RTCA Special Committee 186, Working Group 3
EUROCAE WG-51, SG-1

ADS-B 1090ES MOPS Maintenance

WG-3 Meeting #27
SG-1 Meeting #4
Joint Session

United Airlines Operations Center
Elk Grove Township, near Chicago Illinois
12 – 15 May 2009

Issues Related to Vertical Rate Estimation for Squitter Transmissions In Response to Action Item 26-09

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Summary
This Working Paper addresses the issue of how a UAT should calculate the Vertical Rate based on barometric altitude measurements. It focuses on issues that may arise on so-called "minimal installations" (e.g., small general aviation aircraft). ***This Working Paper was originally presented during the UAT MOPS RTCA SC-186 WG-5 Meeting #23 as Working Paper UAT-WP23-06. The text of this Working Paper has not been altered from the original. As discussed during the WG-5 meeting, the resolution of this issue may require an ADS-B MASPS change, and as such should be well understood and agreed upon by WG-3 as well.***

This paper deals with the determination the most appropriate way to use barometric altitude measurements to calculate the Vertical Rate as transmitted as part of the Vertical Velocity field in the State Vector element of all defined message types. It addresses minimal installations (e.g., those on a small general aviation aircraft in which the Vertical Rate derivation may be based on 1 Hz altitude samples from an existing pressure altitude encoder with a 25-foot [or 100-foot] least significant bit) rather than installations with air data systems. According to the UAT MOPS (RTCA DO-282A), the Vertical Rate is based on a Geometric Source or a Barometric Source depending on whether the UAT is in the *Precision* or *Nonprecision* condition, respectively (assuming both are available). A UAT is in *Precision* condition whenever its NAC_p is 10 or higher or its NIC is 9 or higher; otherwise, the UAT is in *Nonprecision* condition. The MOPS do not give any detailed guidance as to how the barometric rate should be determined. It should be noted, however, that the ADS-B MASPS (RTCA DO-242A) Section 2.1.2.8 has the following note: "Future versions of this MASPS are expected to include requirements on the accuracy and latency of barometric altitude rate." Some reasonable alternatives are discussed below.

As defined in Section 2.2.4.5.2.7.1.3 of DO-282A, the Vertical Rate is a 9-bit field representing the magnitude of the Vertical Velocity. Its least significant bit has a value of 64 feet/minute. One simple method for calculating the Vertical Rate is to take the difference in altitudes as measured each second and multiply by 60 to convert from seconds to minutes. This technique was tested during the development of the UAT Beacon Radio (UBR)[1] by The MITRE Corp. It has the advantage of being able to react quickly to vertical accelerations; however, it has the disadvantage of producing a very noisy measurement due to the multiplication by 60.

A unique opportunity to study this issue arose during tests of the UBR in which a single aircraft was equipped with both an UBR and a Garmin GDL-90 UAT. The UBR is always configured to transmit the barometric rate, and the GDL-90 was transmitting the geometric rate due to the high NAC_p and/or NIC values it experienced during the flight segment under discussion. An example of the different outputs is shown in Figures 1 and 2. Note that these two plots represent the same segment of flight. Also, note the difference in vertical scales.

[1] The UAT Beacon Radio is an IR&D project at MITRE --- examining the potential for small, self-contained, potentially portable UAT installations.

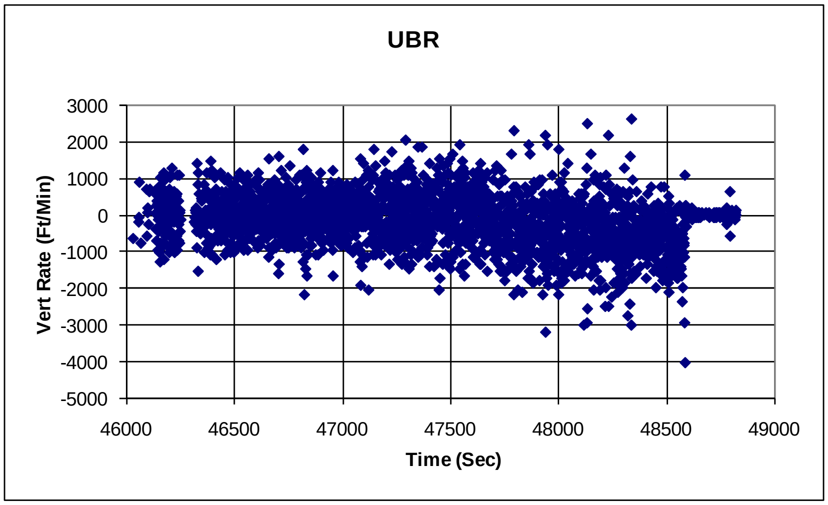

Figure 1. UBR Vertical Rate Reports

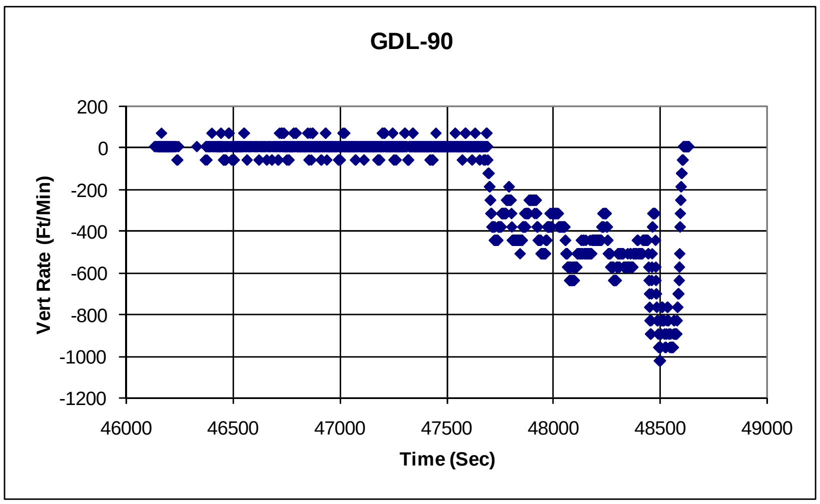

Figure 2. GDL-90 Vertical Rate Reports

The Vertical Rate as reported by the UBR is so noisy as to mask the actual motion as reported by the GDL-90. The noisiness of the one-second-difference method can be quantified by plotting the deviation from zero during a time of level flight. This is shown as the dots in Figure 3. The line represents the distribution expected if the errors of the two barometric altitude measurements used in the difference measurement are statistically independent and are uniformly distributed over a 25 foot range (which corresponds to the significance of the altitude sensor's least significant bit). Mathematically, this is the convolution of two rectangular distributions. The range is ±1500 feet/minute due to the change from seconds to minutes (25 x 60 = 1500). The match is pretty good.

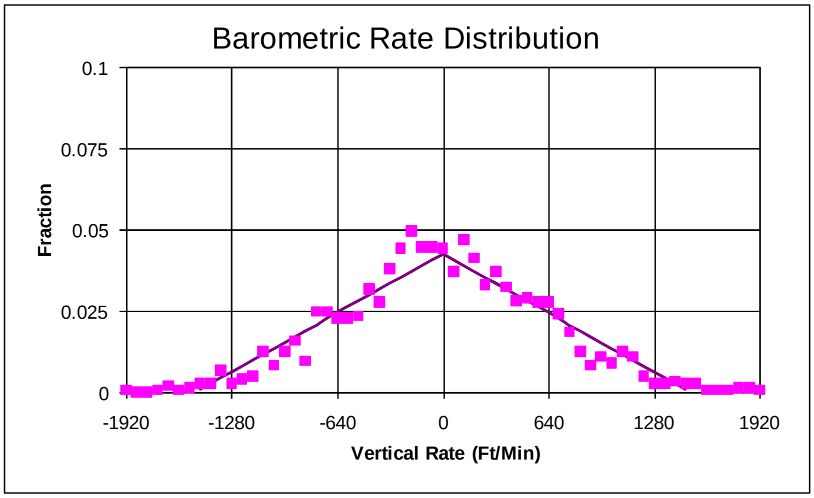

Figure 3. Barometric Rate Error Distribution

A similar plot for the geometric rate broadcast by the GDL-90 is provided in Figure 4 for comparison. Note the difference in the scales of the axes; in this case the rate error is predominantly zero, with just a few samples at ± 64 feet/second. Presumably, the geometric rate is so well-behaved because the GPS engine that provides it includes some type of sophisticated filtering that combines all the position and velocity information at its disposal. In fact, most GPS units employ some sort of (proprietary) Kalman filter.

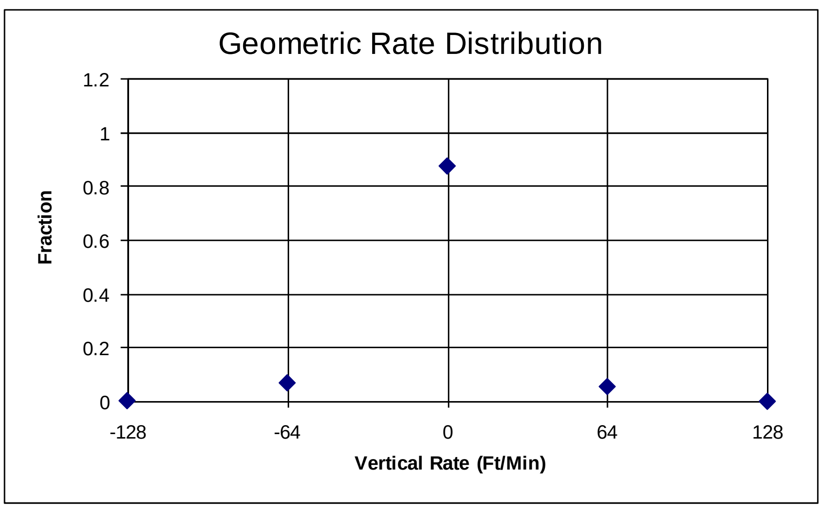

Figure 4. Geometric Rate Error Distribution

In seems that, in order to provide useful information, the UAT should also filter its barometric rate estimate prior to transmission. The goal of this filter should be to reduce the measurement error without introducing excessive latency. There are a number of potential choices.

One simple class of filters can be generalized as follows:

$$V(n) = 60\sum_{k=0}^{K} a_k \left(H(n-k) - H(n-k-1)\right)$$

$$\sum_{k=0}^{K} a_k = 1$$

$H(n)$ is the altitude that is measured each second (measured in feet). The factor of 60 is due to the fact that the Vertical Rate is reported as feet per minute.

(1) The simple method of reporting the "instantaneous" rate corresponds to setting

$a_0 = 1$

$a_k = 0$ if k>0

(2) Taking the moving average of the most recent K measurements corresponds to setting

$a_k = 1/K$ if 0≤k<K

$a_k = 0$ otherwise

Note that this filter can be rewritten as follows:

$$V(n) = \frac{60}{K}\sum_{k=0}^{K-1}\left(H(n-k) - H(n-k-1)\right) = \frac{60}{K}\left(H(n) - H(n-K)\right)$$

(3) A simple recursive filter (which is an easily implemented weighted average) is given as follows:

$V(n) = (1-\beta)\,V(n-1) + 60\,\beta\,(H(n) - H(n-1))$ if n>0

$V(0) = v_0$

This corresponds to setting

$a_k = \beta(1-\beta)^k$ if 0≤k<n

$a_n = (1-\beta)^n$

$a_k = 0$ otherwise

(4) A slightly more complicated example is an alpha-beta filter. It is a recursive filter given by the following equations:

$$x(n) = \alpha\ H(n) + (1-\alpha)\ (x(n-1) + V(n-1)/60)$$

$$V(n) = 60\ \beta\ (H(n) - x(n-1)) + (1-\beta)\ V(n-1)$$

In these equations, $x(n)$ is a smoothed altitude estimate. For critical damping, $\alpha = 2\sqrt{\beta} - \beta$. Note that filter (3) is a special case of (4) with $\alpha = 1$.

Below are some examples of how well these filters do. The scenario depicted begins with an aircraft flying level, with a small amount of up and down movement (±100 feet) for about 1350 seconds. The bobbing motion then ceases for about 150 seconds. Finally, the aircraft smoothly descends at a rate of 480 feet/minute. The noise processes are assumed to result in a total altitude measurement error with a rectangular distribution extending over ±12 feet.

The true pressure altitude versus time profile of the flight is shown in Figure 5.

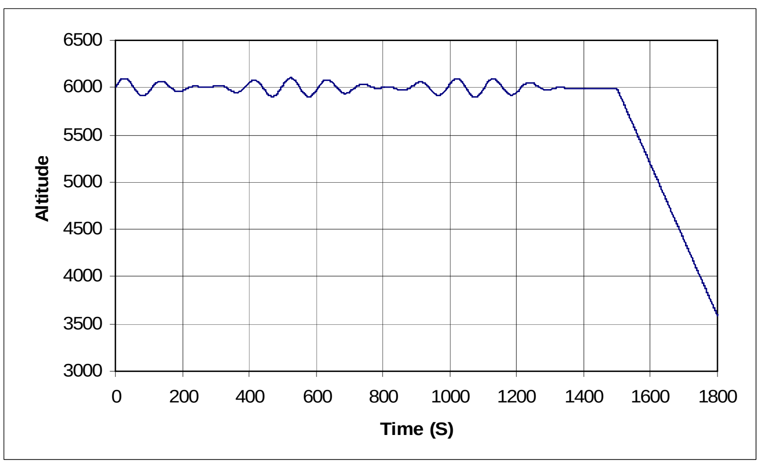

Figure 5: Barometric Altitude versus Time

Figure 6 shows the raw Vertical Rate measurements that result from this profile and the assumed noise. This graph looks a lot like what was seen in the data from a number of flights.

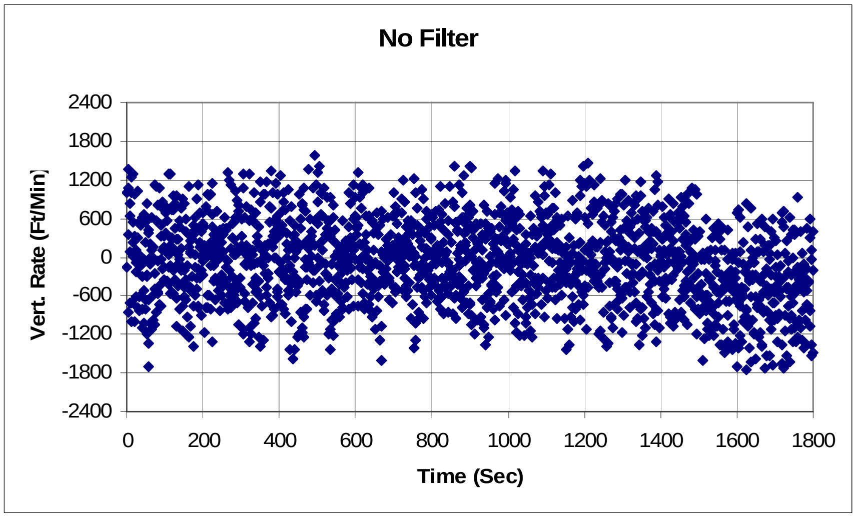

Figure 6. Noisy Vertical Rate Reports

If we apply filter (2) to these data, with K = 30, we get Figure 7. The magenta curve represents the correct vertical rate --- that due to actual aircraft motion. The blue dots are the output of the filter.

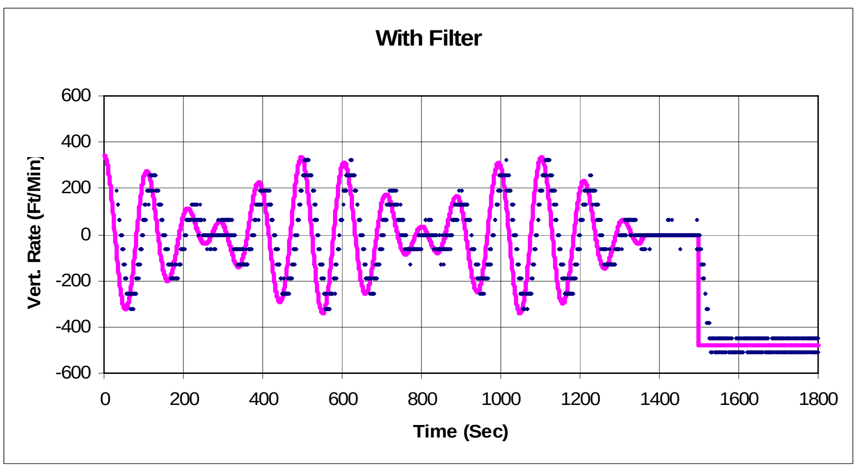

Figure 7. 30-Second Moving Average

Figure 8 shows what filter (3) does to the noisy data if $\beta = 0.08$.

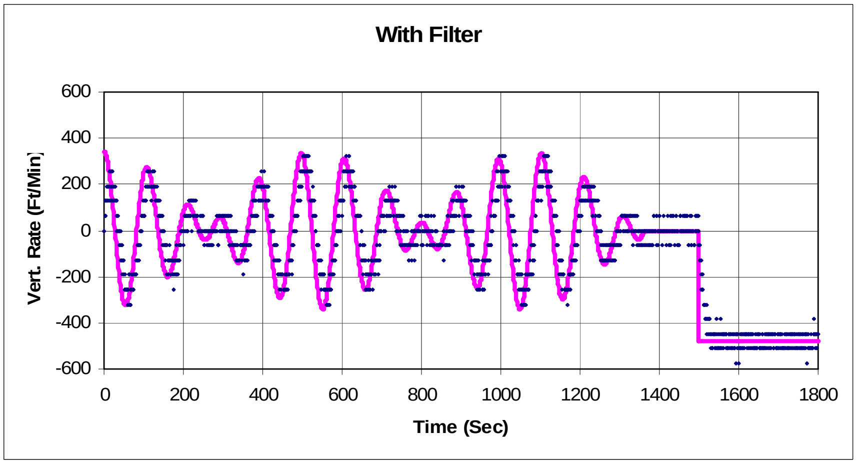

Figure 8. Recursive Filter with $\beta = 0.08$

Finally, the alpha-beta filter, with $\alpha = 0.36$ and $\beta = 0.04$, yields Figure 9.

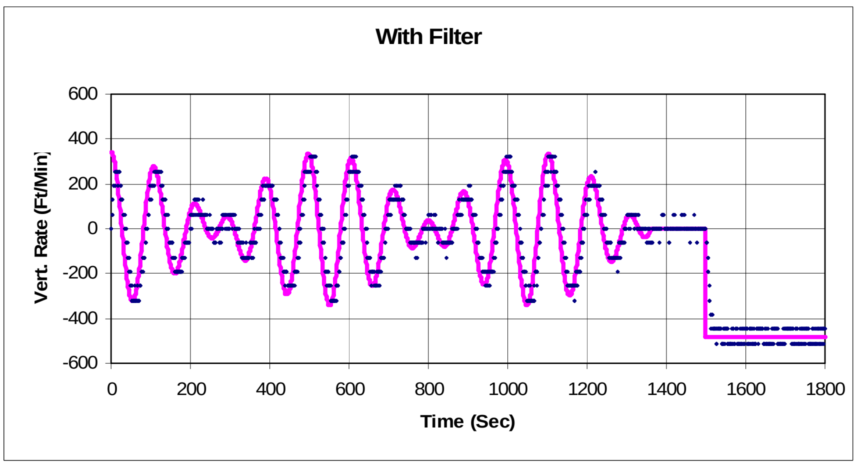

Figure 9. $\alpha - \beta$ Filter with $\alpha = 0.36$ and $\beta = 0.04$

The parameters of the filters were chosen so that all of them would have a similar capability to extract the true Vertical Rate from the noisy data in the particular environment chosen. [Note that there are still some subtle differences in performance. For example, there is a noticeable delay in the first filter that gets reduced in subsequent filters.] If we keep the scenario fixed but change the parameters to improve noise filtering, relative performance can vary. For example, if the filtering is doubled in each case, the results are shown in Figures 7a, 8a and 9a. The filter outputs get less noisy, but the delays increase. In the case of the first two filters the estimates are also unable to keep up with the rapidity of the real Vertical Rate changes to such an extent that they cannot report the maximum rates. The $\alpha - \beta$ filter performs better in this regard. Other combinations of aircraft motion and noise may give different results.

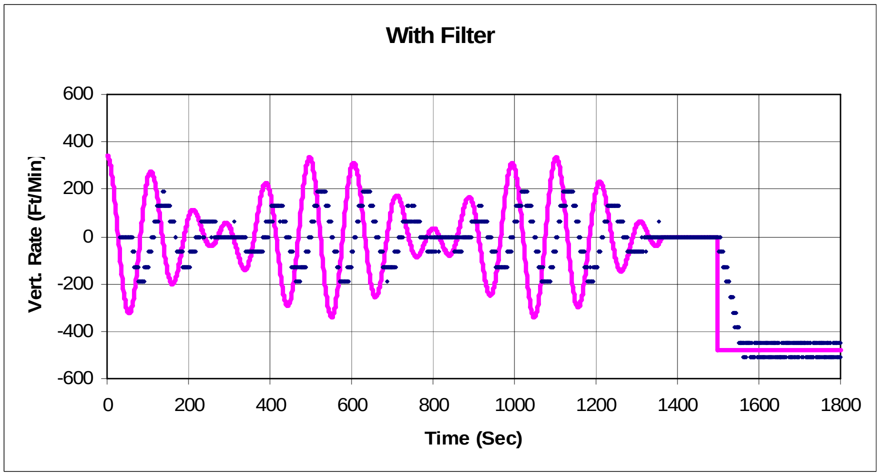

Figure 7a. 60-Second Moving Average

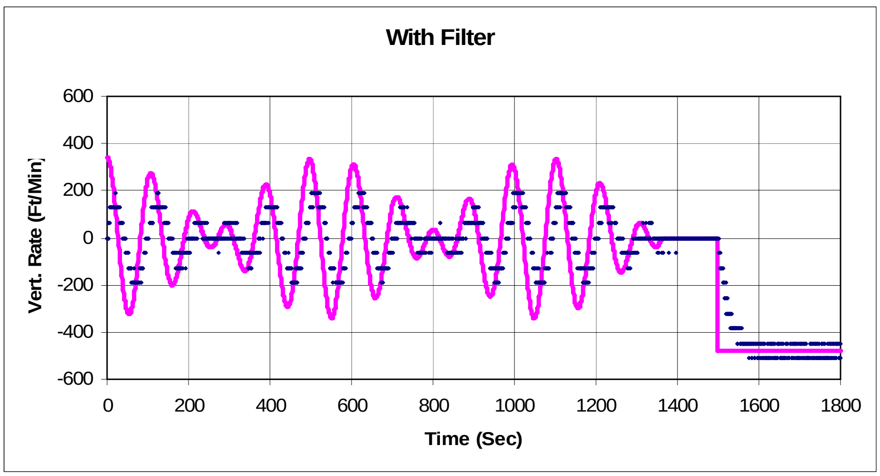

Figure 8a. Recursive Filter with $\beta = 0.04$

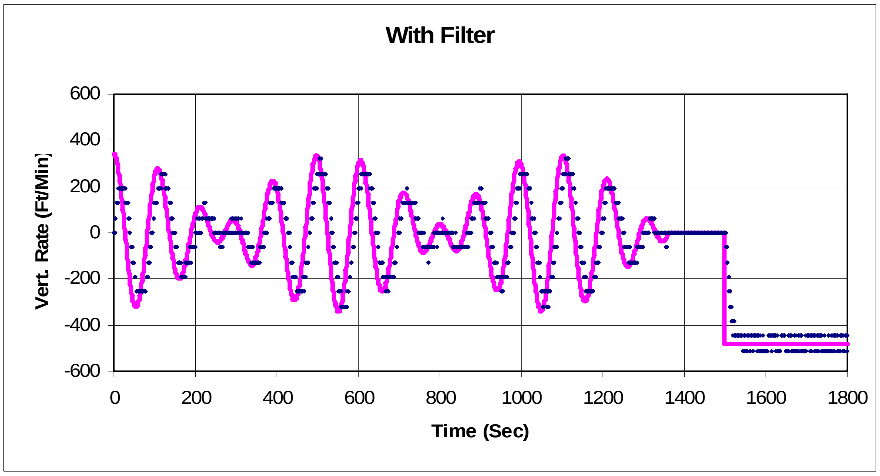

Figure 9a. $\alpha - \beta$ Filter with $\alpha = 0.263$ and $\beta = 0.02$

In summary, all these filter types can do a pretty good job. It seems that (4/alpha-beta) is better than (3/recursive), which is better than (2/moving-average). Filter (4) seems the best at tolerating a wider range of scenarios. There are other, more sophisticated filters, such as a Kalman filter; but one of these may suffice.

Note that in most cases the current version of the UBR uses the simple type (2) filter with K = 4. In other words, the difference is averaged over 4 seconds. The performance of this type of filter, showing a small portion of the same scenario as Figure 5, is shown in Figure (10). This appears to be an adequate compromise between noise reduction and latency. For certain Emitter Categories, where very high accelerations might be common, the K factor remains at 1. (The specific categories are Highly Maneuverable [6] and Space/Transatmospheric [15].)

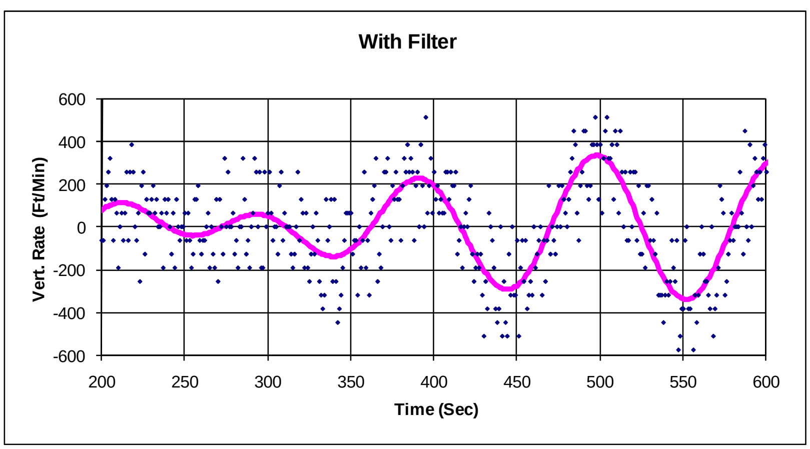

Figure 10. 4-Second Moving Average

A different type of installation with a sensor whose least significant bit corresponds to 100 feet would presumably need to average over 16 seconds to achieve the same accuracy as that shown in Figure 10. In that case, it might happen that a significant latency would be introduced. This case has not been studied.

Summary

Experience has shown that Vertical Rate broadcasts based on second-by-second altitude estimates may need to be filtered so that the measurement noise does not overwhelm the actual aircraft motion. There is always a trade-off between noise filtering and latency, and judgment must be used to arrive at an acceptable compromise. There are many choices for implementing such a filter; however, it appears that a simple averaging technique works well in most cases when tested on general aviation aircraft. Whether this will be suitable for *all* UAT applications depends on the accelerations that are expected to be experienced and the resolution of the pressure sensor. For example, if the resolution is 100 feet instead of 25 feet, the averaging time might need to be increased by a factor of 4 in order to get the required accuracy; however, this would introduce extra latency that might render the UAT incapable of following accelerating maneuvers.

An alternative approach would be to broadcast the Vertical Rate based on GPS whenever it is available, regardless of the NAC_p and NIC values. There are well-known reasons why the Pressure Altitude is an important parameter to be transmitted, but the geometric *rate* may be a more useful parameter than then barometric *rate* (especially if the least significant bit of the pressure sensor corresponds to 100 feet). (Because the real difference between the barometric and geometric altitudes is expected to change relatively slowly, the real difference between the two *rates* will normally be very small.) This would probably require a change to the ADS-B MASPS.

Recommendations

It is recommended that WG-5 of SC-186 consider whether or not it should address this issue:

(1) The WG-5 could examine vertical rate performance of a set of GPS sensors and compare that with the expected performance based on the barometric rates derived from both 25-foot- and 100-foot-resolution sensors. If geometric rate shows more consistent performance, consider allowing geometric rate *only for minimal installations*.

(2) If, instead, the barometric rate is required, WG-5 could provide performance requirements that would allow for the definition of an adequate filter design, if possible.