly)* reproducible height pattern. To check against a good absolute height, a dedicated reference station was installed within 100 m of the track.

The height profile of the bicycle track typically has single or multiple waves with level stretches in between. In frequency language the level stretches show up as a very low frequency contribution to the signal spectrum. As discussed above, to render that part of the spectrum correctly is a “mission impossible” for any kind of stand-alone heave measurement device. One might argue that, in a realistic sea, if there are any waves, there are hardly any smooth portions. However, we have deliberately chosen the scenario as a challenging test case.

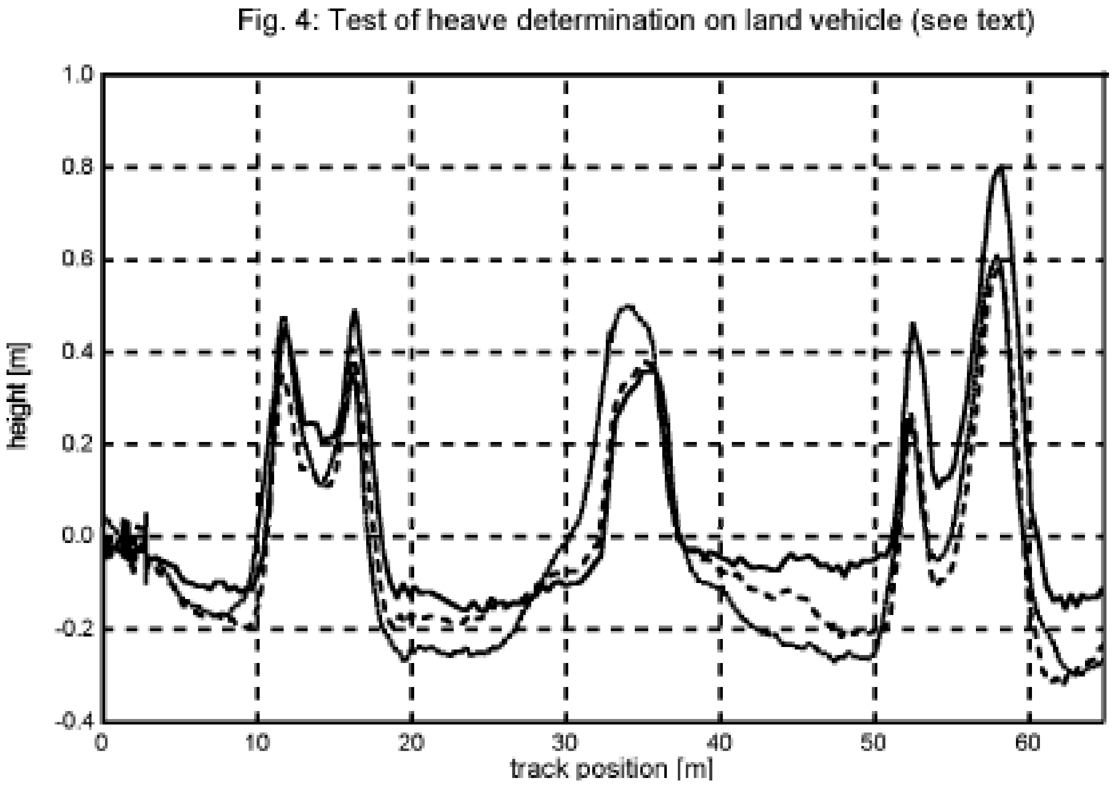


Fig. 4 shows results for the passage of the cart over a series of humps on a straight section of the course. Speed was approximately 1.5 m/s. Height as determined by DGPS with the nearby stationary reference receiver is indicated by the solid curve. The quality of this solution was checked to be better than 1.5 cm. Both of the independent methods of heave determination have been applied to this case and will now be discussed.

Vertical acceleration measured by the motion sensor has been integrated and then passed through a Butterworth 6th order digital high-pass filter with a cut-off frequency of 0.05 Hz. The result is indicated by the dotted curve. A fore-aft offset of 0.5 m to the GPS antenna has been taken into account geometrically. The integrated vertical velocity as obtained from the stand-alone epoch-to-epoch phase differences underwent the same filtering procedure and yielded the dashed curve. As in section 4.1 phase distortions were avoided in post-processing. The direct real-time output of the motion sensor *(with bandwidth set to "medium")* is so poor in this case that it's not worth showing.

Both, dotted and dashed curves are close together, indicating that they represent indeed alternatives with a similar performance. Comparisons with the solid line are, however, not overall satisfactory. Especially at the transitions between up-down and level sections an unrealistic oscillatory behaviour is forced by the necessity of cutting off low frequencies. These pathologic track sections exhibit the limit of state-of-the-art heave determination by stand-alone apparatus.

5. Summary and conclusions

The material presented in this paper points to principal problems of heave measurement.

A method has been developed to determine heave from epoch-to-epoch phase differences of a single moving GPS receiver. An analogous method has been applied based on the raw measurements of vertical acceleration of an inertial motion sensor. The necessary high-pass filtering has been done in post-processing to avoid frequency-dependent phase distortions.

Both methods compare well and perform better than the real-time output of the motion sensor. Especially in situations of lateral vessel acceleration or height profiles with a high bandwidth demand fundamental limitations cannot entirely be overcome.

The authors suggest the application of epoch-to-epoch GPS phase differences in addition to inertial motion sensors since, on most surveying craft, a high-precision GPS receiver is on board anyway. It seems probable that a combination of the two alternative methods could lead to an improvement of vessel autonomous heave determination.

It remains to be investigated whether an overall improvement of real-time systems can be achieved by an integration of GPS and inertial based heave.

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6. References

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