The Theory and Performance of NovAtel Inc.'s Vision Correlator

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BIOGRAPHY

Mr. Patrick Fenton is currently Vice President and Chief Technology Officer at NovAtel Inc. Mr. Fenton was appointed Chief Technology Officer in January 2002 and became an executive officer of the Company in April 2003. Mr. Fenton has held various research and development roles within NovAtel since the company ventured into GPS product development in 1989. Mr. Fenton holds a key role in developing core products that have positioned NovAtel on the leading edge of GPS and other precise positioning technologies. He made his mark on the GPS industry as inventor of the Narrow Correlator technology. This technology and follow-on multipath reduction techniques have revolutionized the accuracy of the public accessible C/A code GPS signal, leading the way to sub-meter positioning. Pat has developed, published and patented many other receiver improvement technologies. He received his geomatics engineering degree from the University of Calgary in 1981. Pat is a Fellow Member of the Institute of Navigation (ION), has served as ION '98 Technical Chair and has Chaired or Co-Chaired many technical sessions at ION conferences.

ABSTRACT

This paper provides an overview of the general principles and early performance results of the Vision Correlator. The Vision Correlator is a new method of measuring and processing the synchronization signals of a received PRN code. It is a significantly different process than any of the various correlation methods used in GNSS receivers today. It works by precisely measuring the received Radio Frequency (RF) characteristics in the time domain of the phase transitions of the modulated signal broadcast from the satellite. It is particularly useful in detecting and removing close-in multipath. Simulation results show that the Vision Correlator can remove the effects of a multipath signal on the code and carrier measurements when the delay of the multipath signal is less than 10m from the line of sight signal, and mitigate their effect to a fraction of a meter (code). It also provides a very useful statistic that can be used for Signal Quality Monitoring of the received signal. This statistic can be used to filter data that is unrepairable.

INTRODUCTION

NovAtel Inc. has been incrementally developing GNSS signal processing methods to reduce the effects of multipath for over 16 years. A list of the processes that have been developed and their dates of introduction into product include:

- Narrow Correlator (1992), [1], [2]
- Multipath Eliminating Technique (1994), [3]
- Multipath Eliminating Delay Lock Loop (MEDLL) (1996), [4]
- Pulse Aperture Correlator (PAC) (1999), [5]

The Vision Correlator is based on a large body of early work that was licensed from Dr. Ben Fisher and Dr. Larry Weill of Comm Sciences Corporation (CSC) in development of their Multipath Mitigating Technique (MMT). Their early published papers include [6] and [7]. According to Drs. Weill and Fisher, this technique very nearly reaches the theoretical limit of accuracy called the Cramer Rao Boundary. Further improvements and optimizations were developed at NovAtel through the process of commercialization of this technology, and NovAtel has licensed all commercial rights to these patents and works.

STANDARD CORRELATION

Standard Correlation is accomplished by correlating the incoming signal (assuming the signal has been down converted to base band), with a locally generated replica of the broadcast PRN code.

$$Cor_{\tau} = \sum_{t=0}^{T} s(t) * CA(t+\tau) \qquad (1.0)$$

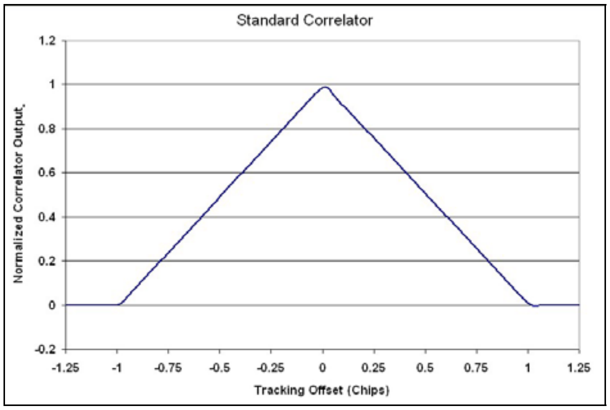

Figure 1 Standard correlation output of GPS Prnl

The Standard Correlator, represented mathematically by Equation 1, output value represents the sum of all of the RF samples multiplied by a locally generated PRN code operating at a specific code phase delay. Fig 1 represents a typical Correlation function sampled at the continuum of code phase delays between +/- 1 chip from zero offset. Although the small variations from a perfect straight line can been seen in the correlation function (Fig 1), due to RF anomalies and the presence of multipath, a significant amount of the fine detail of the RF chip transitions are lost due to this summation process.

All prior and current receivers use various combinations of Standard Correlator measurements to perform their functions.

THE VISION CORRELATOR

The Vision Correlator uses a significantly different process in the hardware within the receiving equipment to collect GNSS signals. The fundamental principle is to measure the Radio Frequency (RF) properties of the chip transition in fine detail. One of the unique properties of signal containing PRN ranging code is that there are typically hundreds of thousands of chip transitions happening per second. Each transition is fundamentally the same as the others. The 1 to 0 transitions are identical to 0 to 1 transitions except that they are inverted. Fig 2 illustrates in the time domain the signal modulation of the base-band In-Phase channel during a sequence of PRN codes.

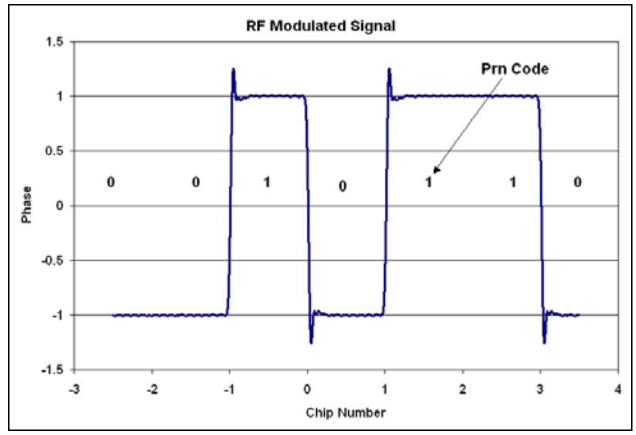

Figure 2 Time domain simulation of the In-phase channel of a GPS receiver

The Vision Correlator is generated by filtering all of the transitions over a period of time. A clear picture of the transitional "shape" can be extracted. Fig 3 represents an average bit transition shape as measured from a specific satellite and GPS receiving equipment.

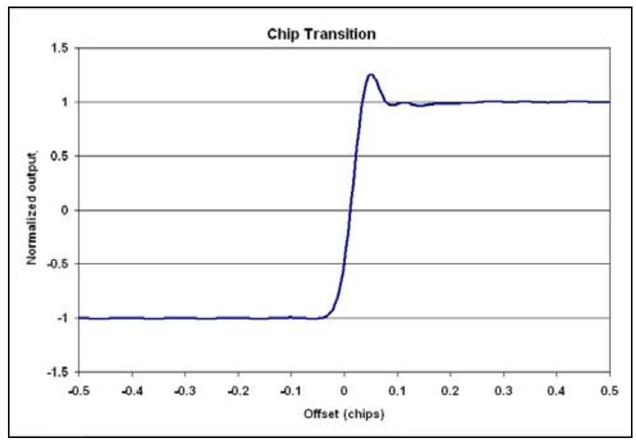

Figure 3 Average chip transition of GPS PRN 1 as measured using NovAtel ME3 GNSS receiver

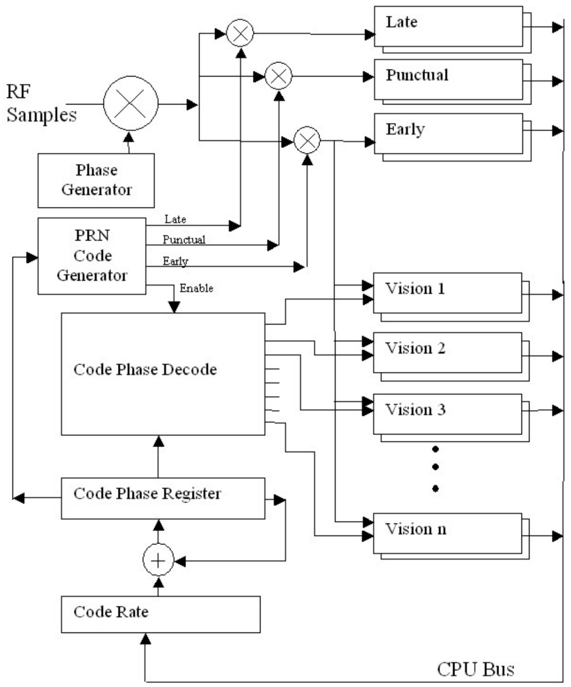

Figure 4 Vision Hardware

Fig 4 shows an overview of the necessary hardware circuitry required to accomplish the new signal processing necessary to extract the Vision Correlator data. The advanced Vision Correlator hardware filters the noise by super-imposing successive chip transitions during a specific time interval to form an average chip transition "shape". Illustrated in Fig 5, the Vision Correlator Samples consist of a vector of discrete complex measurements that represents the chip transition shape. A detailed description of the Vision hardware can be found in [9].

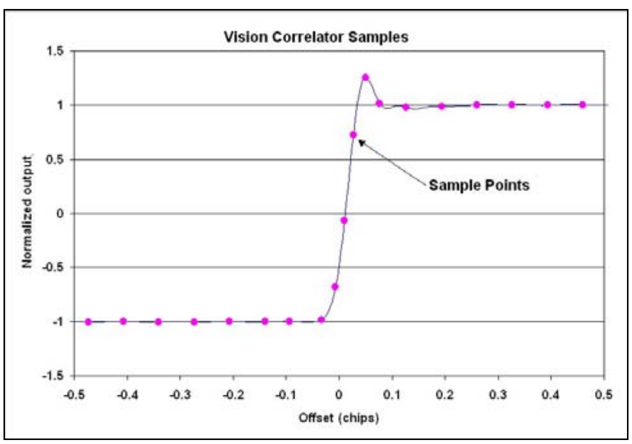

Figure 5 Vision Correlation measurements

The Vision Samples are then processed through the Multipath Mitigating Technique (MMT).

A BRIEF DESCRIPTION OF MMT

The MMT process is an algorithm that processes an array containing pulse shape information to produce an estimate of the Direct Path Signal and one or more MultiPath Signals. Each signal is represented by 3 parameters: $[\tau, A, \theta]$. τ represents the time offset or code delay, A represents the amplitude, and θ represents the carrier phase angle. The basic form of a MMT algorithm that extracts the direct path signal, $[\tau_d, A_d, \theta_d]$ and two multipath signals, $[\tau_{mp1}, A_{mp1}, \theta_{mp1}]$ and $[\tau_{mp2}, A_{mp2}, \theta_{mp2}]$ takes the form:

$$\left[\tau_d, \mathrm{A}_d, \theta_d, \tau_{mp1}, \mathrm{A}_{mp1}, \theta_{mp1}, \tau_{mp2}, \mathrm{A}_{mp2}, \theta_{mp2}\right] = f\begin{bmatrix} I_1, Q_1 \\ I_2, Q_2 \\ I_3, Q_3 \\ \bullet \\ \bullet \\ \bullet \\ I_n, Q_n \end{bmatrix} \quad (2.0)$$

where the array of I_i, Q_i values are the measured complex "shape" samples measured at discrete code phase offsets along the length of the expected PRN chip, as illustrated in Fig 5.

OVERCOMING COMPUTATIONAL PROBLEMS IN MINIMIZING Γ (THE MEDLL CHALLENGE)

$$\Gamma = \int_0^T \left[x(t) - A_1 \cos\phi_1 m(t-\tau_1) - A_2 \cos\phi_2 m(t-\tau_2)\right]^2 dt + \int_0^T \left[y(t) - A_1 \sin\phi_1 m(t-\tau_1) - A_2 \sin\phi_2 m(t-\tau_2)\right]^2 dt \quad (3.0)$$

This is a highly coupled, nonlinear, six-dimensional minimization problem. However, it is enormously simplified by the <u>invertible</u> transformation

$$a = A_1 \cos\phi_1 \qquad c = A_1 \sin\phi_1$$
$$b = A_2 \cos\phi_2 \qquad d = A_2 \sin\phi_2 \quad (4.0)$$

A detailed description of the MMT processing is described in [7] and [8]. Of notable interest, and repeated here for completeness, are equations 3 through 6. Equation 3 shows a form of the fundamental system of equations to be solved for minimal residual error Γ. The point of minimal error, Γ, will be the solution that "best fits" the data. However, the equations contain non-linear terms and are difficult to solve in an efficient manner. The simple substitution of equations 4 into 3 transformed (3) into equations (5). These new sets of equations are linear and are solved by using the Least Squares direct solution.

SIMPLIFIED LIKELIHOOD STATISTIC Γ

MINIMIZE WITH RESPECT TO $\tau_1, \tau_2, a, b, c, d$:

$$\Gamma = \int_0^T \left[x(t) - am(t-\tau_1) - bm(t-\tau_2) \right]^2 dt + \int_0^T \left[y(t) - cm(t-\tau_1) - dm(t-\tau_2) \right]^2 dt \qquad (5.0)$$

INVERSE PARAMETER TRANSFORMATION:

$$A_1 = \sqrt{a^2 + c^2} \qquad A_2 = \sqrt{b^2 + d^2}$$
$$\phi_1 = \arctan 2(a, c) \qquad \phi_2 = \arctan 2(b, d) \qquad (6.0)$$

The MMT algorithm was developed by Larry Weill and Ben Fisher of Comm Sciences Corporation. MMT is an optimized maximal likelihood process that attempts to estimate the "best fit" of the Vision Correlation vector with multiple versions of the reference function, the first representing the line of sight signal, the subsequent representing possible multipath additive signals. The MMT process results in an N-dimensional search involving only the delays of the direct path signal and possible multipath signals. N=2 if we are only looking for a single multipath signal. After the best fit has been found, the relative amplitudes and carrier phase angles of the signals can be computed using equations (6). The significant advantage of the MMT algorithm is that it reduces the number of search parameters (in the case of 1 signal and 1 possible multipath signal) from 6 unknowns to 2 unknowns. This reduction in the search space makes the process manageable within the limitations of the imbedded processors used in today's GPS receivers. A detailed description of this technique can be found in [8], and further described with illustrating results in [7]. According to Weill, the MMT algorithm is extendable to mitigate more then one multipath signal however, at the time of this writing, only single and dual path Maximal Likelihood processes are used.

The following graphs illustrate the advantage of the Vision Correlation technique. Fig 6 shows the classic correlation output signal with a ½ amplitude multipath signal delayed 0.1 chips. The top curve shows the correlation function when the multipath is "in-phase" with the line-of-sight signal, in other words when the phase of the multipath signal is the same as that of the direct path signal. The lower curve is the correlation function when the multipath is "out-of-phase" with the line-of-sight signal, or in other words the phase of the multipath signal is 180 degrees rotated with respect to the direct path signal's phase.

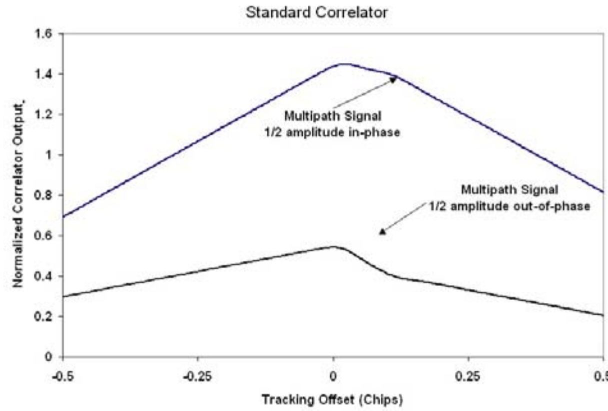

Figure 6 Standard Correlator with ½ amplitude MP at 0.1 chip delay, in-phase and out-of-phase

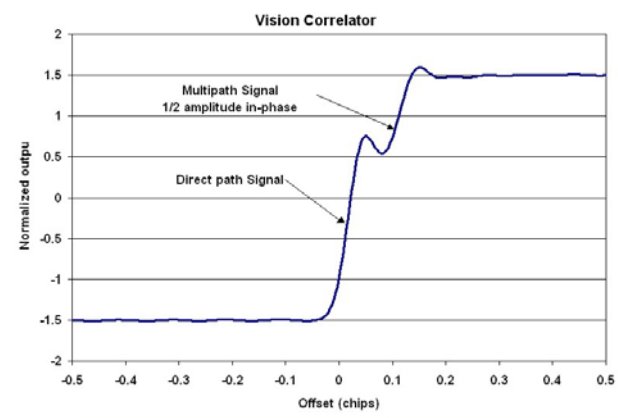

Figure 7 Vision Correlator with ½ amplitude MP at 0.1 chip delay, in-phase

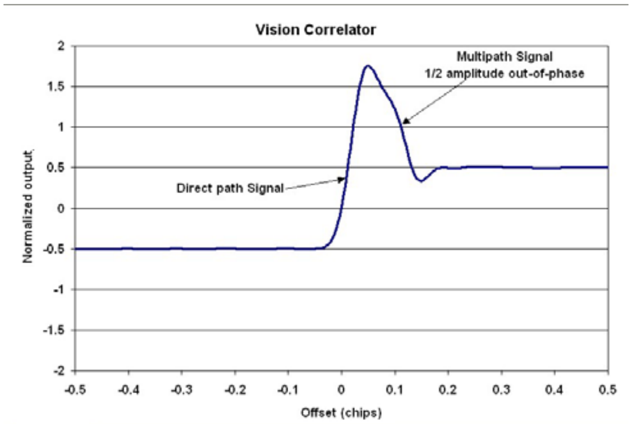

Figure 8 Vision Correlator with ½ amplitude MP at 0.1 chip delay, out-of-phase

Fig 7 shows the output of the Vision Correlator with the same single ½ amplitude signal delayed by the same 0.1 chip. Fig 7 represents the output of the Vision Correlator when the MP signal is in-phase with direct path signal. Fig 8 represents the shape of the Vision Correlator output when the MP signal is out-of-phase with the direct path signal. The effect of the multipath interference on the Vision Correlator is much more dramatic than the subtle variations that occur (other than the C/No) with the Standard Correlator. Deviations of the Vision Correlator from the standard "reference function" caused by multipath can be observed (and corrected) at substantially closer path delays than the Standard Correlator.

The MMT requires a reference function "shape" to be used to fit the incoming data with direct path and secondary path reference signals. The reference function must include the Radio Frequency (RF) properties of the signal-in-space generated from the satellite as well as the RF distortions introduced by the receiving equipment's antenna and down-converting radio section. A procedure was developed that used a long-term average of measured pulse shapes from a high elevation satellite to form the reference function. Alternative procedures could use a high quality simulator in a lab environment. Fig 9 shows examples of a measured reference function using a high elevation angle GPS satellite (GPS-PRN21) and our lab Global Simulation Systems GPS Simulator. The RF differences between live and lab-generated signals can clearly be seen. The overshoot of the bit transition could be a result of the group delay variance across the frequency in the radio equipment of the satellite.

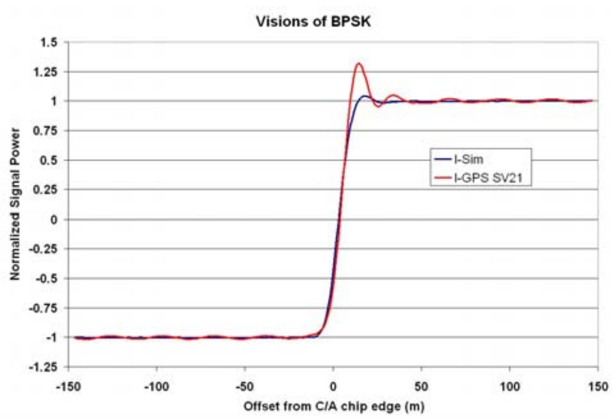

Figure 9 Reference function from GPS PRN 21 and STR4760

PERFORMANCE

Once the reference function has been established, the MMT algorithm can be employed to separate the Vision Correlation signal into its sub components, namely, the direct path signal and multipath. Fig 10 illustrates the performance of the Vision Correlator and MMT processing algorithm with respect to the other Standard multipath processing correlation methods used in receivers sold today. Our Global Simulation Systems (GSS) STR4760 GPS Simulator was used to generate the direct and multipath signals for this test. The multipath signal delay was slowly increased at 1mm/s (0.005Hz Doppler) from zero separation from the direct path signal and swept out to beyond 50m. The various MP methods were used on the same generated signal. The signal to noise power in this simulation was 50 dBHz. The amplitude of the multipath signal was ½ that of the direct path signal (-6 dB in terms of power).

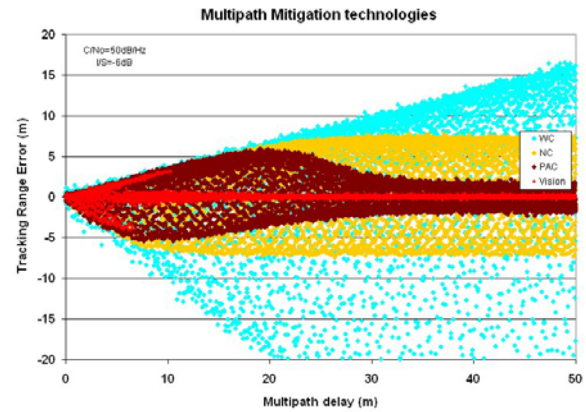

Figure 10 Comparison of multipath processing techniques

Fig 10 displays the error envelopes of various multipath techniques. The Wide Correlator (WC) is represented by the magenta color, Narrow Correlator (NC) by yellow, Pulse Aperture Correlator (PAC) by brown, and the new Vision Correlator by red. The Vision Correlation process provides a significant improvement over older multipath mitigating techniques. It is particularly sensitive to close-in (less than 1/10 of a chip) multipath delay separation.

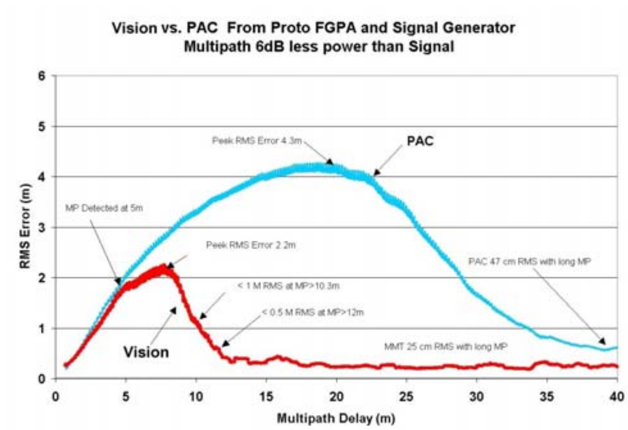

Figure 11 RMS errors of Vision and PAC multipath performance

Fig 11 shows the RMS performance of the Vision and PAC processes as from the multipath sweep test data. For very close-in multipath (<4m) it shows no benefit. At around 4m, the Vision starts to detect and correct for the multipath interference. The Vision Correlator reaches a maximum RMS error of 2.3m at around the 7m mark and is back below 1m RMS at 10.3m.

At this bandwidth, the Vision Correlator can completely correct for multipath signals that have a separation from the direct path signal of greater then 12.5m. The Vision Correlator works by examining the transition area of the signal. The greater the bandwidth (and sample frequencies) of the Vision process, the more effective the Vision process is.

An interesting by-product of the MMT process is the Sum of Squares of Residuals (SSR). The SSR can be used as a quality-of-fit statistic. The better the signal can be fit to the reference functions, the smaller residuals and SSR statistic. A large value would indicate that the signal has been corrupted with some kind of interference. Possible sources of signal interference are RF interference (jamming) or more multipath signals than the MMT algorithm can handle. The receiving equipment can use this statistic to de-weight or throw-out the measurement until the quality improves.

LIVE DATA

Figure 12 North parking lot at NovAtel Inc.

Data was collected in what we considered a high multipath environment for several days (Fig 12). Two receivers were used: one employing our PAC correlation technique, the other had the new Vision Correlation method. Fig 13 shows the typical behaviour of the pseudorange errors as a function of tracking time. Typically there are large multipath errors when the satellite is low to the horizon (rising or setting). Fig 13 shows the improvement of the Vision Correlator during the "Multipath Interference" section of the data. Fig 14 and Fig 15 show the pseudo-range errors of all satellites tracked during the duration as a function of elevation angle. The Vision processing included both correcting ranges when possible and rejecting range measurements when the SSR exceeded a threshold indicating uncorrectable signal.

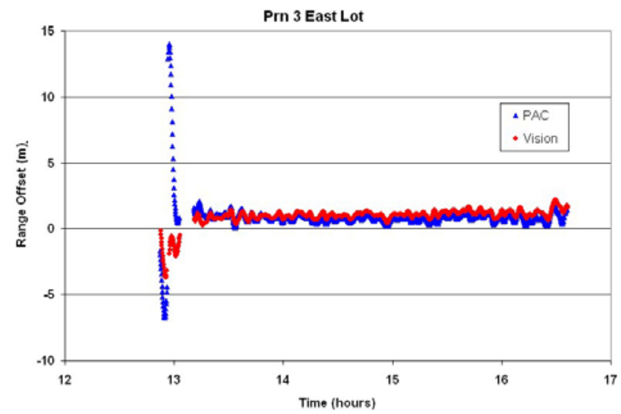

Figure 13 Typical satellite pass (Prn 3 East parking lot)

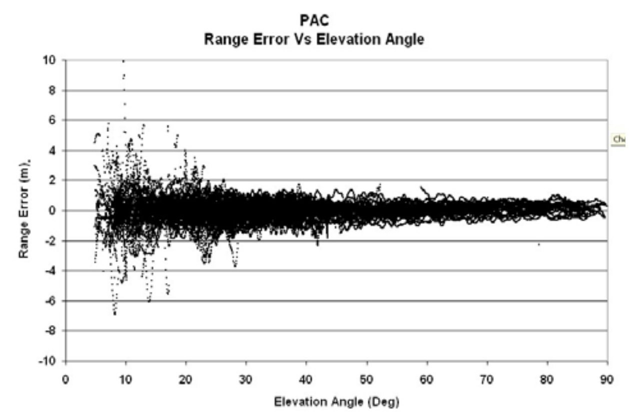

Figure 14 North parking lot data PAC

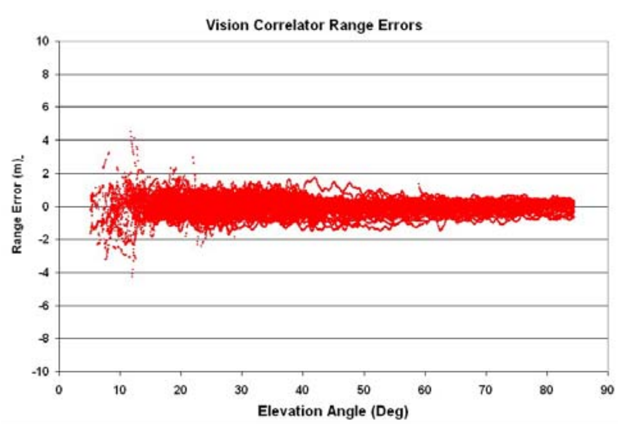

Figure 15 North parking lot using the Vision Correlator

	Elevation Angle (Degrees)				
Correlator Type	0-10	10-20	20-30	30-45	45-90
PAC RMS (m)	1.82	1.13	0.70	0.49	0.34
number of samples	2894	10,318	17,140	24,880	32,715
Vision RMS (m)	1.00	0.79	0.52	0.47	0.36
number of samples	1159	7,438	14,809	24,603	32,306
Improvement	45%	30%	25%	4%	-5%

Table 1 Elevation angle vs. RMS range error (Number of samples)

The range error data was sorted according to the satellite elevation angle. RMS values were computed at various elevation angles (see Table 1). The number of samples used in the RMS calculations are also listed in the table (in the bottom half of each cell). The number of samples listed in the PAC row provides nearly the total number of samples measured. The PAC process provides very little editing of the data. The PAC edits some of the data around cycle slips and very low signal to noise ratio. The bottom row indicates the percentage improvement in RMS error. Notice that the 0-10 degree column shows a 45% improvement. Also notice that the Vision process has discarded nearly 2/3's of the data in that region. Fig 16 illustrates the same data in graphical form.

The Vision Correlator technology provides improvements only on signals where multipath occurs. Notice, with the high elevation angle satellite data, the Vision Correlator provides very similar results as the PAC and may be a little noisier because it is solving for more parameters than PAC.

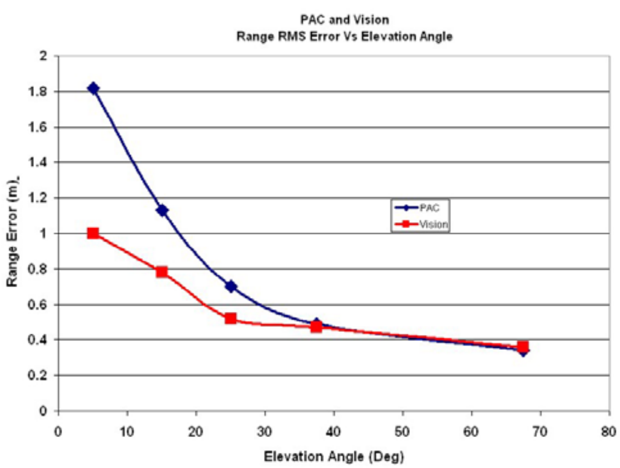

Figure 16 RMS error of Vision and PAC on North parking lot data

Signal Quality Monitor

Evil waveform testing on our early prototype receivers was performed using our Evil Waveform Signal Generator. The Generator generated waveforms for Threat Models A, B and C. Figures 17 through 19 provide examples of these waveforms. Threat Model A is generated by an unbalanced 1 & 0 duty cycle. In other words, the length of time the transmitter uses to represent a bit value of 1 is not the same as that used to represent a bit value of 0. Threat Model B could be generated by an RF quasi-stable modulator. The quasi-stable modulator causes ringing of the RF signal at each bit transition. Threat Model C is a combination of threat models A and B.

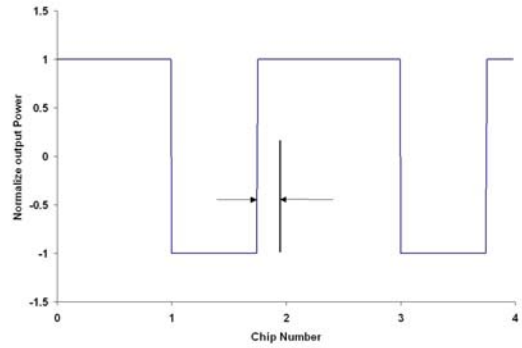

Figure 17 Threat Model A Unbalanced Duty cycle

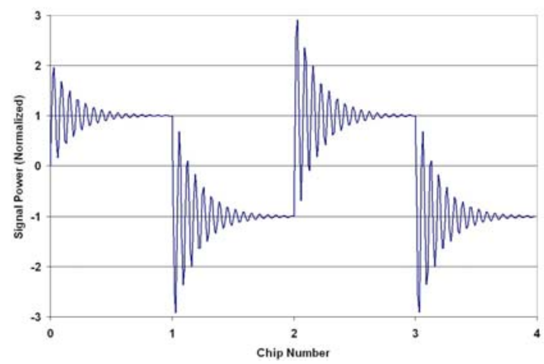

Figure 18 Threat Model B RF Transition Ringing

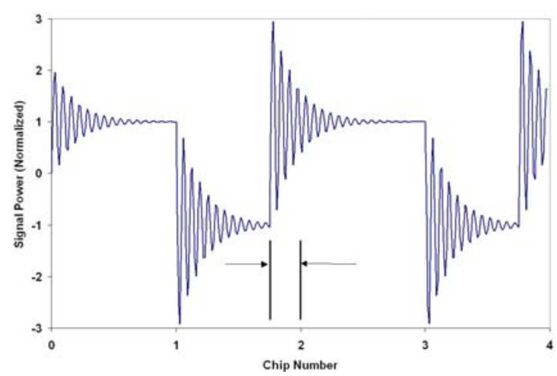

Figure 19 Threat Model C Unbalanced Duty cycle and RF Ringing

The procedure for running these tests used a period of approximately 150 seconds with the evil waveform generator turned OFF followed by a period of 600 seconds with the generator turned ON. The receiver was reset before each new test run. The receiver was placed into calibration mode which allows sampling of the entire C/A code chip at an interval of approximately 2.4 m (293m/122 bins).

The results from the testing are illustrated in Figures 20 through 24.

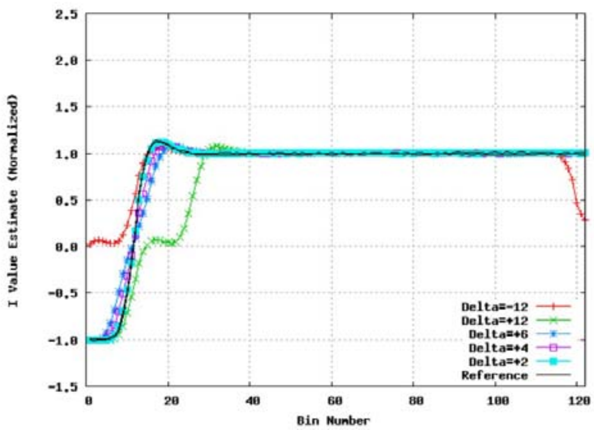

Figure 20 Vision Output of I-Channel of Threat Model A at various levels

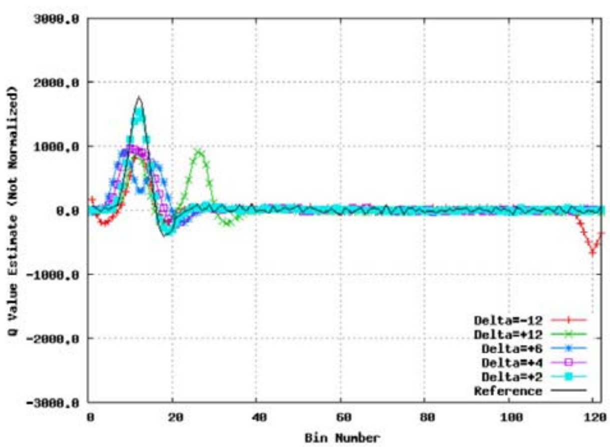

Figure 21 Vision Output of Q-Channel of Threat Model A at various levels

The effects of Threat Model A (Figs 20 & 21) can be seen by changes in the transition area. Small levels of error result in a decrease in rise time. Larger duty cycle offsets result in a flat zone half way through the transition.

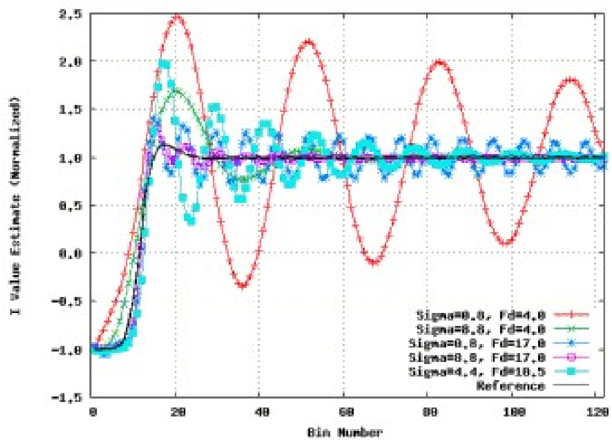

Figure 22 Vision Output of I-Channel of Threat Model B at various levels

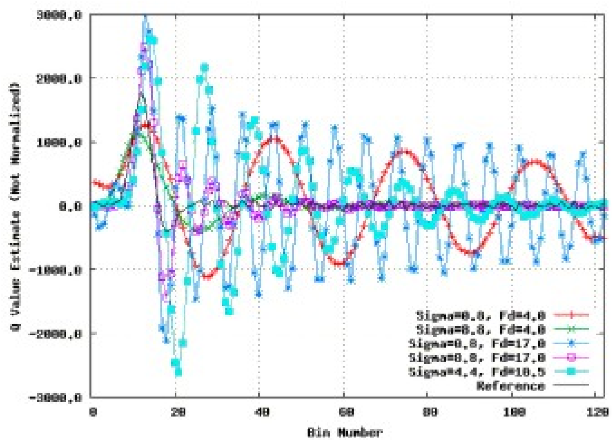

Figure 23 Vision Output of Q-Channel of Threat Model B at various levels

The effects of Threat Model B can clearly be seen in Figs 22 and 23. The Vision Correlator could be used to directly measure and characterize this error.

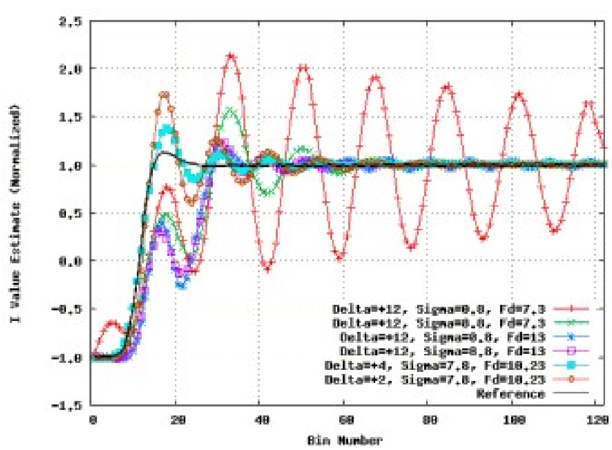

Figure 24 Vision Output of I-Channel of Threat Model C at various levels

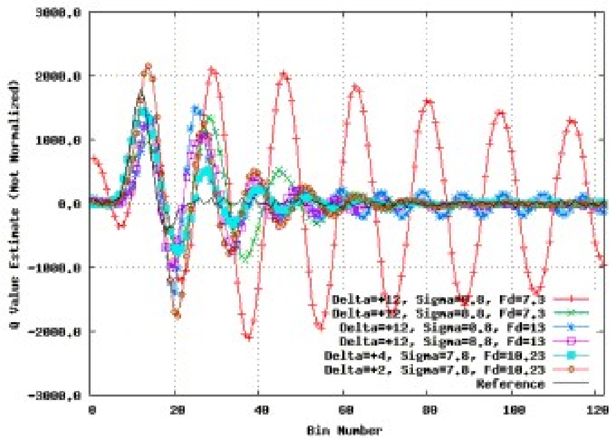

Figure 25 Vision Output of Q-Channel of Threat Model C at various levels

The effects of threat model C again can clearly be detected by the Vision Correlation technique as shown in Figs 24 and 25.

CONCLUSIONS

The Vision Correlator provides a significant improvement in detecting and removing multipath signals. It is able to correct for the effects of multipath, where delay from the direct path is as low as 10m. In the test data collected, it showed up to a 50% improvement in reducing the effects of multipath in low elevation angle measurements. It also provides an excellent Signal Quality Monitoring (SQM) capability. Tests showed that the Vision Correlator was able to detect Evil Waveforms caused by unbalanced duty cycle, RF transition ringing and a combination of the two.

ACKNOWLEDGEMENTS

I would like to acknowledge all of my co-engineers at NovAtel who were involved in the integration of this technology. Special thanks go to co-author Jason Jones, who developed a significant amount of the receiver software required to process the Vision Correlator data as well as the collection and processing of hours and hours of data, and to Drs Ben Fisher and Larry Weill of Comm Sciences Corporation for their support and ideas during the transfer and integration phase of this technology. I would also like to acknowledge and thank Karl Shallberg of Zeta Corporation for providing test results from our early prototype receivers that underwent the Evil Wave simulator tests.

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