CARRIER PHASE PROCESSING WITH ROBUSTNESS

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ABSTRACT

"Problem" – GPS carrier phase track has been lost. Therefore our mission capability has become lost. Continuity is gone and we've been thrown into limbo. Furthermore, when valid phase information returns we must reacquire – we have to face delay, uncertainty, and various additional operational ramifications that accompany reacquisition. Right?

Wrong. Read on for a solution.

THE GOOD NEWS

The industry has constructed an unnecessary mental equivalence between carrier phase lock continuity and *operational* continuity – but, aside from surveying, most applications don't require locating position to within a volume smaller than a vehicle's size. Performance will be totally acceptable when *velocity* is known to within a few cm/sec while its position is known to within a meter or two. That is achievable without *ever* resolving the cycle count ambiguity, by using

- Pseudorange double differences
- Adjusted triple differences (ATDs) of carrier phase.

Adjustments needed for carrier phase were defined in Ref. [1] and adapted for usage with a low-cost GPS/INS algorithm in Refs. [2-4]. Adjusted triple differences in carrier phase were used in a *dynamics* Kalman filter which then supplied a precise forcing function to a separate 3-state *position* Kalman filter updated via pseudorange double differences, with data collected from a van test in a path shown in Fig. 1 and an attitude history shown in Fig. 2.

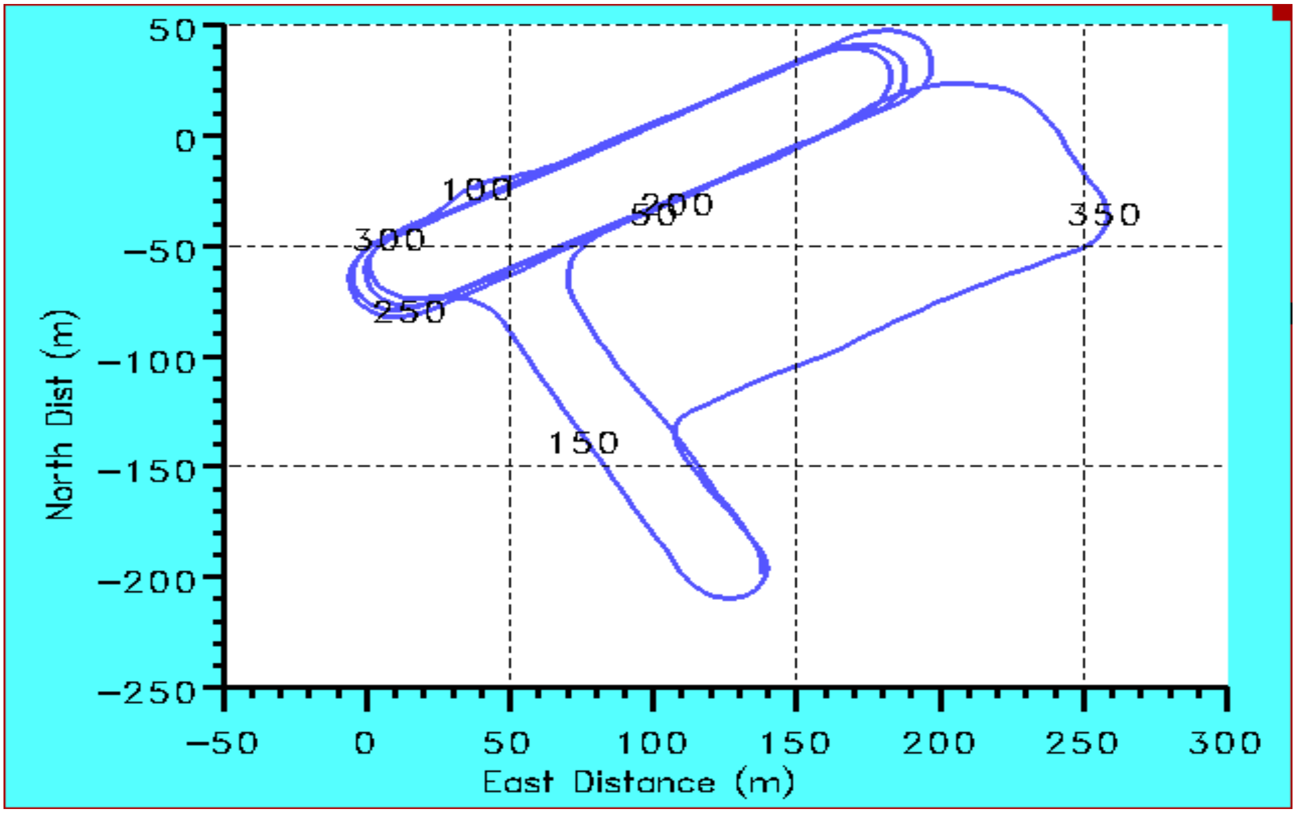

Fig. 1: Path Plan View

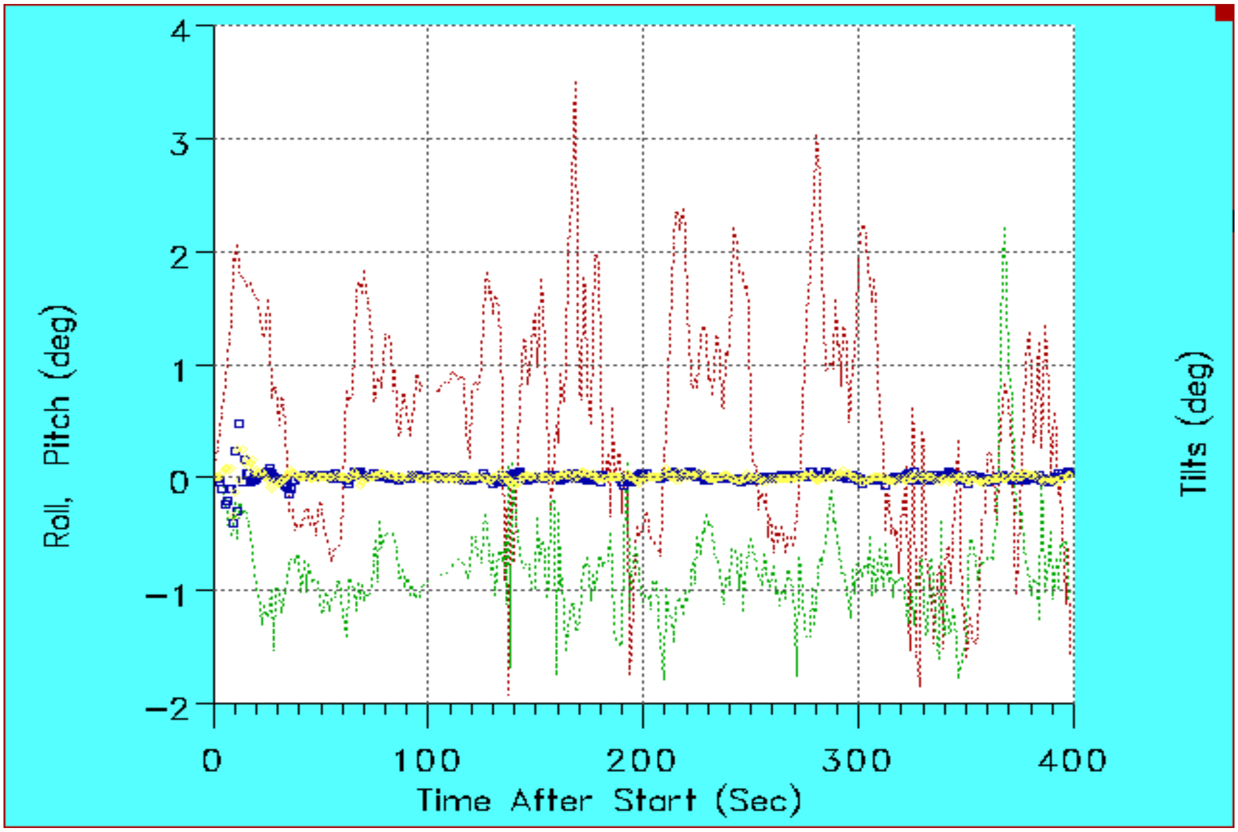

Fig. 2: Attitude and Leveling Corrections

No measurements were edited out in the run that produced this output file. Aside from an assumed *4%* yaw gyro scale factor adjustment (inferred from repeated runs with the same data), the IMU was uncalibrated – spec sheet values were used to interpret the IMU outputs. Initialization transients affected some of the plots (*i.e.*, for approximately the first 30 seconds, consistent with the effective Kalman filter data-averaging intervals used in this processing). With that understanding, these pull-in transients receive only cursory attention in the ensuing description of performance.

The path plan view shows no problems. Numbers represent time elapsed since start of the run. The concurrent plot of attitude exhibits moderate roll and pitch excursions [pitch usually within ±*1* degree from its downward static offset of about a degree, and roll of a few degrees] which coincide with direction changes. Of greater interest are the Kalman filter tilt corrections also shown ("hugging" the abscissa) on the attitude plot; these are a fraction of a milliradian RMS (specifically, about *1/3*-mr as observed from an expanded-scale plot, not shown here) -- indicative of a very close model fit for short-term error propagation. That amount of tilt would only slightly exceed typical error from a nav-quality INS capable of long-term coast. Especially for a low-cost means of tying data together in the short-term { Ref. [5] -- with no pretense of coast capability over extended durations } -- *1/3*-mr per-axis verticality error is quite acceptable for many operations.

Accompanying plots show residuals in pseudorange (Fig. 3) and carrier phase (Fig. 4):

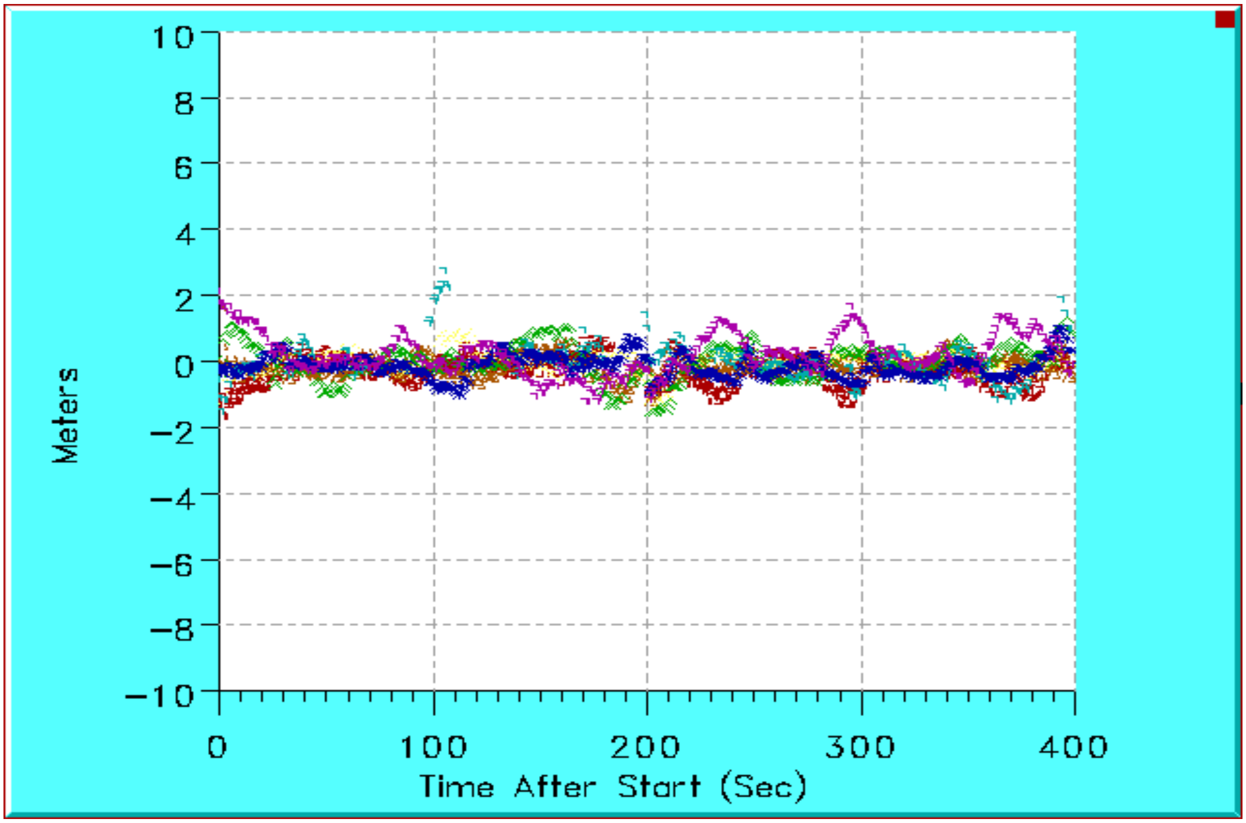

Fig. 3: Pseusorange Residuals

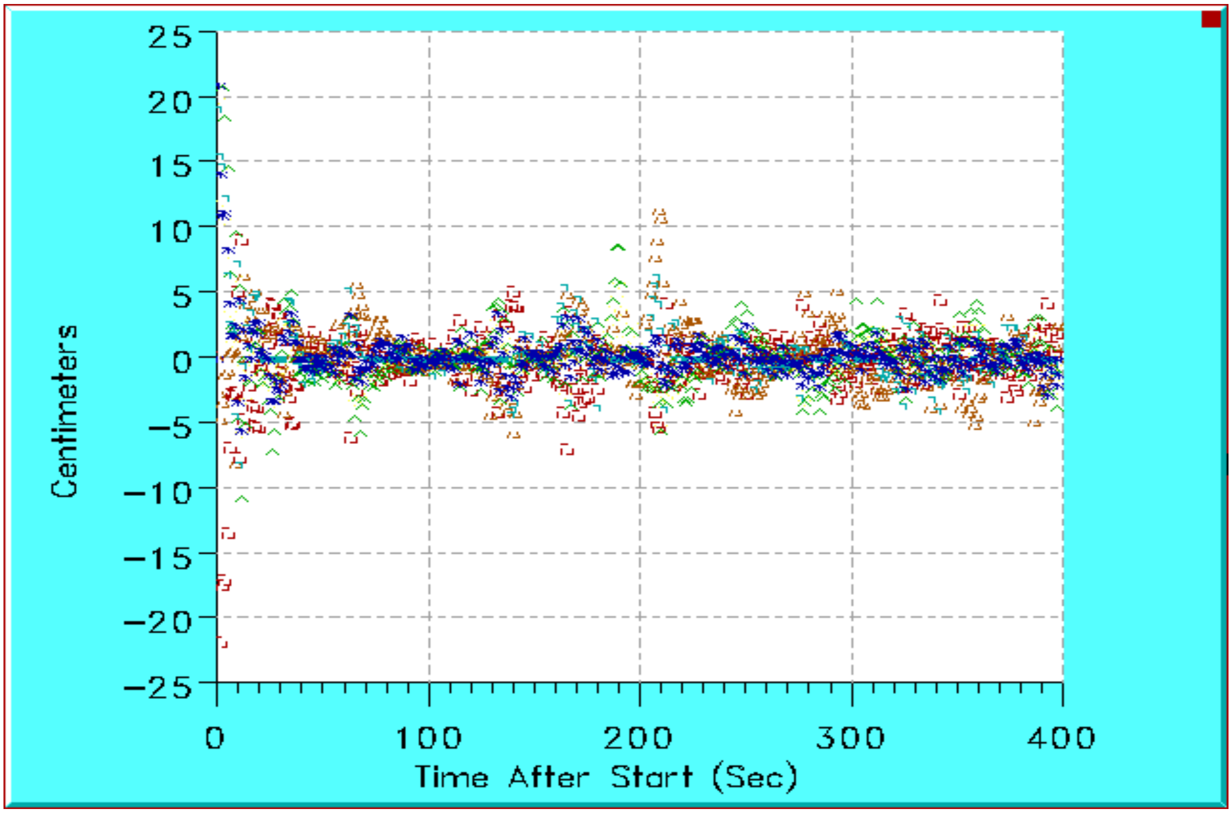

Fig. 4: Phase Residuals

The total range of about three meters for pseudorange residuals implies an RMS value on the order of a half-meter. Amplification by any reasonable GDOP still produces position accuracy quite acceptable for most non-surveying applications. For carrier phase, behavior exhibited within certain time periods was governed by transients (not representative of tracking capability):

- *Initial pull-in*: As previously noted
- *Switching events*: At 184 seconds the SV used as differencing reference underwent loss of carrier phase lock, and subsequently recovered at 203 seconds. In the interim another SV of course had to be used as subtraction reference. Residuals were affected only momentarily.

Performance outside of those time periods varies slightly with dynamics. Phase residuals rarely exceed 5 cm. The larger residual values correspond in time and direction to turns (therefore clearly arising from short-term motion-sensitive inertial instrument degradations). Significantly, in another road test conducted with fewer turns, a 4-cm maximum absolute value was exceeded only by short-lived excursions a few cm larger – and it was noticed that those were all from one SV. At first a check was made to see whether that was the lowest elevation satellite; since that was not the case, multipath was not suspected. It was then investigated whether the double differences from that SV were changing faster than those from other satellites; since that was not the case, minor time-alignments were not deemed necessary.

Finally it was noticed that the SV (#3) with the larger residuals dropped phase track shortly after veering off -- which happened while experiencing dynamics. The obvious conclusion is that the receiver was loosening phase track on that SV. If the scope expanded to access the receiver's internal processing and include what the industry calls “ultra-tight” coupling – wherein velocity history is used as an aiding signal to maintain phase continuity – loss of phase lock could be avoided while also improving phase track performance for every channel during turns and speed changes. To use the experience just noted as a guide, that step could then produce improved ATD residuals during dynamics -- precisely when improvement would be most valued.

Aside from the transients at acquisition and at ref-SV switching, previously noted, phase residuals of about *5* cm maximum absolute value imply less than *2*-cm RMS level. Since the total residual level represents the RSS of measurement variance with the contribution from state uncertainty (Kalman's $\mathbf{HPH}^T$), this implies that state uncertainty alone is less than *2*-cm RMS. Furthermore, for the larger residuals, $|\mathbf{H}|$ is closer to *2* than to *1*; thus the RMS velocity error from Kalman's uncertainty covariance matrix **P** is smaller still. To be complete, the last statement applies only to the largest residuals – but the smaller ones (already below sub-cm RMS) don't need further reduction. Velocity estimates, then, perform at a level to be expected of carrier phase data.

Before leaving this subject it is recalled that, as triple differences, there is a factor of ($2 * 1.414$) separating these values from the RMS error in each individual phase measurement. In combination with the additional factor just discussed, within the range (*1.414* to *2*) to account for RSS of $\mathbf{HPH}^T$ with measurement error variance, this translates into RMS individual phase measurement errors well below a cm. The data collection was obviously done with precision.

If cm/sec velocity and *1/3*-mr RMS verticality cannot satisfy system needs, further refinement is available. Performance just shown was obtained with carrier phase treated as *1*-Hz samples, sequentially uncorrelated. With sequential correlations included (from running accumulations for integrated doppler), errors in both velocity and attitude could be further reduced. For Kalman estimation averaging time values used here the reduction would be less than an order of magnitude but, with a higher quality IMU, the improvement could be more dramatic.

Immediately a frequently overlooked caveat is warranted here: IMU quality is ***not*** to be judged on the basis of the usual quotes in terms of deg/hr ("steady" drift) or nmi/hr (nav). Other effects such as accelerometer degradations and the type of gyro cross-axis miscalibrations described in Ref. [5] – and shown herein to correlate with increases in residuals – are far more important for ***instantaneous*** performance in the short-term. The nmi/hr figure, a theoretical average during cruise conditions over a Schuler period, is ***irrelevant*** in this and in many other applications.

Other plots (not shown) were made to show additional time histories such as

- ***Speed*** : Variations from near-zero to nominally *15* m/sec were recorded.
- ***Altitude*** : Van altitude estimate stays within (*-1*:*+3*) meters of ground receiver altitude.
- ***Azimuth drift*** : After pull-in, the heading estimate stayed generally within a degree of the changing (turning) velocity vector direction. Deviation increased to a few degrees only when the speed was low (heading error transients are not important at speeds near zero). It was verified that the heading, not the velocity vector direction, veered. This is as it must be, since velocity is highly observable while vehicle heading is deduced only indirectly.

FURTHER APPLICATIONS

One way of describing the IMU's function is that of a quick-react dead-reckoning device between updating observations. A GPS/INS Kalman filter with effective memory longer than vehicle maneuver time (*i.e.* an estimator without high responsiveness) can track satellite signals, despite abrupt changes in speed and/or direction, due to information supplied by the IMU. Opportunity thus exists for extending this operation: in many applications the path to be determined does *not* undergo radical maneuvers within the Kalman filter's effective averaging duration {the entire realm of air-to-air tracking depends on ability to use simple kinematics[§] as the only dynamic model for Kalman tracker averaging durations of a few seconds; see, for example, Ref. [6] – which was the basis for many real-world implementations with radar and E/O sensors}. More pertinent here, the opportunity extends to operations wherein IMU data cannot be accessed by the computer used for path determination – during flight phases with little or no maneuvering. An airborne or ground observer receiving ADS-B transmissions {Refs. [7,8]} – containing raw measurements rather than coordinates as explained in Ref. [9] – will then be able to reconstruct a highly accurate path history for the transmitting vehicle. This offers a much-needed capability for future generation ATC (Air Traffic Control) operations including collision avoidance – both in-air and on surface (to prevent runway incursions).

SUMMARY

Velocity and attitude accuracies commensurate with carrier phase operation are achieved with no attempt whatever to resolve cycle ambiguities. Performance with a low-cost IMU is easily acceptable for a variety of applications. Van test has validated the method, even without the benefit of accounting for integrated doppler's running accumulation character (measurement errors were treated as sequentially independent). Aside from moderate disturbances from either turns (motion-sensitive IMU errors) or a receiver losing its grip on phase lock, residuals agree with theoretical levels. The approach is extendible in two important directions:

- *No ground station* . With SA off, sequential differences in SV clock error largely cancel.
- *No IMU* . Flight paths in near-straight-and-level phases can be accurately determined on the basis of GPS data alone – with complete robustness even while carrier phase is highly intermittent (as long as it does not disappear completely for extended durations).

Overall implications are expected to be quite far-reaching for future applications.

[§] The classical meaning is intended in this context for "kinematics" – i.e., referring to stamdard relations between position, velocity, and acceleration.

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