

Gregory Smith \*  
Cubic Communication  
305 Airport Road  
Oceanside, California 92054

# ON THE DESIGN, IMPLEMENTATION, AND PERFORMANCE OF A MICROPROCESSOR CONTROLLED AGC SYSTEM FOR A DIGITAL RECEIVER

Microprocessor management of the automatic gain control (AGC) loop for a DSP based radio receiver brings the flexibility of an intelligent controller to the task of satisfying operational and signal dependent requirements such as variable attack, hold, and decay times. We present details of the design, some important hardware and software considerations, and the measured performance of an AGC loop controller we have implemented and inserted in a high performance digital surveillance receiver. The algorithms, based on an EMS adaptive filter, are implemented in a TMS-32020 DSP chip.

## ABSTRACT

## INTRODUCTION

With the advent of high performance, reasonable cost, analog to digital converters (ADC) and with the evolution of enhanced arithmetic capabilities of low cost microprocessors, digital signal processing techniques are being used to perform many of the back end signal conditioning tasks in radio receivers.

These signal conditioning tasks include frequency shifting, filtering, and demodulation. To implement these tasks with DSP chips the analog signal

must be sampled and digitized at some point in the signal conditioning chain. This is usually done at the output of the final intermediate frequency (IF) amplifier though the tendency today is to insert this interface further back in the signal conditioning chain. The digitized signal is then processed by the DSP subsystem which offers all the obvious advantages of software flexibility. For instance, different filter bandwidths can be obtained by simply downloading different sets of filter coefficients. The processed digital signal is then converted back to an analog signal by a digital to analog converter (DAC) and an analog filter. The digital subsystem must also generate and output the analog control signals, normally tuned in the back end of the receiver, which are required for the receiver's AGC feedback loop. An alternate approach is to replace the original analog AGC network with a digital one operating as a subsystem background task.

The advantage of performing the loop control in the digital subsystem are many. The primary advantage is the ease with which we can implement conditional tests based on short term changes of the signal levels and signal duration. Also the responses to the conditional tests can be more varied and larger in number than those to which we would have access in a standard analog

\* Now with GSS & Associates, PO BOX 3250, Vista, CA 92084

based control loop.

### THE AGC-LOOP: AN LMS-ADAPTIVE FILTER

The function of an AGC loop is to hold the rms signal at the output of the receiver to a specified level over a wide range of input signal levels. The loop regulates the receiver's output level in much the same way as a voltage regulator maintains a constant output voltage. We each have an intuitive understanding of how the AGC regulation occurs. The output of the receiver is envelope detected and compared to the desired level. This difference (or error) is used to change the forward gain of the receiver in the direction to reduce the error.

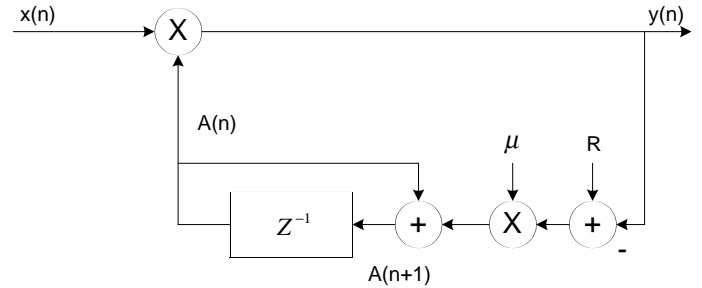
This is the classical description of a control system and at first glance, it would appear that the design mechanism for an AGC loop would be found in classical control theory. This is not true however, which is the reason much of AGC design is empirical and why so little material on this topic is published in the literature. The classic regulator is a time invariant linear system which, via feedback, reduces the input signal level variation by the system's fixed loop gain. The AGC loop on the other hand is a time varying and data dependent system which performs its function by varying the system's gains in response to input signal level variation. Thus the AGC loop is an adaptive feedback loop and is best examined from the viewpoint of adaptive signal processing.

Figure 1. shows a simplified AGC loop consisting of a single variable gain attenuator (or amplifier) represented by a multiplier. The output of the multiplier is the product of the input and the time varying, data dependent control weight [eq 1a]. At each iteration of the loop, the output of the attenuator is compared to the desired reference  $R$  and the difference is used to change the weight in the direction which would reduce the error [eq 1b]. The loop equations are shown in equations 1. To be stable, the gain  $A(n)$ , would be bounded by upper and lower limits.

$$y(n) = A(n) * x(n) \quad (1a)$$

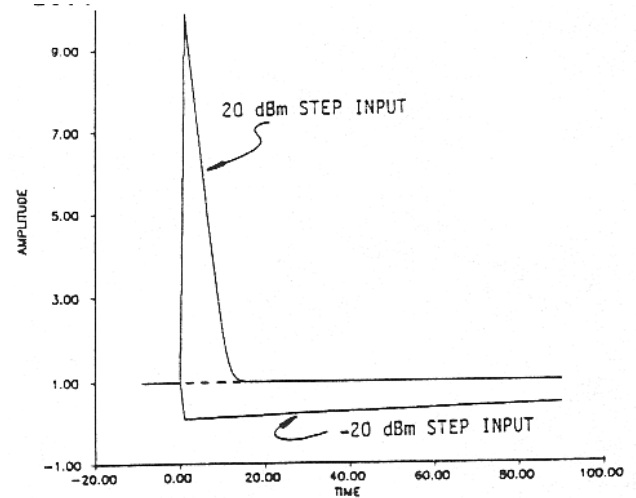
$$A(n+1) = A(n) + \mu(R - y(n)) \quad (1b)$$

$$A(n+1) = A(n)[1 - \mu x(n)] + \mu R \quad (1c)$$



■ Figure 1. Simple AGC loop

The classical tools of analysis, in particular the Z-transform, can not be used to form the solution for equation 1c except in special cases, as for instance when  $x(n)$  is a step change. Equation 1c can be programmed very simply, however, and figure 2. shows the output response of this simple loop for input step changes of +20.0 db and of -20.0 db.

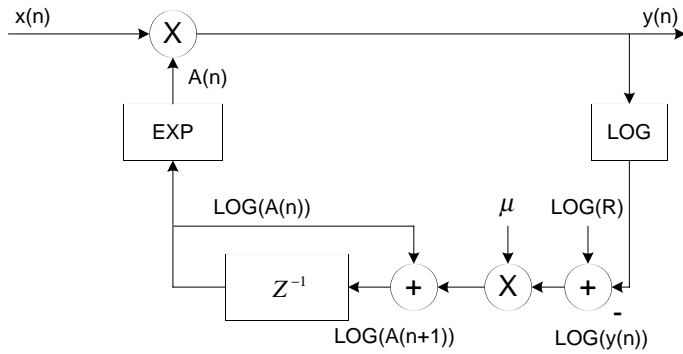


■ Figure 2. Step response, linear loop

Note that, in the present simple model, the error term used to correct the attenuator setting behaves very different for large increases than for large decreases in input signal level. For instance, if the input decreases by a factor of 100, the weight correction term (at the first iteration) is proportional to 0.99 (ie.  $1-0.01$ ), while if the input increases

es by the same factor of 100, the weight correction term is proportional to 99 (ie. 100-1). Large feedback terms may cause too large a correction which in turn may cause the loop to overcompensate and will likely induce an oscillation. To avoid such an oscillation, the parameter  $\mu$  can be made small in anticipation of the large feedback terms, but small  $\mu$  will result in very slow response to small feedback terms.

An alternate approach, is to make the weight correction terms proportional to the log of the ratio as opposed to the difference between the actual and desired levels. Figure 3 shows the simplified loop modified to operate in log coordinates and equations 2 presents the loop equations in these log coordinates.



■ Figure 3. Exponential-gain AGC-loop

$$y(n) = A(n) * x(n)$$

$$\log[A(n+1)] = \log[A(n)] + \mu \{ \log[R] - \log[A(n)x(n)] \} \quad (2a, 2b)$$

By simple rearrangement of equation 2b we have equation 2c.

$$\log[A(n+1)] = \log[A(n)](1 - \mu) - \mu \log\left[\frac{x(n)}{R}\right] \quad (2c)$$

We note, that equation 2c describes a simple leaky integrator model in the variable  $\log[A(n)]$  which is now unconditionally stable for any  $\mu$  with magnitude less than unity and is independent of the input variable. We now have a linear system

which can be analyzed using classic tools. In particular, if the input sequence is an arbitrary exponential we can obtain a closed form solution to equation 2c. For instance, if the input is a step change of amplitude S. the step response is presented in equation 3.

Figure 4. presents the step response of the log coordinate loop to +20 db and -20 dB step changes.

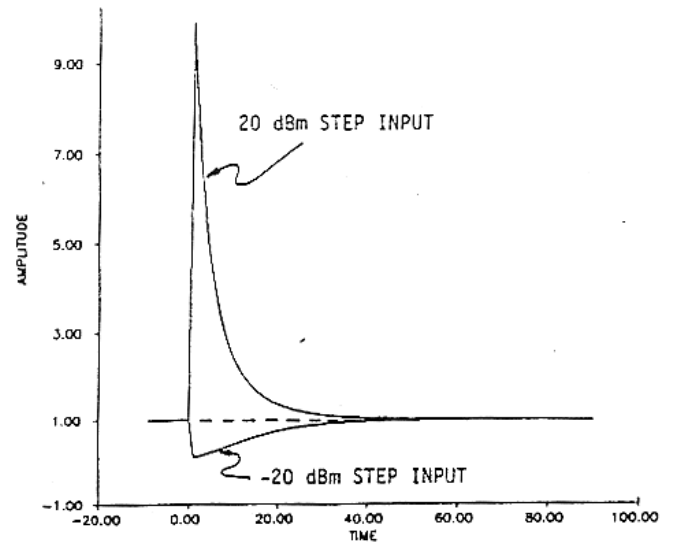
$$\log[A(n)] = \log\left[\frac{R}{S}\right] [1 - (1 - \mu)^n] \quad (3a)$$

$n = 1, 2, 3, \dots$

Exponentiating both sides of equation 3a, we have equation 3b.

$$A(n) = \left(\frac{R}{S}\right)^{[1 - (1 - \mu)^n]} \quad (3b)$$

Figure 4. presents the step response of the log coordinate loop to +20dB and -20dB step changes.



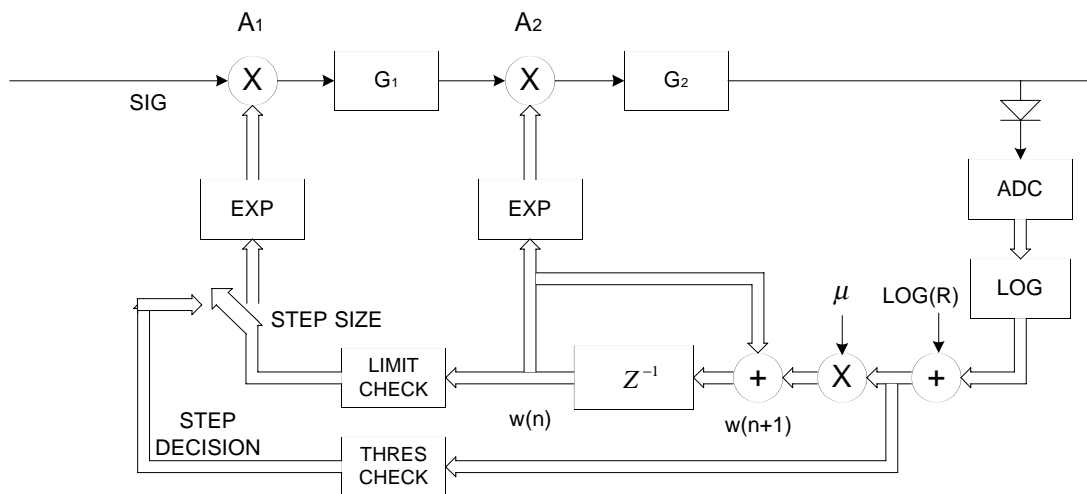
■ Figure 4. Step response of log loop

## RECEIVER DESCRIPTION

The receiver consists of four radio frequency (RF) channels covering the frequency range of 1-30

Mhz. Each RF channel is controlled independently from a TMS-32020 DSP processor. A block diagram of the IF chain for one of the RF channels is presented in figure 5. For purposes of discussion, the various local oscillators and frequency conversion segments of the receiver channel have been omitted.

The channel IF path consists of the first programmable attenuator A1, a narrowband amplifier G1 at the first IF frequency, the second programmable attenuator A2, and a narrowband amplifier G2 at the second IF frequency. The attenuators utilize PIN diodes which, when switched on, act as



■ Figure 5. BLOCK DIAGRAM: IF sections

shunts to the IF signal path.

The attenuators each cover a 50 dB range with A1 and A2 programmable in 10.0 dB and in 0.25 dB step respectively.

Amplifier G2 is followed by an envelope detector consisting of a diode rectifier and lowpass filter which provides a low-pass signal proportional to the envelope of the IF signal.

The detected signal is quantized by an 8-bit ADC at a 5.0 KHz rate per channel. The quantized signal is processed by the DSP chip to operate the attenuators A1 and A2.

### ALGORITHM DESCRIPTION

The algorithm operating the AGC loop is a modi-

fied form of the log coordinate loop presented in equations 2. The arithmetic used in the loop is performed with 32-bit fixed point precision with an implied binary point separating the upper 16-bits from the lower 16-bits.

The algorithm starts with a log conversion of the quantized envelope signal. This conversion is performed by a straight table look-up from a 256 point table. The log table is normalized to the ADC reference level of 63 which is -12 dB relative to the ADC full scale output of 255. This converted error is scaled by  $\mu$  and added to the previous filter weight to obtain the new weight.

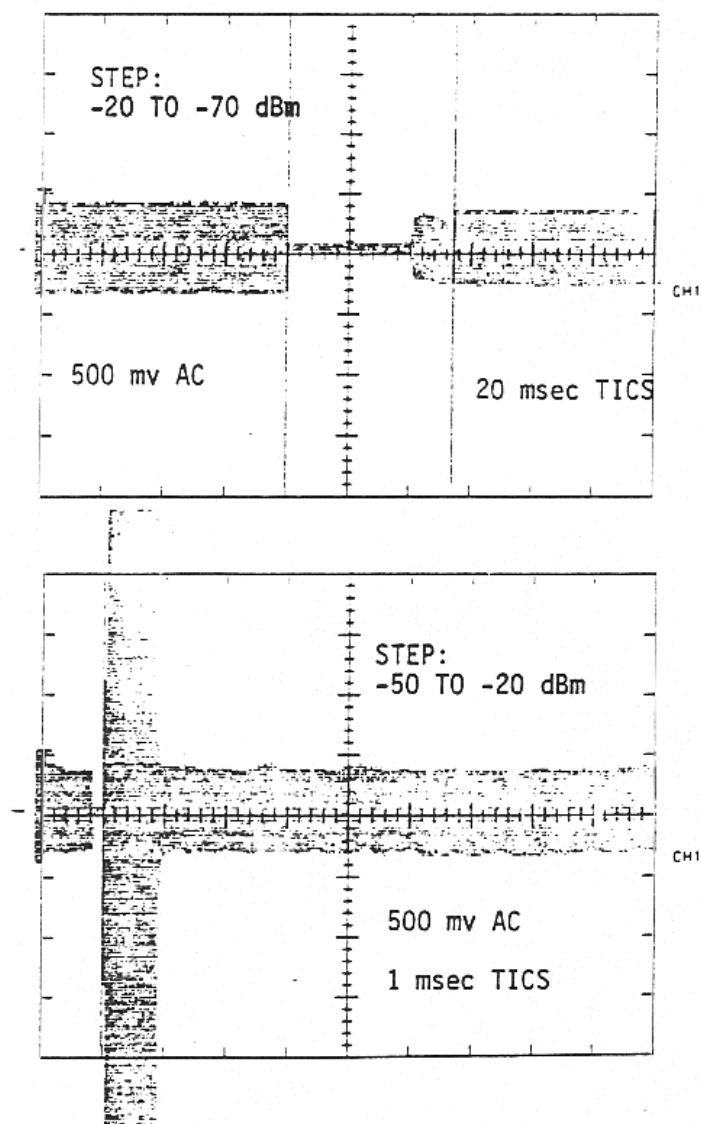
Before the new weight is applied to the attenuators the controller performs a number of conditional checks. We first examine the size of the error. If the error is small, and if attenuator A2 has sufficient residual range to correct the error, attenuator A1 is held fixed and only A2 is permitted to respond

to the new weight.

If the error is large, attenuator A1 must be changed. Step change sizes in multiples of  $\pm 10$  dB from changes in attenuator A1 will induce a transient in the bandpass amplifiers G1 and G2 following A1. This transient will be observed by the AGC control as a significant change in signal level. Unless prohibited from doing so, the loop could conceivably respond with an instruction to reverse the attenuator change which induced the observed change in the first place. A sequence of these contrary instructions may delay the loop from settling and in fact may support an amplitude hunting mode equivalent to an unstable oscillation. To prevent this scenario, a timing interval is initiated which prevents any additional changes in the attenuator A1 till the conclusion of

the expected transient induced in the bandpass amplifiers  $G_1$  and  $G_2$ . The duration of this time-out is primarily related to the bandwidth of amplifier  $G_1$  which is operator selected between 1-50 KHz.

Figures 6 demonstrate the performance of the AGC loop. Figure 6a shows the loop response to a large step change from -20 to -70 dBm and figure 6b shows the loop response a step change from -50 to -20 dBm.



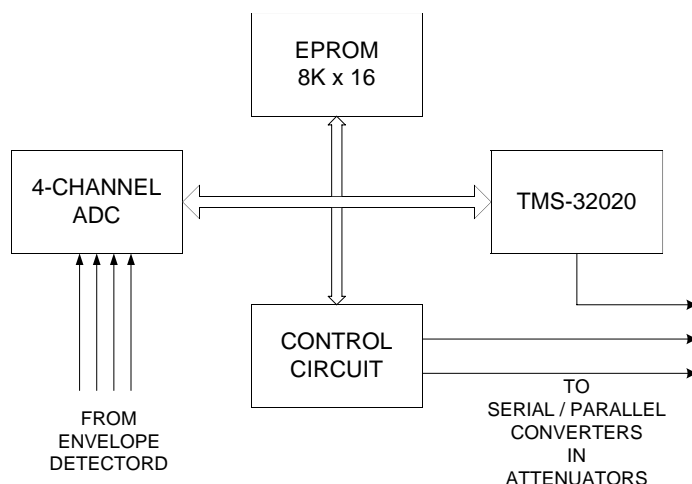
■ Figure 6. Receiver Step Response

The digital AGC system easily incorporates an operator selected time delay. This delay, long or short, is an operational decision which, on one

hand, makes it possible to quickly respond to a low level signal after the cessation of a high level signal, and on the other, hand prevents the loop from trying to cancel slow amplitude variations which may be signal modulation.

## IMPLEMENTATION DETAILS

A block diagram of the hardware required to implement the AGC system described here is shown in figure 7. The hardware consists of a TMS-32020 DSP chip operating at 20 MHz, 8-K of no wait state ROM, a four channel ADC, two 4-bit I/O ports and two UART devices for command/control interface to the user.



■ Figure 7. Hardware block diagram

The software consists of approximately 3-K words (16-bits/word) of firmware configured as 1-K word of code and 2-K words of tables. The software operates a foreground loop which monitors I/O activity in the UARTs and other time insensitive events. A background loop, which is interrupt driven by timers, consists of four state machines which implement the algorithms and control the receiver channels.

The software utilizes the internal RAM of the TMS-32020, devoting 128 words to each channel and 32 words for general purposes and status information. No external ram was required to

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operate the four AGC loops.

### REVIEW AND COMMENTS

We have described the standard operation of an AGC loop and justified its implementation with a digital controller. We noted that the time varying, data dependency of the loop prevented us from applying standard analysis tools (such as Z-transforms) to design the loop. We first surmised that the loop is best examined as an adaptive filter and proceeded to simulate the performance of a simple loop. We then noted that by changing the update segment of the LMS loop to log coordinates the product relationship between the weighting coefficient and the data became a summation and the LMS loop equation reverted to a standard linear one tap filter.

We described the structure of the receiver in which the AGC loop was designed to operate and commented on particular software considerations required to keep the loop stable for that structure. We demonstrated the successful performance of the digitally controlled AGC loop and then commented on the hardware required to implement the loop.

### REFERENCES

1. **J. Smith**, *"Modern Communication circuits"*, McGraw-Hill, 1986.