ADVANCED TELEVISION TECHNOLOGY CENTER

On-Channel Repeaters for Digital Television Implementation and Testing

Walt Husak, Charles Einolf, and Stan Salamon

Presented at the
NAB99 Broadcast Engineering Conference
Las Vegas, NV
April 20, 1999

Advanced Television Technology Center, Inc.
1330 Braddock Place, Suite 200
Alexandria, VA 22314-1650
Telephone: (703) 739-3850
Fax: (703) 739-3230
www.attc.org

On-Channel Repeaters for Digital Television Implementation and Field Testing

Walt Husak, Charles Einolf, and Stan Salamon
Advanced Television Technology Center
Alexandria, Virginia

Abstract

The Advanced Television Technology Center successfully developed and demonstrated an On-Channel Repeater (OCR) for Digital Television (DTV). The demonstration repeated WETA-HD's primary signal beyond the Blue Ridge Mountains into Charles Town, West Virginia. OCRs provide local broadcasters with a means to replicate or extend their current NTSC coverage while having no impact on the DTV allocation table. The OCR allows rebroadcast of a DTV signal, without frequency shifting, into an area previously unable to receive the originally transmitted signal. This paper describes the design, construction, and field testing of the ATTC On Channel Repeater.

Introduction

The ATSC Digital Television (DTV) standard through the use of the 8-VSB modulation technique, provides sufficient performance margins to allow for the practical introduction of an On-Channel Repeaters (OCRs). 8-VSB receivers have been shown to be immune from the effects of noise up to a 15.2 dB C/N ratio.[1] In addition, 8-VSB receivers can tolerate ghosts as large as -3 dB relative to the primary signal. Therefore, 8-VSB should permit the application of OCRs for DTV, even though additional noise and ghosts may be introduced. The Advanced Television Technology Center (ATTC) has undertaken a project to develop and test the OCR concept.

The project was divided into three phases. The first phase was a paper study to determine whether the system is feasible. A repeater would be constructed and tested in the second phase. The third phase tests the interaction between the repeater and the main transmitter, also known as mutual interference. The phases are sequential however, a new phase has been added extending the study of high power terrain isolated OCRs. This report summarizes the project up to the end of the second phase.

The paper study focused on issues such as the type of repeating action, repeater and receiver expected performance, and critical elements in the system.[2] The results of the study showed a repeater was possible and could augment a digital broadcaster's audience. The repeating action can be either regenerative, providing error correction prior to retransmission, or non-regenerative which provides no error correction. The study also highlighted antenna isolation and the repeater's main signal received power as being the two most critical elements contributing to the repeater's retransmit power.

In order to focus on the antenna design, the non-regenerative repeating action was selected as the design approach in the second phase. This would allow a reflection or antenna mutual coupling to manifest itself as a measurable ghost at the repeater's receive antenna. Experiments were conducted which tested antenna isolation both on and off the tower in order to understand the types of reflections and interferences that occur on a functioning tower. A terrain shielded site was chosen to isolate the repeater's transmission pattern from the main transmitter's signal.

Presented at the NAB99 Broadcast Engineering Conference, Las Vegas, NV, April 20, 1999.

Background

WETA-HD provided the primary DTV signal for the OCR implementation. The transmitter is located in Arlington, VA near Washington, DC. During the period of their experimental license, WETA-HD was broadcasting on UHF channel 34 with an ERP of 100 kW (+20 dBk or +80 dBm). The antenna had a cardioid pattern pointed toward the east. Charles Town and Harpers Ferry, WV could not receive channel 34 due to the Blue Ridge Mountains located between the transmitter and the target communities. An existing railroad microwave relay facility was selected for the repeater's location. The tower has a line-of-sight view of the WETA-HD transmitter and provided a panoramic view of the Shenandoah Valley.

Two antennas were selected for the repeater's receiver and transmitter. Antenna placement on the tower was chosen and appropriate wind and tower loading analysis performed. Interference and radiation studies were done in preparation for modifying the existing DTV license to include the repeater. No significant interference condition was discovered and an extension to WETA's license was granted.

System Design

Figure 1 illustrates the operation of the repeater. The system design includes a main transmitter, the repeater, and one or more receivers. The top of the ridge is approximately 1000 feet above the transmit and receive sites. This provided an excellent opportunity for line-of-sight to both locations. The resulting received power at both sites could be reasonably estimated using the free-space loss formula.

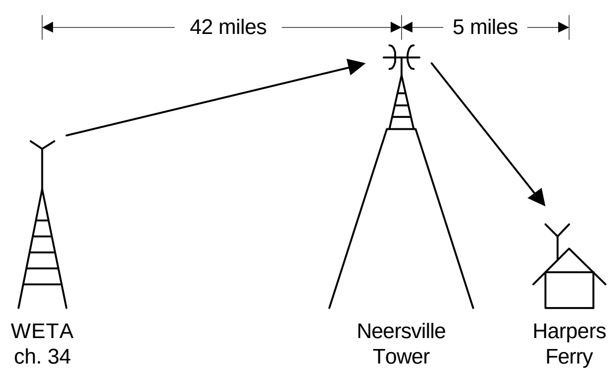


Figure 1

System topology of the OCR showing the relative location of all major sections.

Free space loss can be calculated using Equation 1.[3] The loss for the WETA to repeater leg is 125 dB using 68 km (42 miles) and 593 MHz (chan. 34).

$$L = 32.45 + 20Log(f) + 20\log(d)$$

Where :

L = Loss in dB
f = Frequency in MHz
d = Distance in km

Equation 2

Free space loss formula.

The received power formula is shown in Equation 2.[3] The estimated receive power at the repeater site is –50 dBm. An adjustment of 5 dB needed to be included to account for being on the backside of the cardioid.

$$P_{rx} = ERP - L - A_{pat}$$

Where :

P_{rx} = Repeater receive power at antenna
ERP = Primary transmitter ERP in dBm
L = Free space loss
A_{pat} = Cardioid adjustment

Equation 1

Repeater receive power formula.

The initial estimate of isolation between antennas was 110 dB. The coupling margin for proper operation of the final receivers and to prevent repeater oscillation was determined to be 20 dB. This reduces the useful isolation estimate to 90 dB. The projected repeater transmit power can be calculated using Equation 3. It was believed 10 dB of further isolation could be added once implementation was underway. This meant the target transmit power would be between 10 and 100 watts.

Using Equation 1 for the repeater to receiver leg yielded a loss of 106 dB. Retransmit power of +50 dBm would result in a receive power of –56 dBm. By applying the 131 dBuV/dBm dipole factor, a field strength 75 dBuV/m would be measured at Charles Town. This is 34 dB higher than the 41 dBuV/m set by the FCC.[4]

$$P_{tx} = P_{rx} + m_c - M$$

Where :

P_{tx} = ERP in dBm
P_{rx} = Received power in dBm
μ_c = mutual coupling (dB)
M = coupling margin (20 dB)

Equation 3

Repeater ERP formula.

Tower Design

The design of the tower is important due to the interaction of the antennas. As much vertical and horizontal separation as possible was employed in order to reduce the amount of mutual coupling between antennas. The receive antenna was located above the transmit antenna because of a slight rise behind the tower which would have blocked WETA's signal.

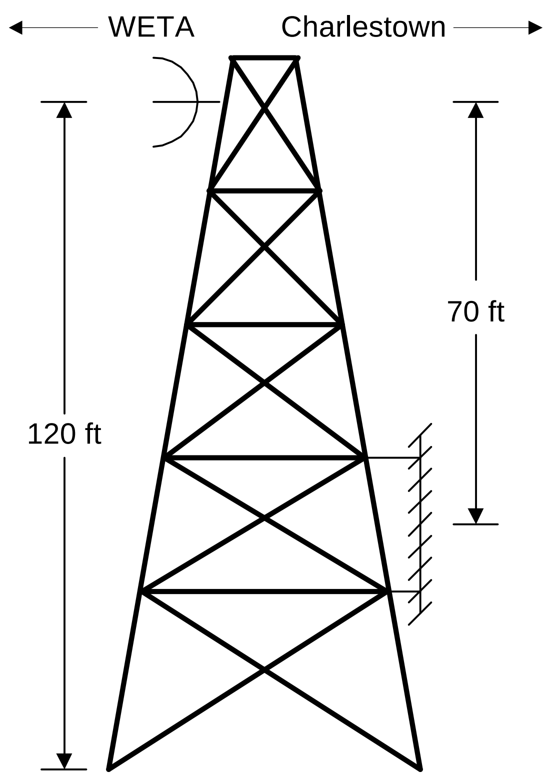


Figure 2

Antenna placement on the tower.

Figure 2 shows the general configuration of the tower. The position and orientation of the antennas on the tower is optimized for best reception and retransmission characteristics while while keeping the mutual coupling between the antennas to a minimum. In general, greater separation between the two antennas results in greater antenna isolation. The relative orientation of the antennas can be adjusted to further reduce the mutual coupling by making use of the nulls in each antenna pattern.

The receive antenna is a wide band, narrow beam, high gain antenna with a high front-to-back ratio in the horizontal plane. The transmit antenna also has a high front-to-back ratio with a wider beamwidth than the receive antenna. Both antennas have a narrow beamwidth in the vertical plane. This is accomplished by using a parabolic antenna for the receive antenna and a multiple stacked element transmit antenna.

Figure 3 illustrates the interaction between the transmit and receive antennas. The main transmitter signal is received at the node labeled P_{rx}. The signal is increased by the gain of the receive antenna and applied to the input of the repeater's electronics. It is then filtered and amplified. The processed signal is then further increased by the gain of the transmit antenna and radiated. A portion of the signal, represented by the chain of attenuators, feeds back into the receive antenna.

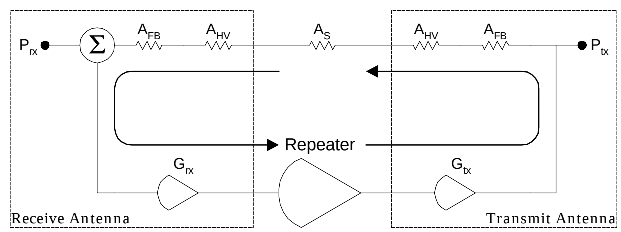


Figure 3

Simplified Schematic of the antennas.

The feedback is the result of mutual coupling in the antenna system. It affects three things, maximum retransmit power, performance of the receiver, and the oscillatory characteristics of the repeater. ATTC chose 20 dB of margin for the amount of feedback relative to the received primary signal, known as coupling margin.

Repeater Design

The repeater electronic design chosen for this phase was the non-regenerative analog design. Figure 4 is a simplified schematic of the design. The design consists of a preamplifier, a channel filter, and a power amplifier. A 6 MHz SAW filter, centered at 44 MHz, isolates the channel of interest from adjacent and near adjacent channels.

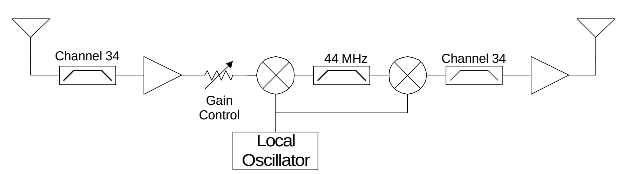


Figure 4

Simplified schematic of the repeater's electronics

The channel of interest is down converted to IF and then up converted back to the original channel by using the same local oscillator in order to ensure small differences in frequency will not manifest itself as dynamic multipath. The effects of mutual coupling appear as multipath due to the feedback being correlated with respect to the primary signal.

The preamplifier stage has a channel 34 bandpass filter in order to eliminate the chance of any N+14 and N+15 taboos. The heterodyne process uses high side injection eliminating N-14 and N-15 taboos. As an additional benefit, channels beyond N±5 are attenuated by more than 30 dB, reducing the possibility of front-end overload. Two notch filters for the visual and aural carriers of channel 32, N-2, were installed to further reduce the possibility of overload and intermodulation. The gain control ensures none of the subsequent amplifiers will either compress or cause excessive intermodulation products.

The IF stage begins with a single heterodyne stage feeding into a SAW filter. Not shown is an amplifier to mitigate the insertion loss of the SAW filter. Also not shown is a 100 MHz low pass filter used to eliminate the residual on channel signal from the IF stage. Once the adjacent and near adjacent signals are filtered, the signal is upconverted back to the original channel.

The power amplifier stage begins with another channel 34 bandpass filter. The purpose of this filter is to attenuate any out-of-channel energy such as the IF signal, the image, and the LO. The amplifier shown is a representation of multiple cascaded stages with a final small RF power amplifier.

Implementation

Once the required leases and licenses were obtained, construction of the shelter began and utilities were installed. The biggest unknown was what the final mutual coupling was going to be. As stated earlier, the performance of several key parameters is directly related to mutual coupling.

The first set of experiments characterized mutual coupling. WETA turned off their transmitter allowing ATTC to transmit a locally generated signal at the repeater without the primary signal being present. This allowed ATTC engineers to do two independent tests to confirm what the mutual coupling would be.

The first test performed was a locally generated signal with an ERP of +42.2 dBm. Figure 5 shows the results of the test. The measured receive power can be approximated as –90 dBm. After adjusting for channel bandwidth, downlead loss, and antenna gain, the power at the receive antenna is –80.6 dBm. The difference, 122.8 dB, is the total isolation between the co-located transmit and receive antennas.

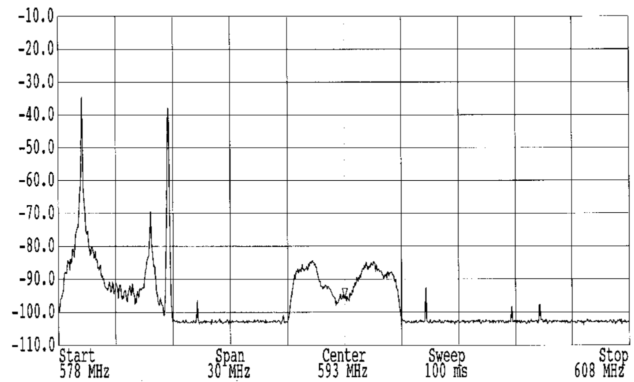
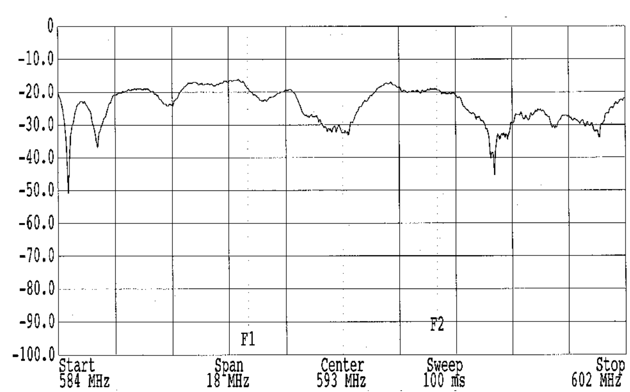


Figure 5

Mutual coupling experiment using a single ended transmission

A two port network analysis was done in order to confirm the isolation in the previous experiment. The results from this experiment are shown in figure 6. Note the similarity of the general shape of the frequency response within the channel between the two methods.

Due to the limited dynamic range of the network analyzer, an RF amplifier was calibrated into the test setup to increase the input sensitivity. A 70 dB pad was also calibrated into the system and removed from the measurement, creating a 70 dB offset. The result is a 25 dB reading. After adjusting for the antenna gains, feedline losses, and the attenuator, the calculated isolation is 123.7 dB. The average of the two measurement techniques is 123 dB.



The isolation determines the repeater's ERP. The ERP is calculated by the formula given in Equation 3. Figure 7 is the spectrum plot taken at the downlead of the repeater's receive antenna of WETA-HD's spectrum. Adjusting the measurement for channel bandwidth, downlead losses, and antenna gain results in a receive power of –52.4 dBm at the antenna. By applying the receive power, mutual coupling, and the coupling margin to Equation 3, the final ERP for the repeater is +50.8 dBm or 120 watts.

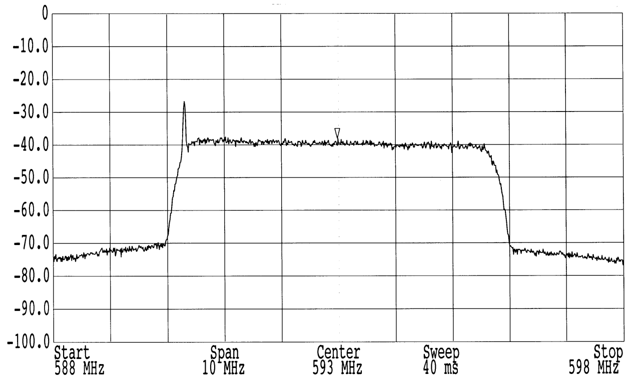


Figure 7

Receive spectrum of WETA-HD at the repeater.

The repeater was then optimized for the new ERP and a final transmit plot was generated. Figure 7 and 8 are the before and after plots respectively of the repeater with and without the repeating action. It is interesting to note the ripple in the spectrum due to multipath formed at the receive antenna because of mutual coupling. The nulls are spaced approximately 250 kHz apart, corresponding to an approximately 4 µsec delay.

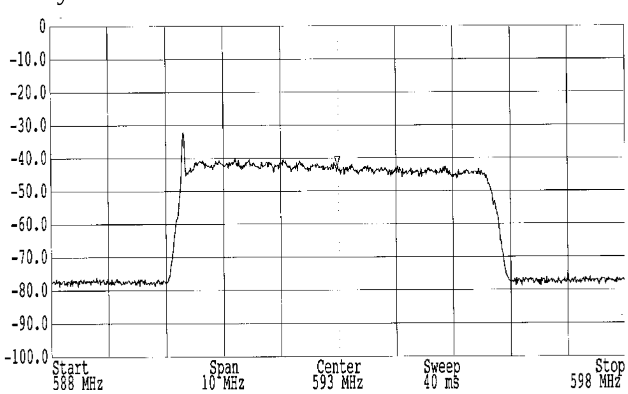


Figure 8

Spectrum plot of the repeating action

A further confirmation that the repeating action is occurring correctly, is shown in Figure 9. This is a graph of the dynamic equalizer tap energies from the ATTC/Wuppertal professional demodulator receiving the repeated signal. The horizontal axis is delay time and the vertical axis is relative tap energy verses the main signal.

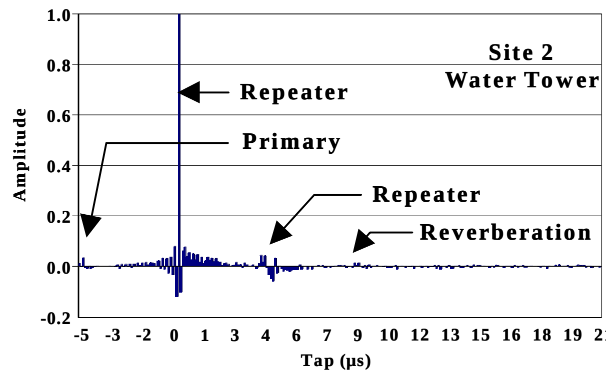


Figure 9

Receiver Dynamic Equalizer tap weights relative to the main signal

Three ghosts of interest can be seen in the plot located at –4.8 µsec, 4.4 µsec, and at 8.8 µsec. The first ghost is the weak primary signal directly from WETA. It appears as a leading ghost and is not delayed by the repeater. The repeating action inherently causes the second ghost. The third ghost is the result of the reverberation within the feedback loop of the repeater.

The definitive experiment involved using a consumer DTV set-top box (STB) to actually receive video and audio. The set-top box and monitor were provided by Panasonic. The receive site was located at the intersection of US Rte. 340 and WV Rte. 9 ("Burger King"), 5.2 miles from the repeater. The site is boresight with the repeater's transmit antenna which offers line-of-site to the tower. The video and audio appeared without any errors as if we were receiving the primary signal without being repeated.

A sensitivity margin test was also conducted. The input signal was attenuated until the picture exhibited blocking artifacts. The receiver was able to withstand nearly 16 dB of additional attenuation before losing lock. Factoring in the power split for additional test equipment and the extra downlead losses, the total margin was 21 dB.

ATTC arranged a demonstration and technical briefing to show the OCR works in a real world environment. The Charles Town Racetrack was selected as the venue because of the location and the ability to see the repeater's tower from the room where the demonstration would take place. A Radio Shack double bowtie antenna was used as the receive antenna and the receiver was the same Panasonic STB/Monitor combination used previously. The entire system was indoors including the antenna.

The demonstration was conducted without reception errors. ATSC provided the video programming. Representatives from ATSC, NAB, CEMA, WETA, and PBS were the first to see an 8-VSB signal repeated without frequency translation.

Field Tests

MSTV provided the use of their field truck to do field tests just prior to the "Great Channel Swap" in the Washington, D.C. Market. On November 1, 1998, the experimental channels used by WETA-HD and WHD-TV were exchanged for permanent licenses on different channels. This gave us several days to execute a preliminary field test based on the original repeater ERP.

A subset of eleven sites from the fifty total sites was performed with satisfactory results. The eleven sites, shown in Figure 10, included five in an urban cluster, five along an arc creating radials, and one behind the repeater to measure the effects of mutual interference with the primary transmitter. There was no measurable mutual interference due to the antenna orientation and terrain shielding.

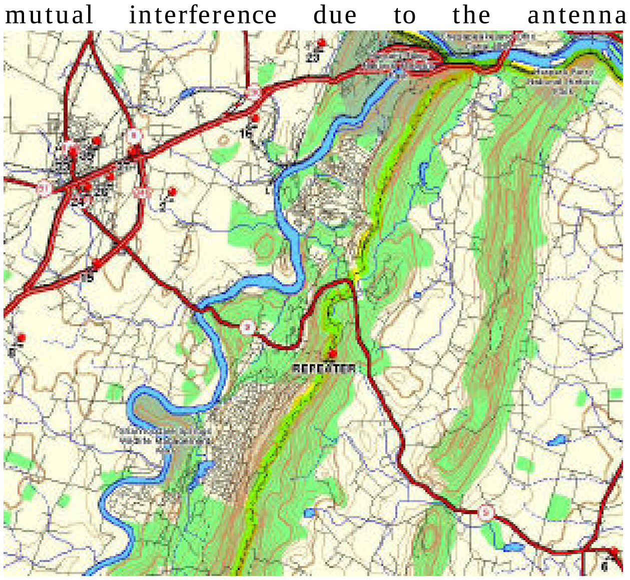


Figure 10
Preliminary Field Test sites.

The final field tests are scheduled for the first two weeks of February 1999. Figure 11 shows the fifty sites selected. The new owner of channel 34, WUSA, has agreed to continue supporting the OCR project.

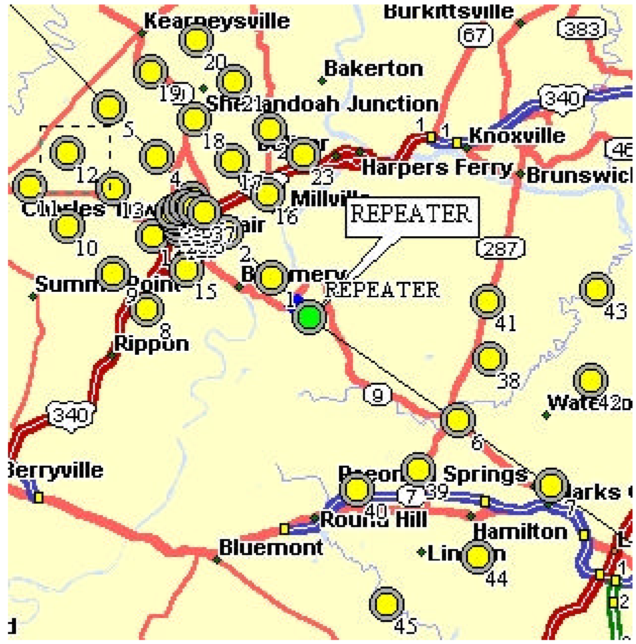


Figure 11
Field Test sites for the high power OCR tests.

WUSA is broadcasting +88 dBm (632 kW) with an omnidirectional antenna. The expected receive power at the repeater will be –37 dBm using Equations 1 and 2. The repeater's maximum ERP can be +66.2 dBm (4.2 kW) by using Equation 3. The tests will be conducted using +60.8 dBm (1.2 kW) for easy correlation to the previous field test results.

The increase in primary transmitter ERP will result in a higher primary signal received beyond the ridge. This will increase the mutual interference measured in the valley. The repeater and the receivers will still operate correctly due to all signals being scaled by the same amount. The repeater's signal, the primary signal, and the interaction between the two (mutual interference) will be measured at all sites. The results will be presented at NAB99.

Conclusions

The On-Channel Repeater works in a terrain isolated scenario. A consumer DTV receiver can demodulate and decode an 8-VSB signal repeated into an area shielded from the primary signal.

The primary interference mechanism is multipath created by co-locating receive and transmit antennas. This phenomenon is known as mutual coupling.

Off-the-shelf antennas that are mounted on a tower in a conventional manner can achieve as much as 123 dB of antenna isolation. Given a design similar to the ATTC OCR and using a 500 kW UHF station as the primary signal, the repeater's ERP can as much as 3 kW.

Since the repeater extends coverage into a new area, the same interference issues as the primary broadcast exists, e.g. adjacent channel, co-channel, and taboos. Furthermore, great care must be exercised in the design and implementation in order for the repeater to effectively retransmit a DTV signal.

In the spring of 1999, ATTC will begin the third phase of the OCR project. This phase will address the interaction between the primary signal and the repeated signal. The regenerative electronic design will be also tested allowing the use of error correction at the repeater site.

---

[1] *digital* HDTV Grand Alliance System, Record of Test Results, Federal Communications Commission, Advisory Committee on Advanced Television Service, October 1995.

[2] Charles Einolf and Walt Husak, "On Channel Repeaters for Digital Television," Proceedings 1998 Broadcast Engineering Conference, April 1998.

[3] Donald G. Fink and Donald Christiansen, "Electronics Engineer's Handbook 2nd Edition," McGraw-Hill, New York, NY, 1982, pp. 18-57.

[4] FCC, Fifth and Sixth Reports and Orders, MM Docket 87-268,both adopted April 3, 1997, amended by the Memorandum Opinion and Order on Reconsideration of the Sixth Report and Order, adopted February 17, 1998.