The University of Kansas

Technical Report

Observations of Potential Secondary User Device Effects on Digital Television Receivers

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Abstract

This report presents further results from an ongoing study of the potential effects of secondary users operating in unoccupied television spectrum. The proposed use of this open spectrum has prompted questions concerning the quantity of available channel space that could be used without negative impact on consumers who view digital television broadcasts. Of particular concern is the viability of secondary use of open channels immediately adjacent to a digital television broadcast channel.

In this work, we investigate secondary device operation in the channels directly adjacent to a desired television channel, with the focus on transmitted intermodulation interference from a single interfering signal, and the effects of such interference upon a selection of digital television receivers.

Introduction

The portions of the VHF and UHF frequency spectrum currently allocated and licensed to television broadcasters, often referred to as the “TV Band”, has remained relatively static since initial television channel allocations in the 1940s, but the use and management of this spectrum is now in the midst of a large-scale transformation. The arrival of digital television (DTV) services1, pending reallocation of UHF channels in the 698 MHz to 806 MHz range, and FCC directives concerning the operation of secondary user “TV Band Devices” [1], promise dramatic changes in the use of the spectral resource.

The shortage of available bandwidth for new wireless services has focused a great deal of interest in the open portions of the TV Band spectrum, prompting debate concerning the potential impact of secondary use upon consumers who view off-the-air television broadcasts.

The quantity of unused, or “white space” portions of the TV Band that could be available varies by the set of parameters used to define open spectrum, and the geographic locality of a prospective secondary user. Determining the boundaries for TV Band device operation raises the topic of secondary use in the numerous white space channels directly adjacent to active television channels.

Adjacent Channel Spectrum

Television broadcasters have expressed the concern that secondary use of open spectrum immediately adjacent to an operational digital television channel could cause interference to viewers of the DTV channel content. However, despite the best efforts of the FCC to allocate adjacent channel frequencies to DTV transmitters with appropriate geographic separation, it is not particularly unusual for viewers to be located in areas where television markets overlap, allowing adjacent DTV channel situations to occur. The Communications and Networking Laboratory at the University of Kansas, is located approximately halfway between Kansas City and Topeka, with access to off-the-air DTV content from both media markets. Two separate instances of adjacent DTV channel pairs can be received at this location, and tests have demonstrated that a selection of consumer DTV receivers are capable of receiving and properly displaying the content of all four channels.

An undesired interfering signal (U) transmitted in a channel adjacent to a desired signal (D) channel can introduce third order intermodulation (IM_3) products generated by transmitter nonlinearities into the desired channel bandwidth, resulting in interference to the desired channel content. In the case of a DTV broadcast, the noise-like characteristics of an 8VSB modulated digital television signal create IM_3 products with the same noise-like properties. These products are often referred to as “sideband splatter” or “shoulders”, and result in what is essentially co-channel interference to other signals occupying directly adjacent channels, as illustrated in *Figure 1*.

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[1] *The transition from NTSC analog to ATSC digital broadcasts in the United States has been Congressional mandated to be completed by 18 February 2009 [2].*

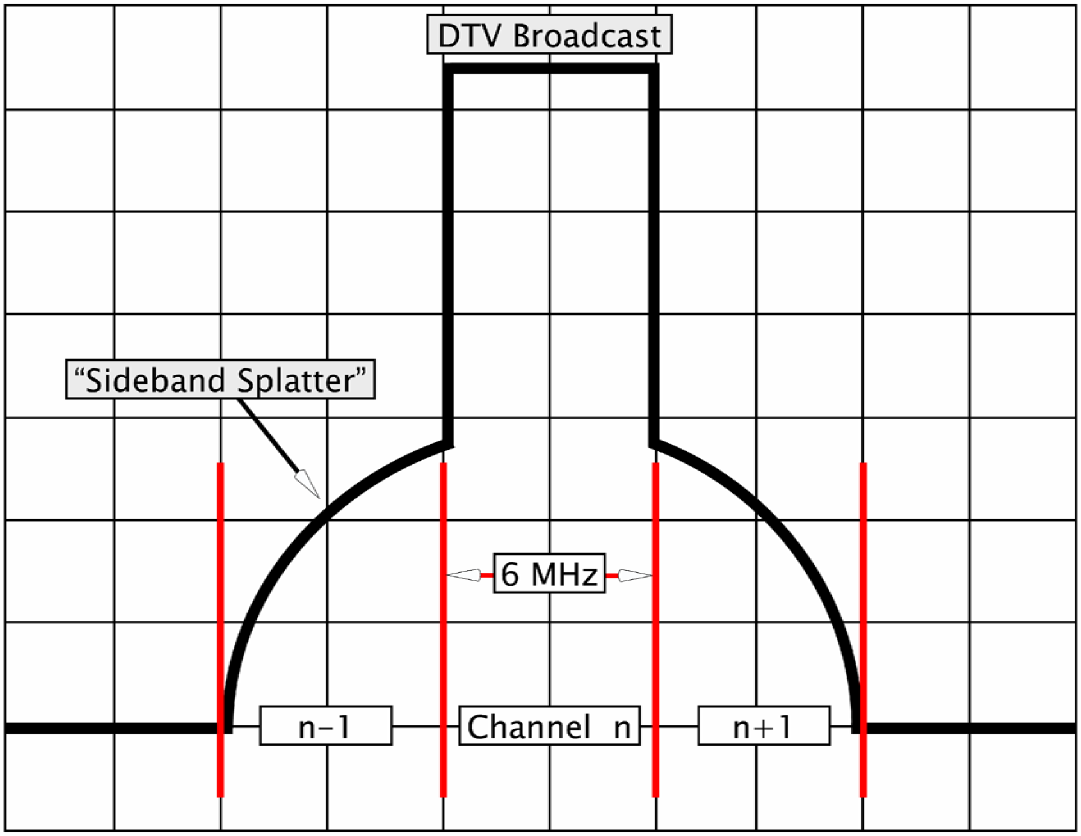

Figure 1: Adjacent Channel Interference

As DTV systems have replaced analog TV equipment, television broadcast professionals have found the need to develop new system performance measurement methods and terminology. Enhancements to the traditional third order intermodulation description for analog signals has been detailed in the article "*Interference Mitigation for Improved DTV Reception*" [3], where the authors encourage the addition of new technical terms to describe DTV transmitter and receiver characteristics.

The proposed "*DTV third order Intermodulation product*" ($IM_{3\ (DTV)}$), "DTV *third order Intercept Point*" ($IP_{3\ (DTV)}$), "*DTV Transmitter-generated Intermodulation product*" ($IM_{3\ (DTV-T)}$), and "*DTV Receiver-generated Intermodulation product*" ($IM_{3\ (DTV-R)}$) parameters offer refinements to the generic IM_3 and IP_3 terms, and encourage more specific analysis of the origins of DTV intermodulation interference. The single interferer adjacent channel measurements contained in this report are presented using the techniques and terminology described in the above-mentioned article. $IM_{3\ (DTV)}$ values in *Tables 1 through 4* are direct measurements; $IP_{3\ (DTV)}$ values were calculated using:

$$IP_{3\ (DTV)} = U + (U - IM_{3\ (DTV)}) / 2$$

KU TV Band Device Emulator and Testbed

The KU TV Band Device Emulator and Testbed (KUTVDET), is an experimental platform constructed to investigate the potential effects of secondary user TV Band devices in the spectrum currently allocated to television broadcasts (54-806 MHz). TV Band Device OFDM modulated operation and ATSC 8VSB broadcasts are emulated using modestly priced PCI form factor digital modulators and RF frequency synthesizers housed in separate desktop computers. Modulated test signals are generated using transport stream content stored on hard drives in each computer. Off-air digital broadcast signals are also available for experiments via a directional rooftop-mounted antenna.

In the case of DTV receivers that incorporate an IEEE-1394 port[2], the received transport stream can be thoroughly analyzed for errors, with inherently more accurate results than the somewhat subjective "Threshold of Visibility" (TOV) benchmark. The KUTVDET is capable of accommodating a variety of experimental scenarios through frequency agility, and flexible configuration of RF amplifier gain blocks, filters, step attenuators, switches, and power combiners. The configuration used for the $IM_{3\,(DTV\text{-}T)}$ measurements presented in this report is shown in *Figure 2*.

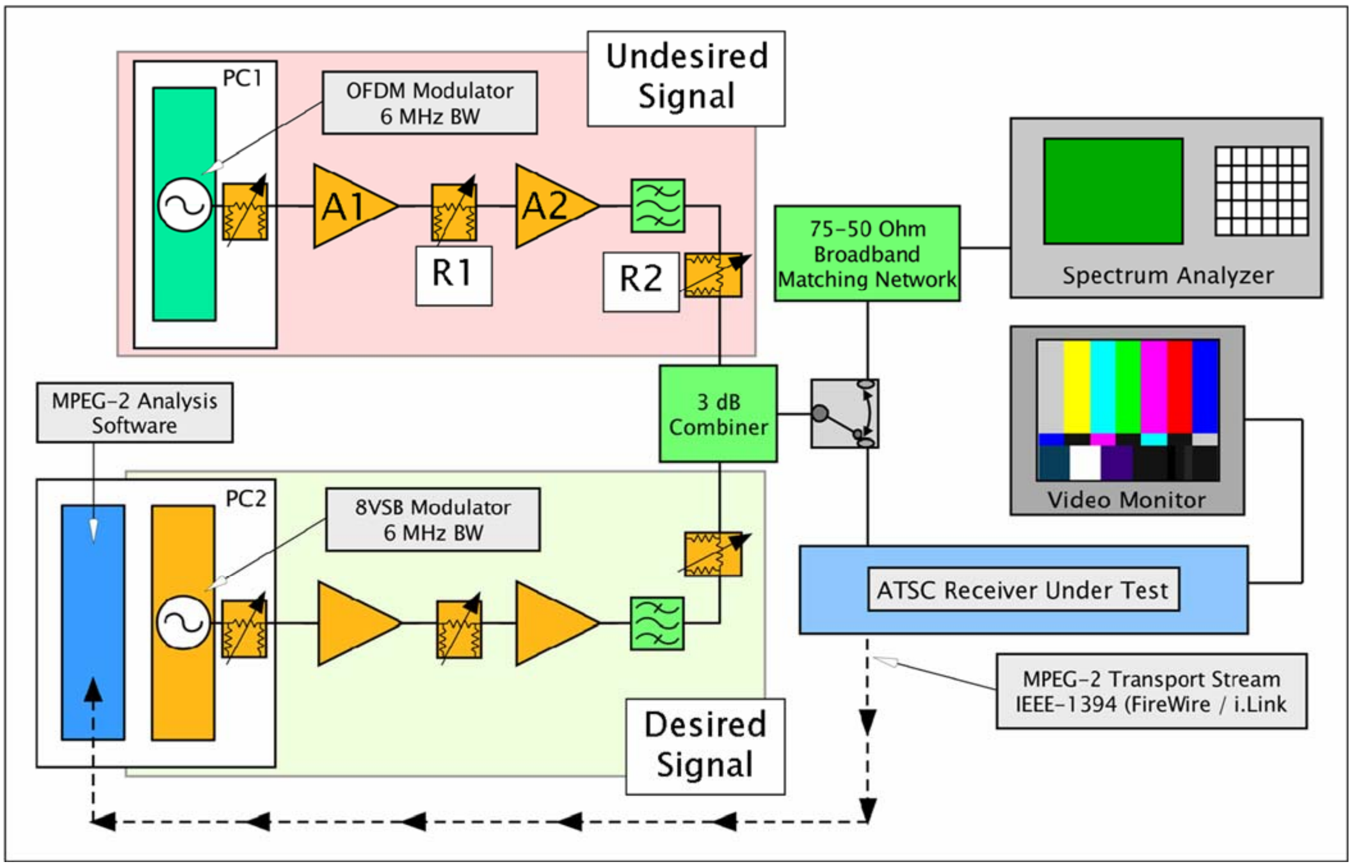

Figure 2: KU TV Band Device Emulator and Testbed (KUTVDET)

[2] *FireWire and iLink are common IEEE-1394 branding labels.*

Nonlinear characteristics of RF power amplifier A2 were used to create $IM_{3\ (DTV-T)}$ interference. The Undesired Signal $IM_{3\ (DTV-T)}$ interference level present at the receiver under test input was determined by the input level to A2. The degree to which A2 was driven into nonlinear operation was controlled using step attenuator R1, while the value of step attenuator R2 determined the final Undesired Signal RF channel power level. Single interferer DTV receiver tests were conducted in the upper and lower adjacent channels to a desired DTV signal at two intermodulation interference levels. R1 was used to adjust the Undesired Signal for maximum RF channel power with the minimum $IM_{3\ (DTV-T)}$ interference present in the adjacent desired channel, and maximum RF channel power with very significant levels of $IM_{3\ (DTV-T)}$.

Observations

Receivers were first tested using a desired channel power level of -53 dBm measured in a 6 MHz bandwidth. Channel 31 (572-578 MHz) was selected as the desired frequency, and the ATSC signal was created using the KUTVDET 8VSB modulator and a looping HDTV MPEG-2 transport stream. The adjacent channel undesired signal was generated using the testbed OFDM modulator and a looping transport stream. The filtered undesired signal level was configured for the minimum level of $IM_{3\ (DTV-T)}$ interference while maintaining operation within the region of the 1dB compression point (P_{1dB}) of amplifier A2. The adjacent channel undesired signal levels required to degrade the -53 dBm desired channel to TOV are indicated in *Table 1*. Example data from the measurement technique reference [3] is also included for comparison purposes; Figure 4 from the reference is reproduced in the Appendix of spectrum plots as *Figure 3*. Spectrum plots representative of a selection of *Table 1* measurements are contained in the Appendix, *Figures 4 through 7*.

	n-1 **Filtered** Undesired (dBm/6 MHz)				n+1 **Filtered** Undesired (dBm/6 MHz)			
Receiver	n-1 CH 30	$IM3_{DTV}$ CH 31	$IP3_{DTV}$	D/U (dB)	n+1 CH 32	$IM3_{DTV}$ CH 31	$IP3_{DTV}$	D/U (dB)
1 (1999 Model Year Set-top)	-24	-67	-2.5	-29	-19	-66	4.5	-34
2 (32" LCD DTV)	-16	-60	6	-37	-14	-62	10	-39
3 (Low Cost Set-top)	-17	-61	5	-36	-19	-67	5	-34
ATSC A/74	-20			-33	-20			-33
Rhodes - Sgrignoli $IM3_{DTV}$ Example (Figure 4; "Interference Mitigation for Improved DTV Reception")					n+1	$IM3_{DTV}$	$IP3_{DTV}$	
					-19.6	-57.8	-0.5	

Levels Required to Degrade Desired Channel to TOV

Table 1: Desired Channel Power = -53 dBm / 6 MHz;
Minimum Undesired Signal $IM_{3\ (DTV-T)}$

The DTV receivers were then tested using a filtered undesired signal configured to generate significant levels of $IM_{3\ (DTV-T)}$ interference in the adjacent desired channel bandwidth, with the same -53 dBm / 6 MHz desired signal used in the previous test. Adjacent channel undesired signal levels required to degrade the −53 dBm desired channel to TOV are indicated in *Table 2*. Spectrum plots representative of a selection of Table 2 measurements are contained in the Appendix, *Figures 8 through 11*.

	n−1 Filtered Undesired (dBm/6 MHz)				n+1 Filtered Undesired (dBm/6 MHz)			
Receiver	n−1 CH 30	$IM3_{DTV}$ CH 31	$IP3_{DTV}$	D/U (dB)	n+1 CH 32	$IM3_{DTV}$ CH 31	$IP3_{DTV}$	D/U (dB)
1 (1999 Model Year Set-top)	−14	−58	8	−14	−11	−59	13	−17
2 (32" LCD DTV)	−1	−46	21.5	−27	−4	−53	20.5	−24
3 (Low Cost Set-top)	−2	−46	20	−26	−3	−50	20.5	−25
ATSC A/74	−20			−33	−20			−33
					n+1	$IM3_{DTV}$	$IP3_{DTV}$	
Rhodes - Sgrignoli $IM3_{DTV}$ Example (Figure 4; "Interference Mitigation for Improved DTV Reception")					−19.6	−57.8	−0.5	

Levels Required to Degrade Desired Channel to TOV

Table 2: Desired Channel Power = −53 dBm / 6 MHz;

Significant Undesired Signal $IM3_{(DTV-T)}$

The desired channel power level was increased to −28 dBm measured in a 6 MHz bandwidth for the next receiver test. Channel 31 (572-578 MHz) was again selected as the desired frequency. The ATSC signal was created using the KUTVDET 8VSB modulator and a looping HDTV MPEG-2 transport stream as in the preceding tests. The filtered undesired OFDM signal was configured to generate minimal levels of $IM3_{(DTV-T)}$ interference in the adjacent desired channel bandwidth, while maintaining operation within the region of the 1dB compression point (P_{1dB}) of amplifier A2. Adjacent channel undesired signal levels required to degrade the −28 dBm desired channel to TOV are indicated in *Table 3*. Example data from the measurement technique reference [3] is again included for comparison purposes.

	n−1 Filtered Undesired (dBm/6 MHz)				n+1 Filtered Undesired (dBm/6 MHz)			
Receiver	n−1 CH 30	$IM3_{DTV}$ CH 31	$IP3_{DTV}$	D/U (dB)	n+1 CH 32	$IM3_{DTV}$ CH 31	$IP3_{DTV}$	D/U (dB)
1 (1999 Model Year Set-top)	−38	−70	−22	−15	−34	−68	−17	−19
2 (32" LCD DTV)	−32	−65	−15.5	−21	−33	−66	−16.5	−20
3 (Low Cost Set-top)	−33	−66	−16.5	−20	−33	−67	−16	−20
ATSC A/74	−20			−33	−20			−33

Levels Required to Degrade Desired Channel to TOV

Table 3: Desired Channel Power = −28 dBm / 6 MHz;

Minimum Undesired Signal $IM3_{(DTV-T)}$

Spectrum plots representative of a selection of *Table 3* measurements are contained in the Appendix, *Figures 12 through 15*.

The same −28 dBm desired signal used in the preceding test was also used for the final receiver test. For this test, the undesired signal was again configured to produce significant levels of $IM_{3\ (DTV-T)}$ interference. Adjacent channel undesired signal levels required to degrade the −28 dBm desired channel to TOV are indicated in *Table 4*.

	n−1 **Filtered** Undesired (dBm/6 MHz)				n+1 **Filtered** Undesired (dBm/6 MHz)			
Receiver	n−1 CH 30	$IM3_{DTV}$ CH 31	$IP3_{DTV}$	D/U (dB)	n+1 CH 32	$IM3_{DTV}$ CH 31	$IP3_{DTV}$	D/U (dB)
1 (1999 Model Year Set-top)	−15	−48	1.5	−13	−11	−45	6	−17
2 (32" LCD DTV)	−8	−41	8.5	−20	−6	−40	11	−22
3 (Low Cost Set-top)	−8	−41	8.5	−20	−9	−43	8	−19
ATSC A/74	−20			−33	−20			−33

Levels Required to Degrade Desired Channel to TOV

Table 4: Desired Channel Power = −28 dBm / 6 MHz;
Significant Undesired Signal $IM_{3\ (DTV-T)}$

Spectrum plots representative of a selection of *Table 4* measurements are contained in the Appendix, *Figures 16 through 19*.

Receiver-Generated Intermodulation Products

Direct spectrum analyzer measurement of *receiver-generated intermodulation products* ($IM_{3\ (DTV-R)}$) was not covered in scope of this report, due to the necessity of receiver disassembly and measurement point insertion. Future investigations may include such an analysis. However, through the use of a purposely misconfigured spectrum analyzer, an effort has been made to illustrate $IM_{3\ (DTV-R)}$, as shown in *Figure 20.* The analyzer display content was first captured with the internal RF input attenuator properly configured, then with the same signal input levels, the analyzer attenuator setting was manually reduced 10 dB, resulting in the overload of one or more analyzer front end components.

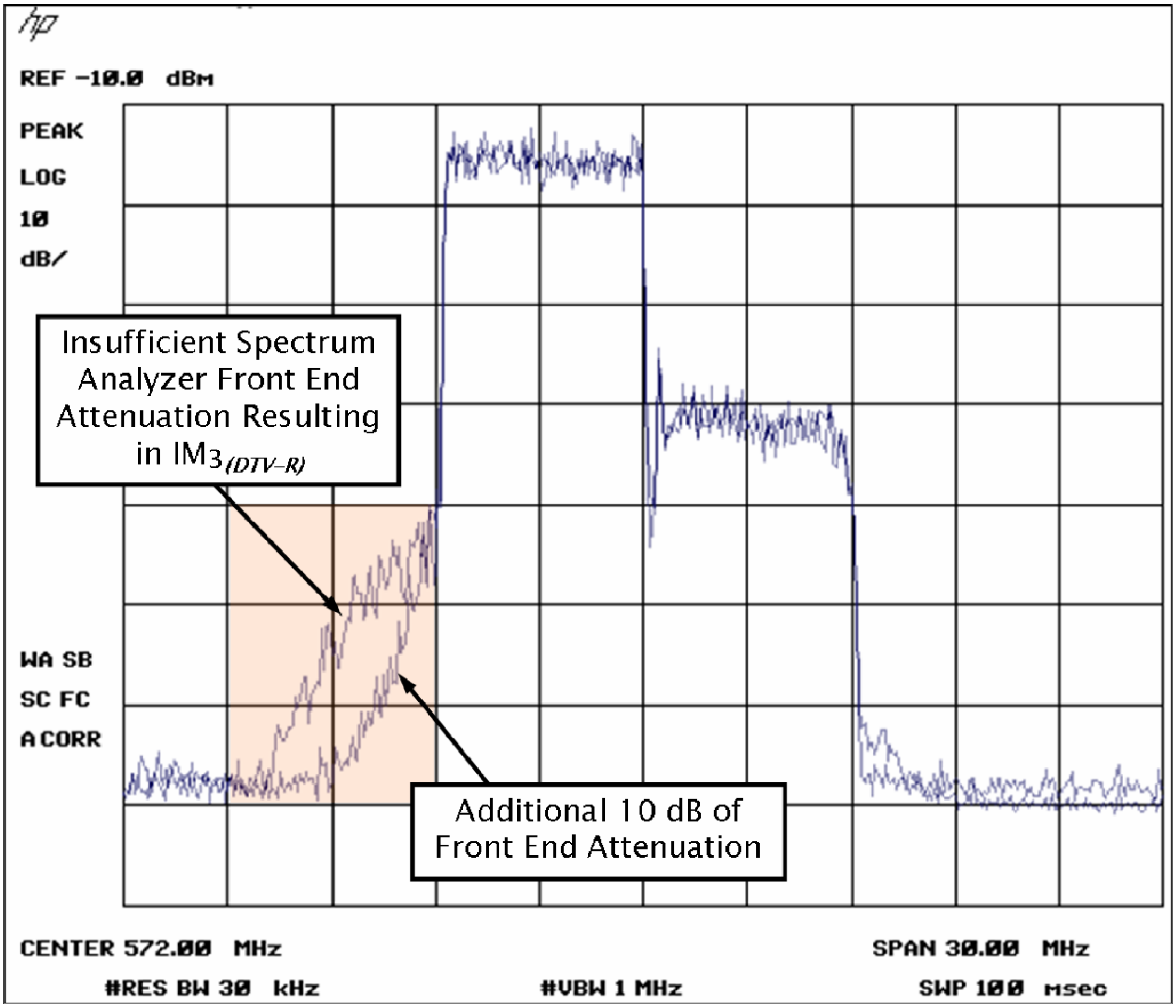

Figure 20: Example of $IM_{3\ (DTV-R)}$ Using an Improperly Configured Spectrum Analyzer

Conclusions

In this report, we have presented the observed effects of a single interfering secondary transmission on a selection of digital television receivers, and explored ($IM_{3\ (DTV)}$) and ($IP_{3\ (DTV)}$) channel characterization techniques. This work indicates that a refinement of $IM_{3\ (DTV-T)}$ measurement procedures, to include standardized measurements over a fractional portion of a desired channel directly adjacent to the interfering signal, would be of value.

The majority of $IM_{3\ (DTV-T)}$ ingress energy occurs in the 3 MHz of desired channel bandwidth immediately adjacent to the interfering signal. Rather than integrating the total average intermodulation interference power across the entire channel, which provides a somewhat non-intuitive $IM_{3\ (DTV-T)}$ measurement result without the inclusion of the undesired signal level or $IP_{3\ (DTV)}$, measurement of the interference power in the adjacent 3 MHz of the 6 MHz channel could provide more valuable $IM_{3\ (DTV)}$ information.

The results presented here indicate that carefully implemented secondary use of open channel bandwidth immediately adjacent to a licensed digital television transmission is a viable practice, given the expectation that TV Band device designs will place an emphasis on the protection of television broadcasts.

Device design challenges include RF power amplifier and output filtering implementation, and development of suitable cognitive properties and adaptive capabilities to provide the maximum amount of protection to DTV broadcasts, insuring the successful coexistence of primary and secondary users in the TV Band spectrum.

References

[1] Federal Communications Commission, "Unlicensed Operation in the TV Broadcast Bands", First Report and Order, FCC-06-156A1, p. 2, Oct. 2006.

[2] Public Law 109-171, 109th Congress, Title III, "Digital Television Transition and Public Safety Act of 2005", 120 Stat. 21, Feb. 2006.

[3] C.W. Rhodes, G.J. Sgrignoli, "Interference Mitigation for Improved DTV Reception." in *IEEE Transactions on Consumer Electronics*, Vol. 51, pp. 463-470, May 2005.

Appendix: Spectrum Plots

This appendix contains spectrum plot images representative of measurement methods and results discussed in the preceding report.

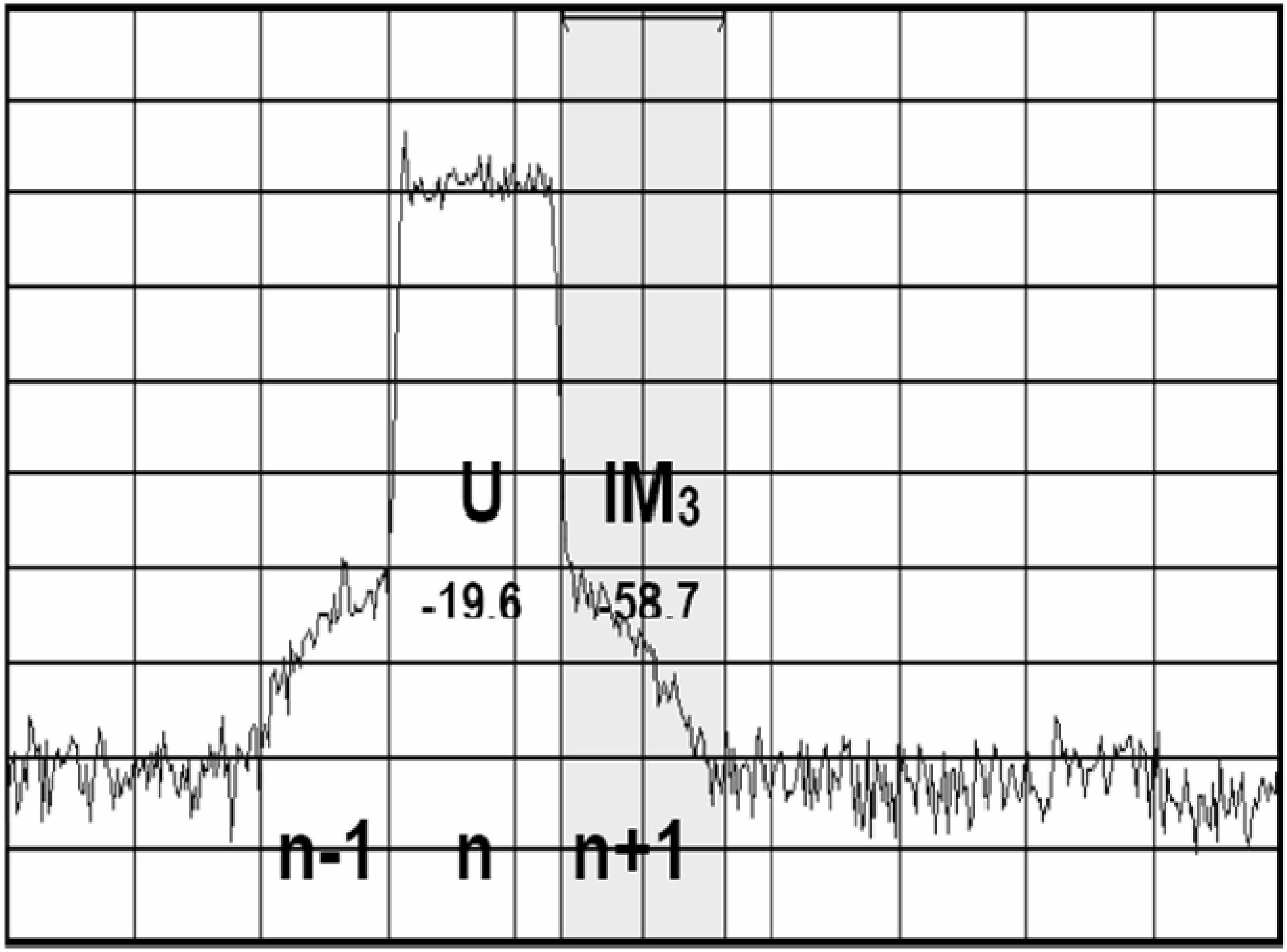

Figure 3: "Interference Mitigation for Improved DTV Reception; Figure 4"

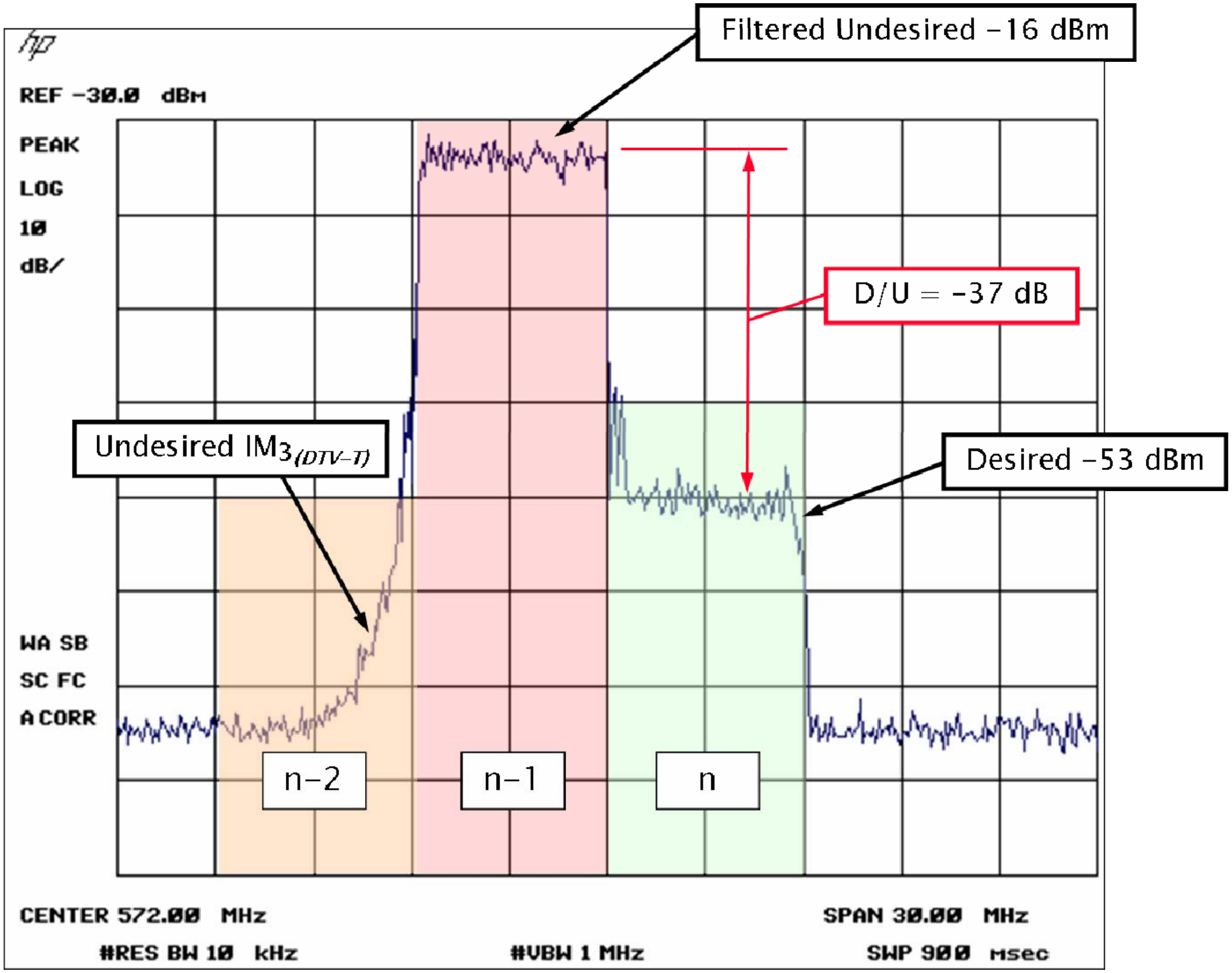

Figure 4: n= -53 dBm; Undesired Signal at n-1; Minimum IM3 (DTV-T) Configuration

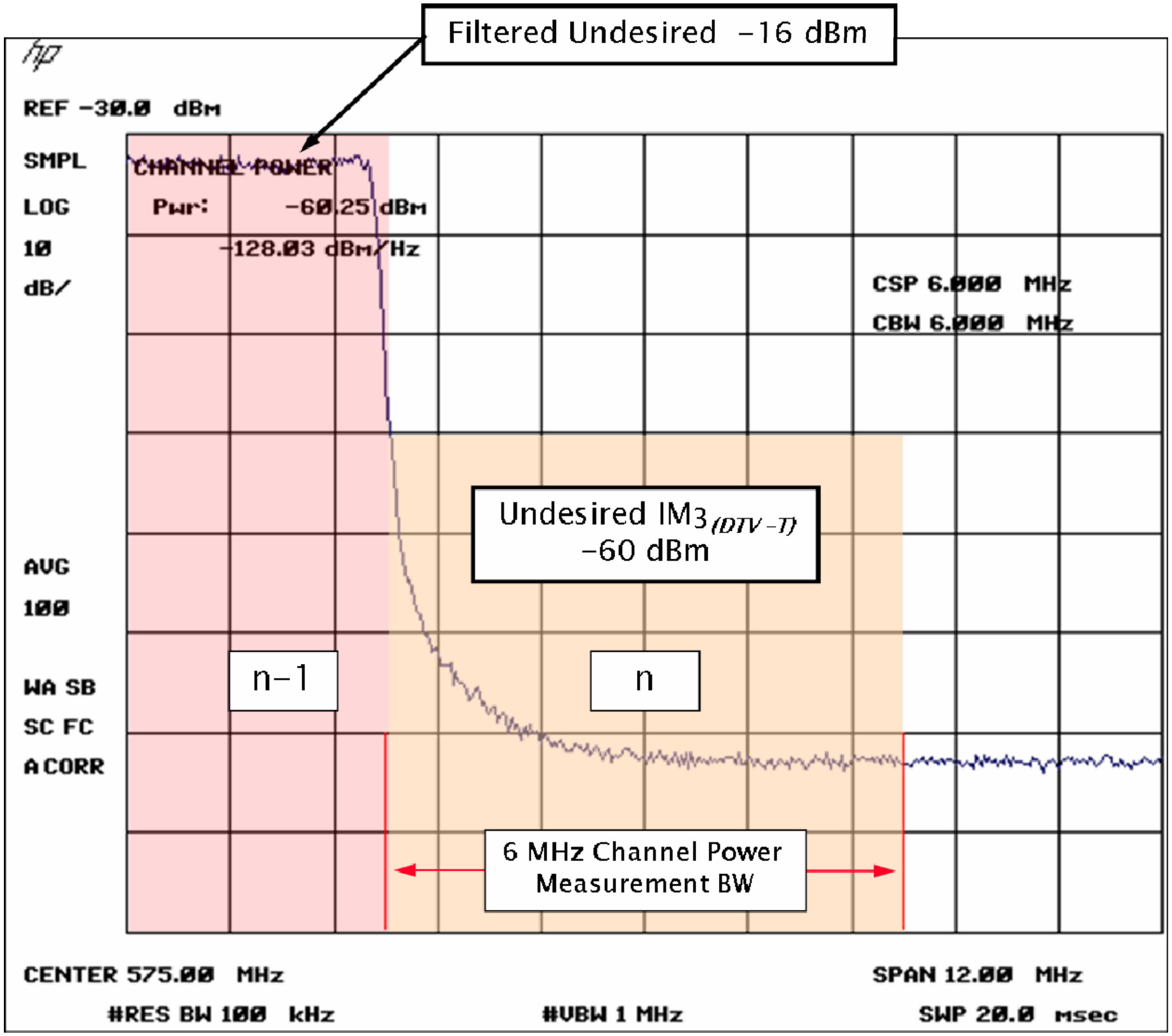

Figure 5: IM_3 (DTV-T) Level Present in Desired Channel n

Undesired Signal at n-1; Minimum IM_3 (DTV-T) Configuration

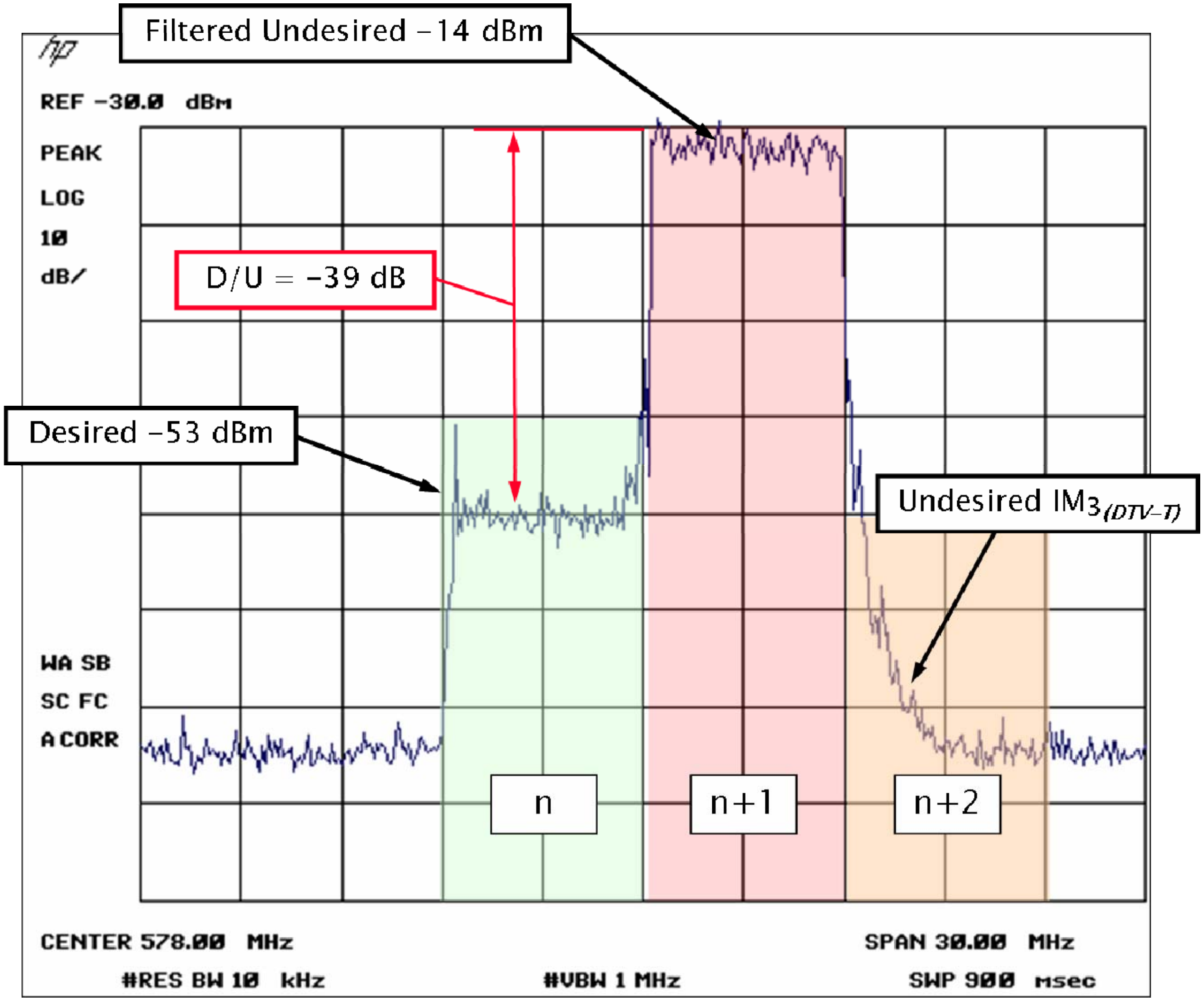

Figure 6: n= -53 dBm; Undesired Signal at n+1; Minimum IM_3 (DTV-T) *Configuration*

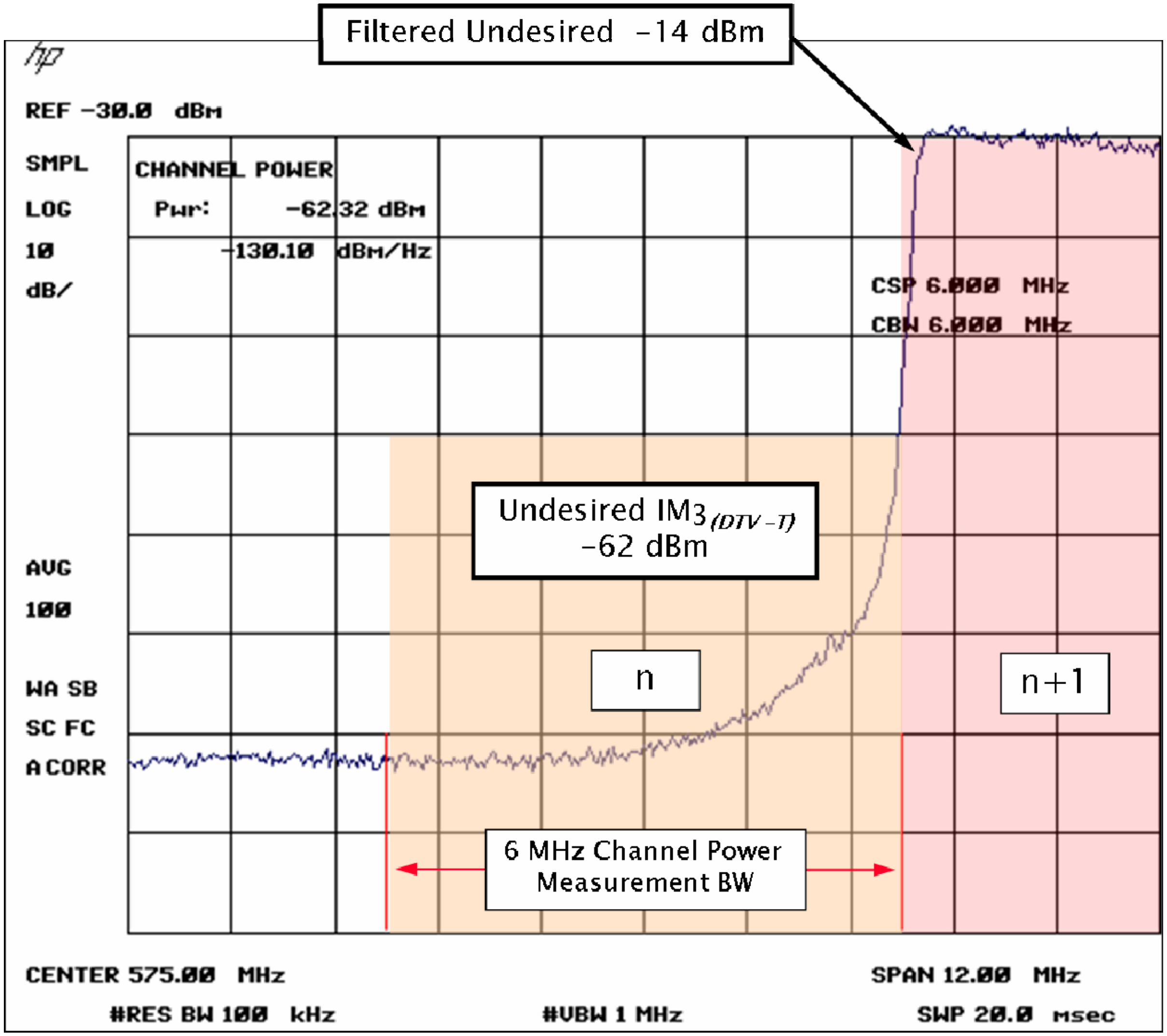

Figure 7: $IM_{3\ (DTV-T)}$ Level Present in Desired Channel n

Undesired Signal at n+1; Minimum $IM_{3\ (DTV-T)}$ Configuration

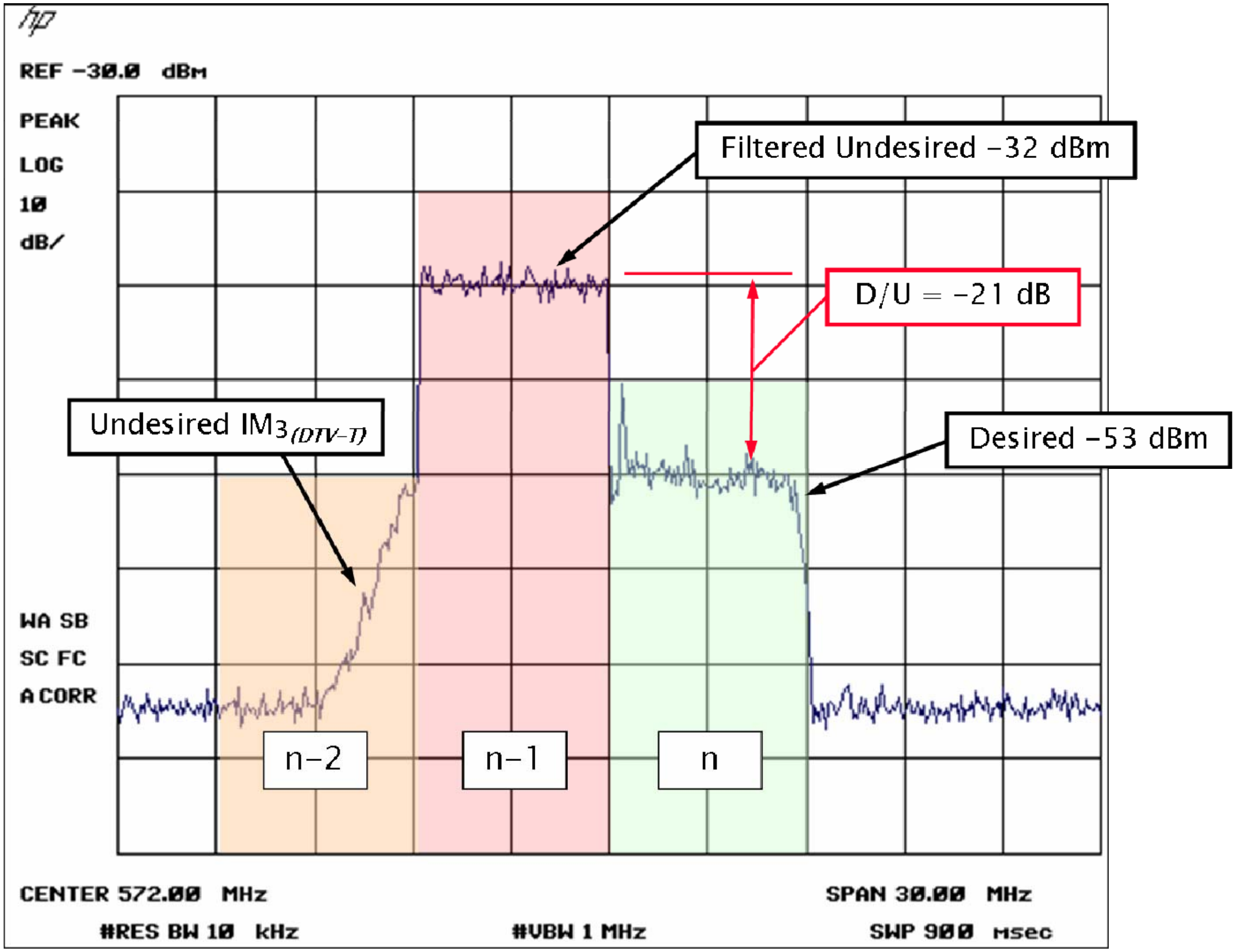

Figure 8: n= -53 dBm; Undesired Signal at n-1; Significant $IM_{3\ (DTV-T)}$ *Configuration*

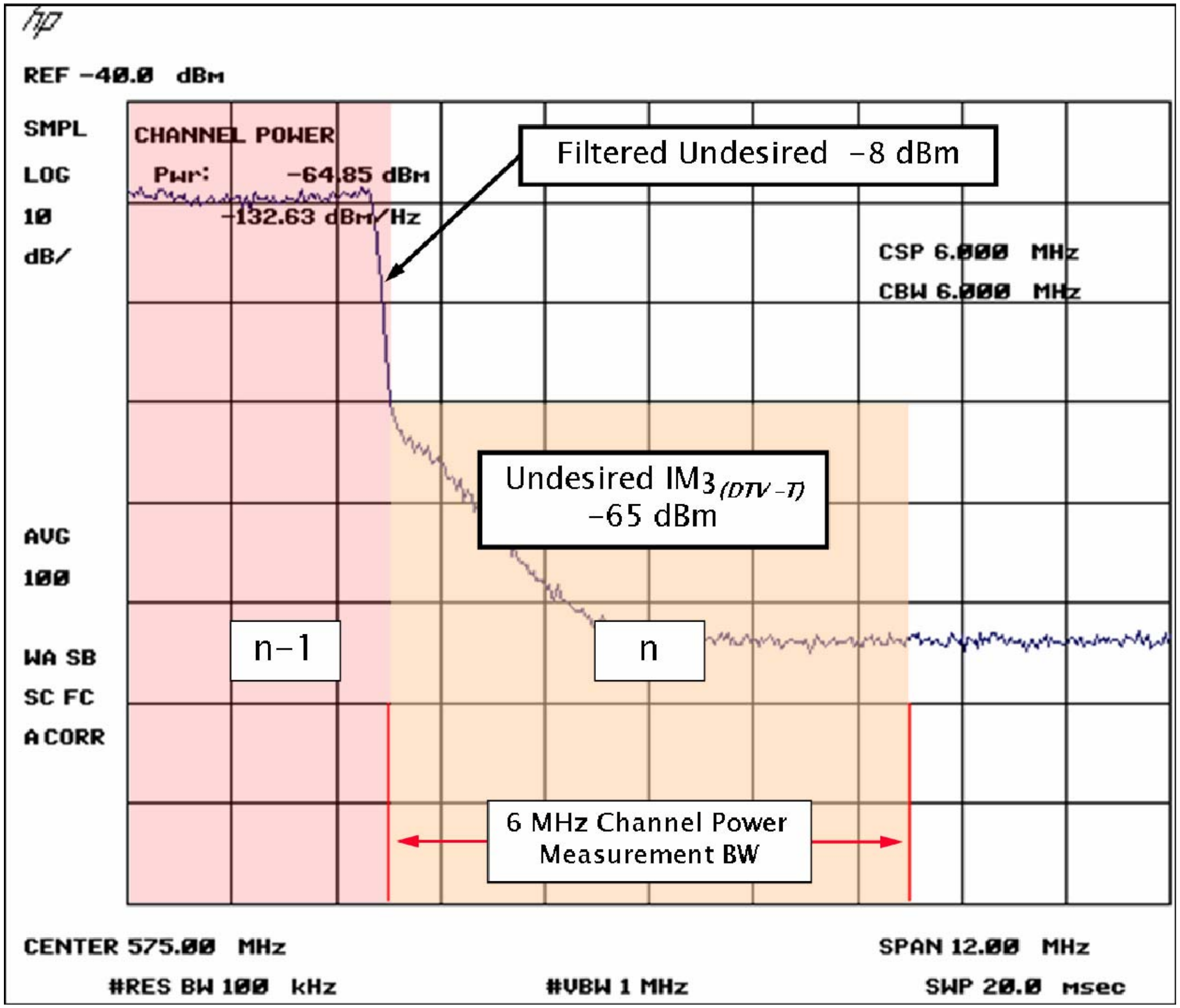

Figure 9: IM_3 (DTV-T) Level Present in Desired Channel n

Undesired Signal at n-1; Significant IM_3 (DTV-T) Configuration

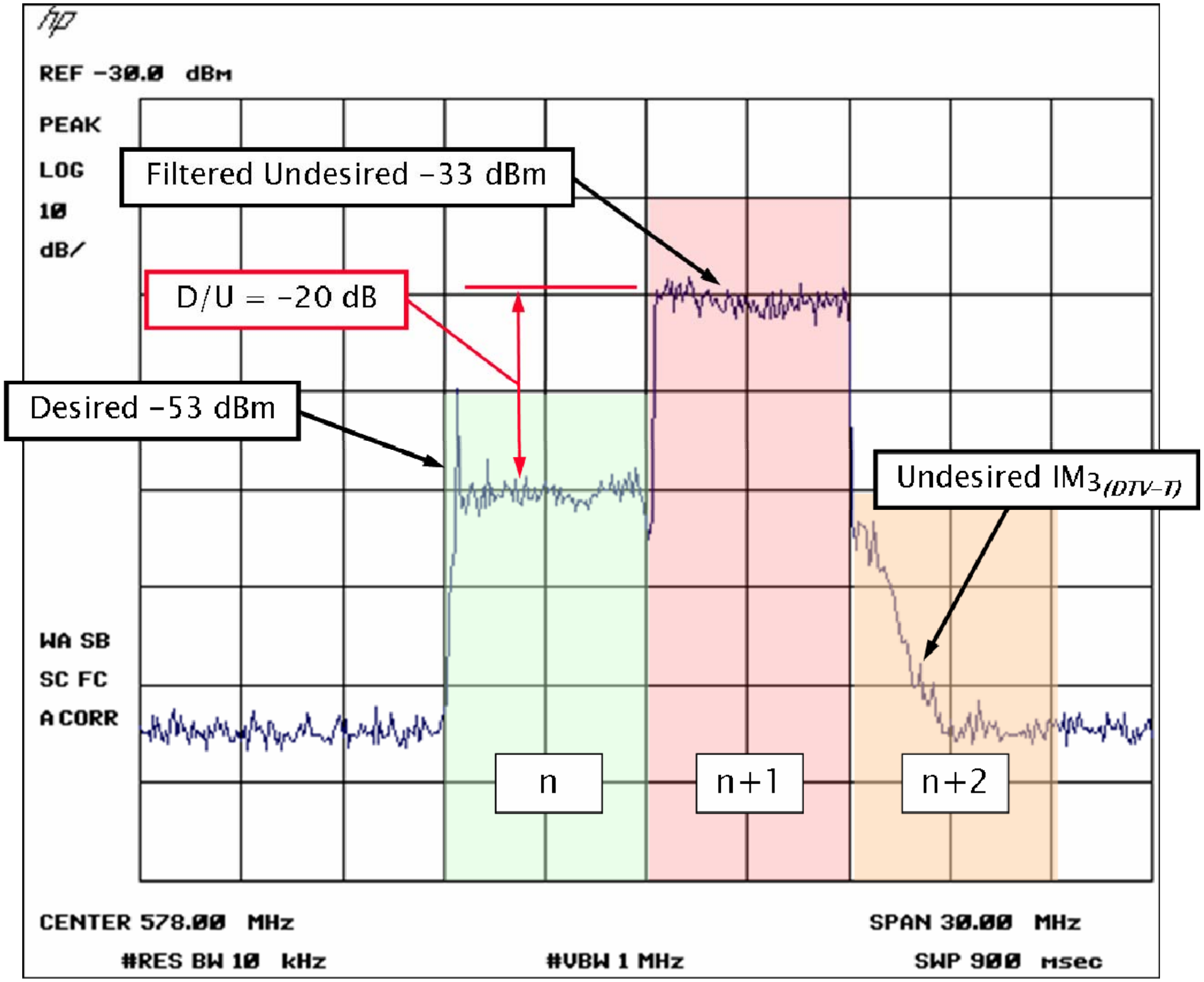

Figure 10: n= -53 dBm; Undesired Signal at n+1; Significant $IM_{3\ (DTV-T)}$ Configuration

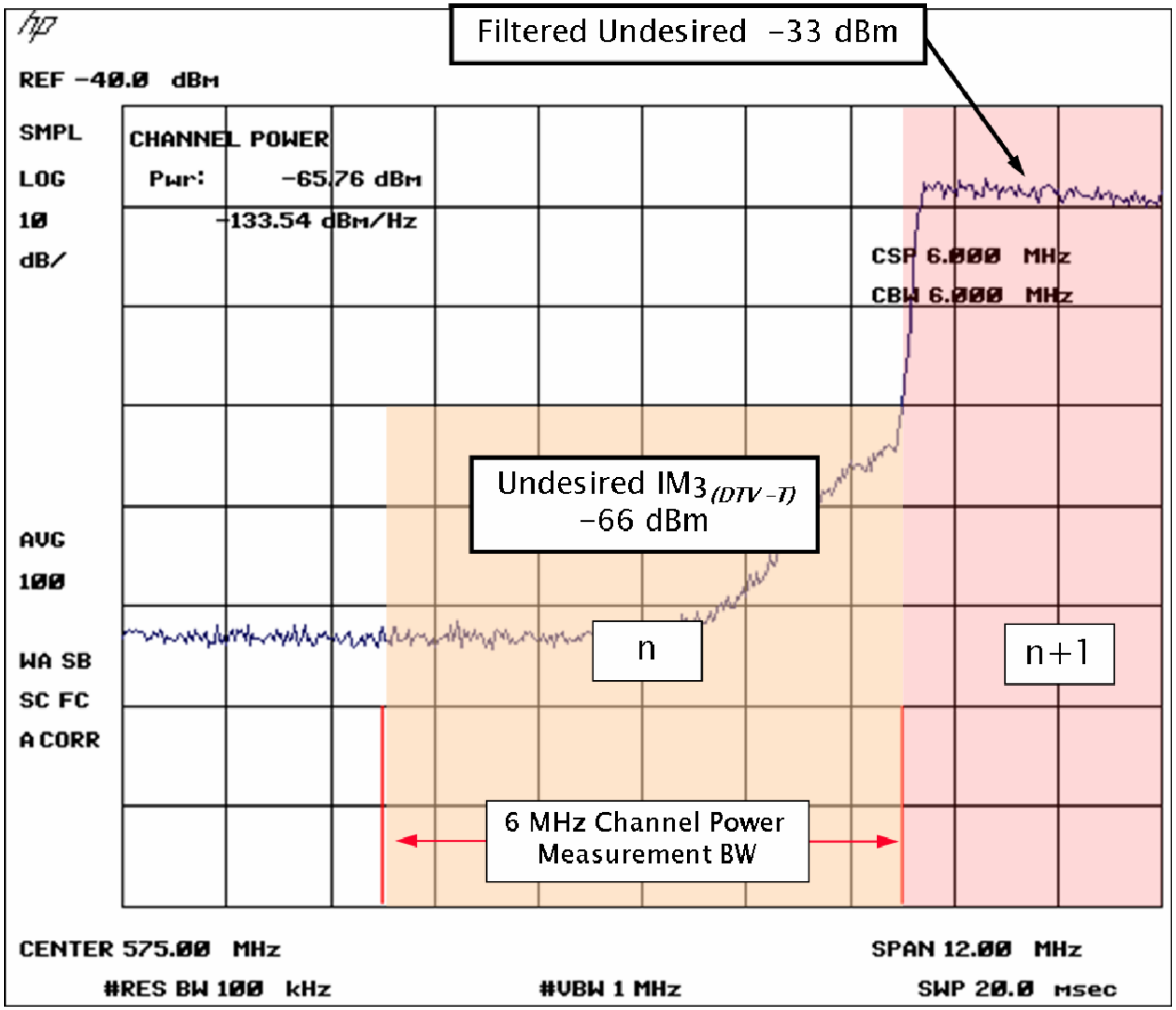

Figure 11: IM_3 (DTV-T) Level Present in Desired Channel n

Undesired Signal at n+1; Significant IM_3 (DTV-T) Configuration

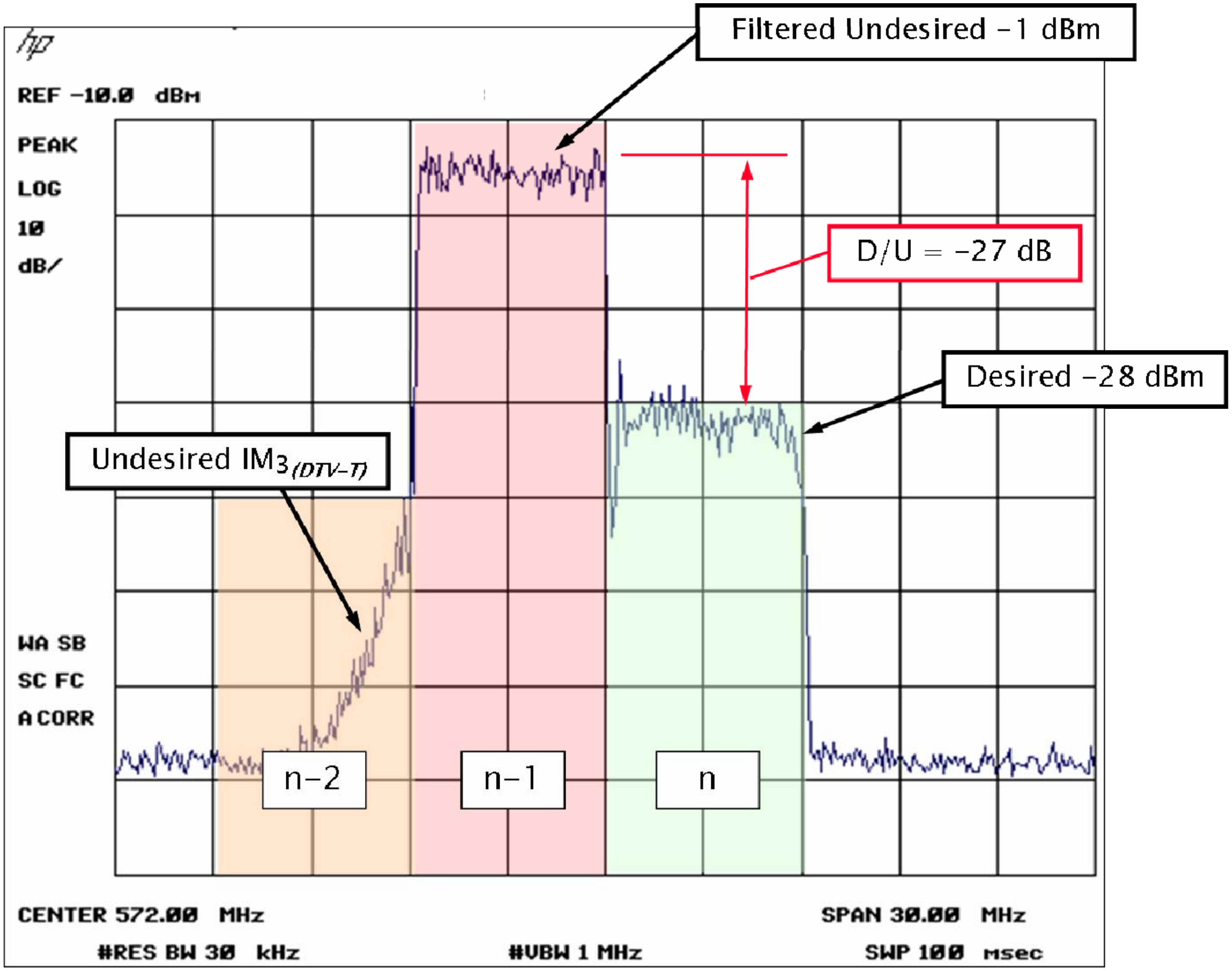

Figure 12: n= -28 dBm; Undesired Signal at n-1; Minimum $IM_{3\ (DTV-T)}$ Configuration

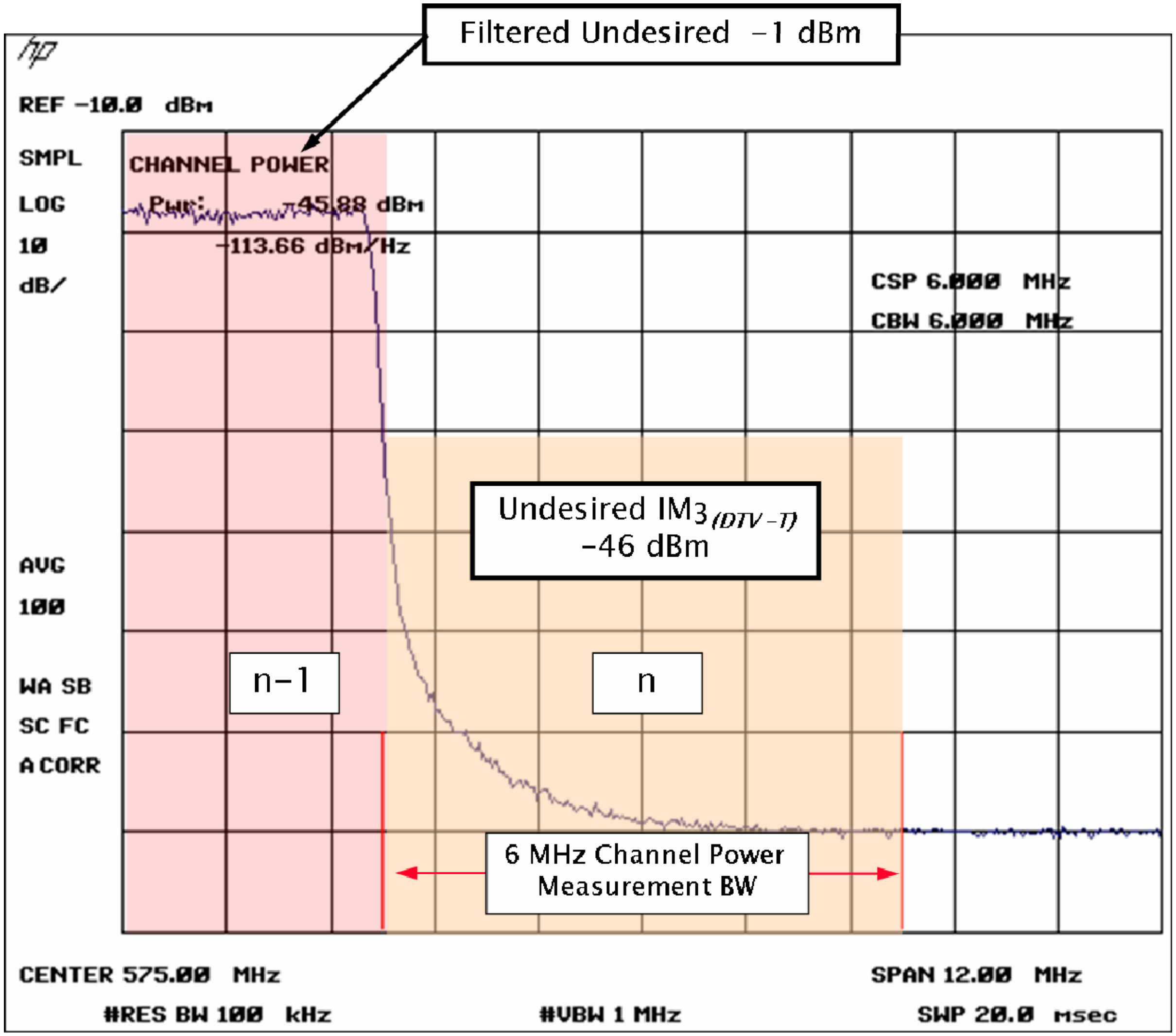

Figure 13: IM3 (DTV-T) Level Present in Desired Channel n

Undesired Signal at n-1; Minimum IM3 (DTV-T) Configuration

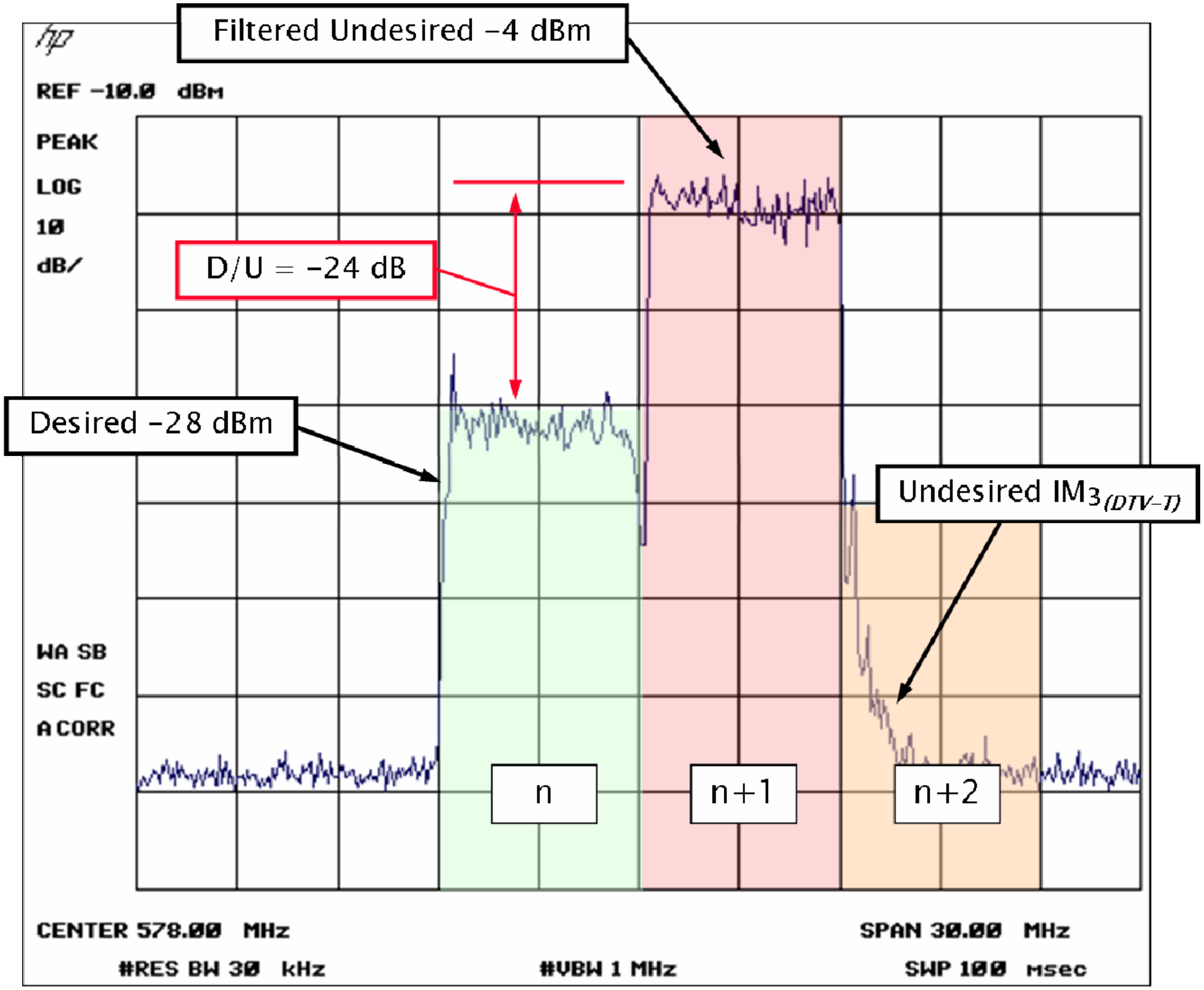

Figure 14: n= -28 dBm; Undesired Signal at n+1; Minimum $IM_{3\ (DTV-T)}$ Configuration

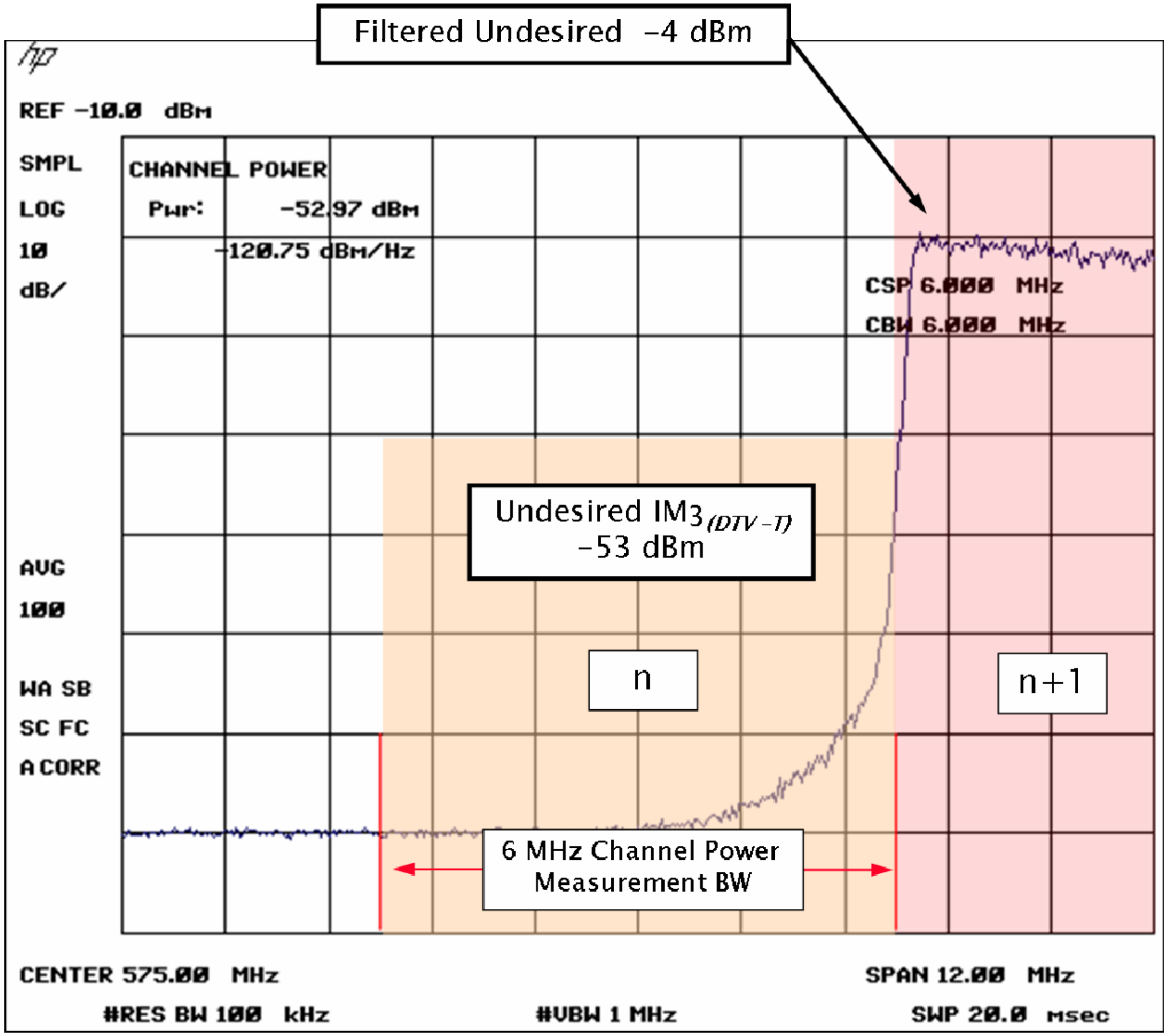

Figure 15: IM3 (DTV-T) Level Present in Desired Channel n

Undesired Signal at n+1; Minimum IM3 (DTV-T) Configuration

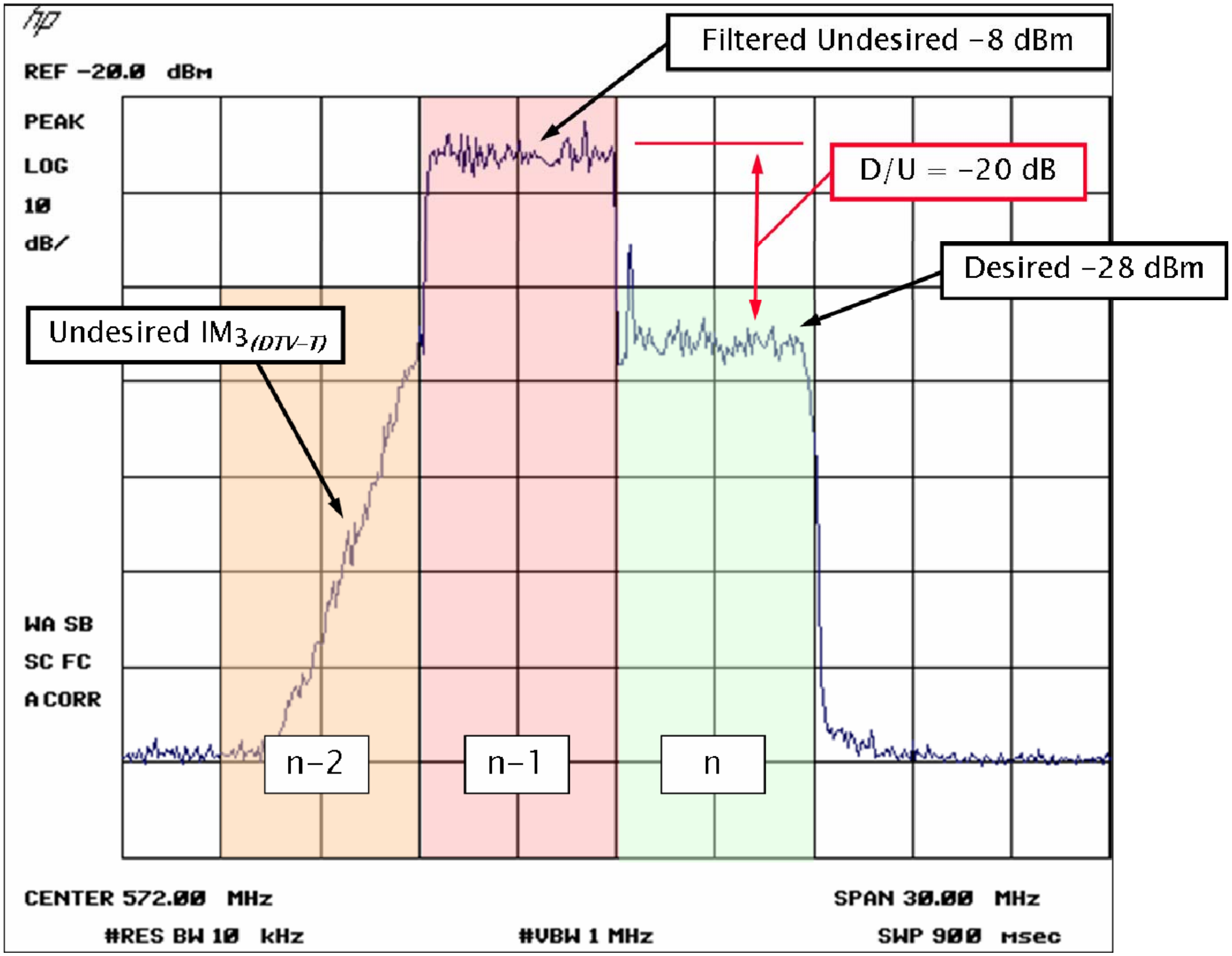

Figure 16: n= -28 dBm; Undesired Signal at n-1; Significant IM_3 (DTV-T) Configuration

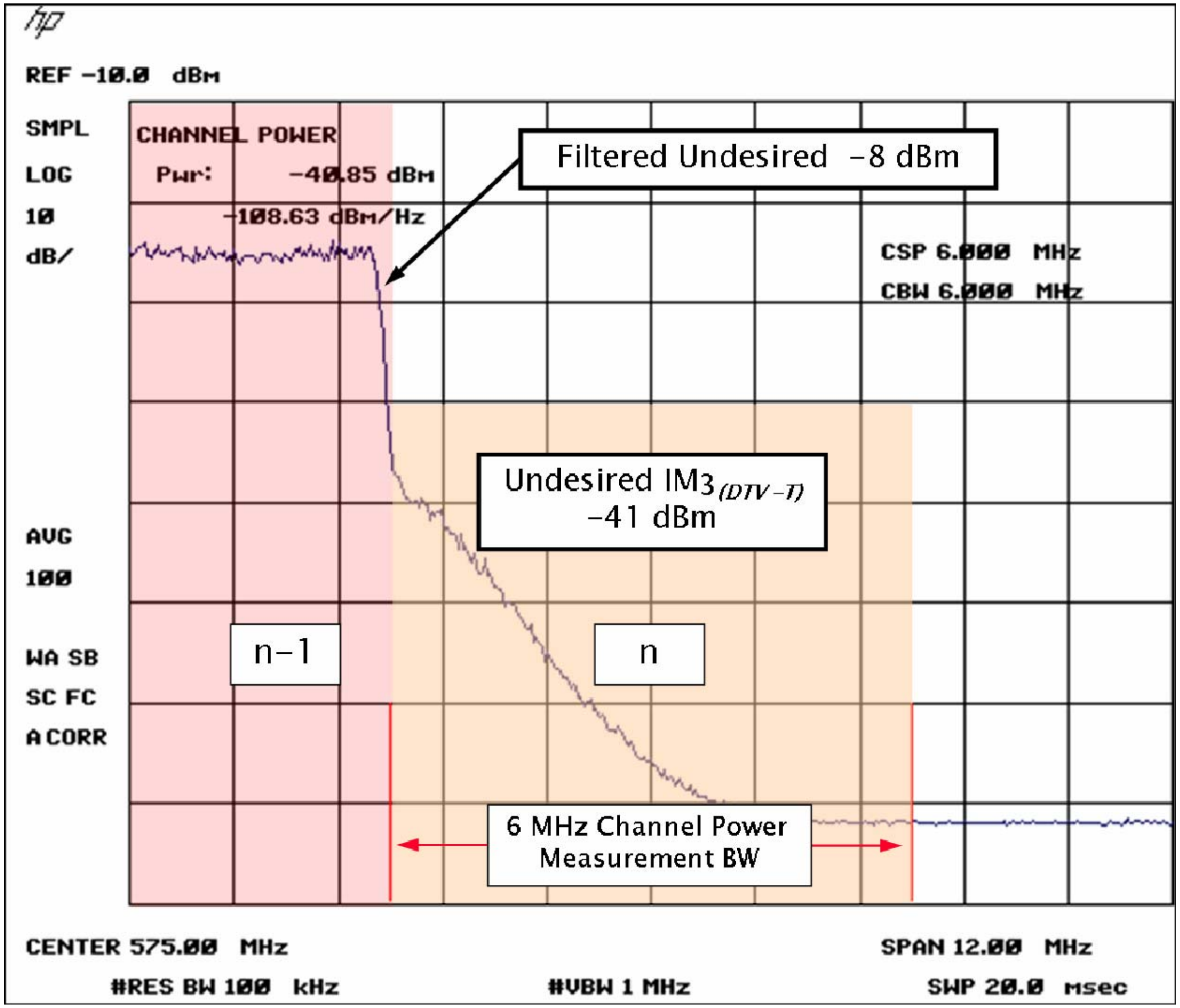

Figure 17: IM_3 (DTV-T) Level Present in Desired Channel n

Undesired Signal at n-1; Significant IM_3 (DTV-T) Configuration

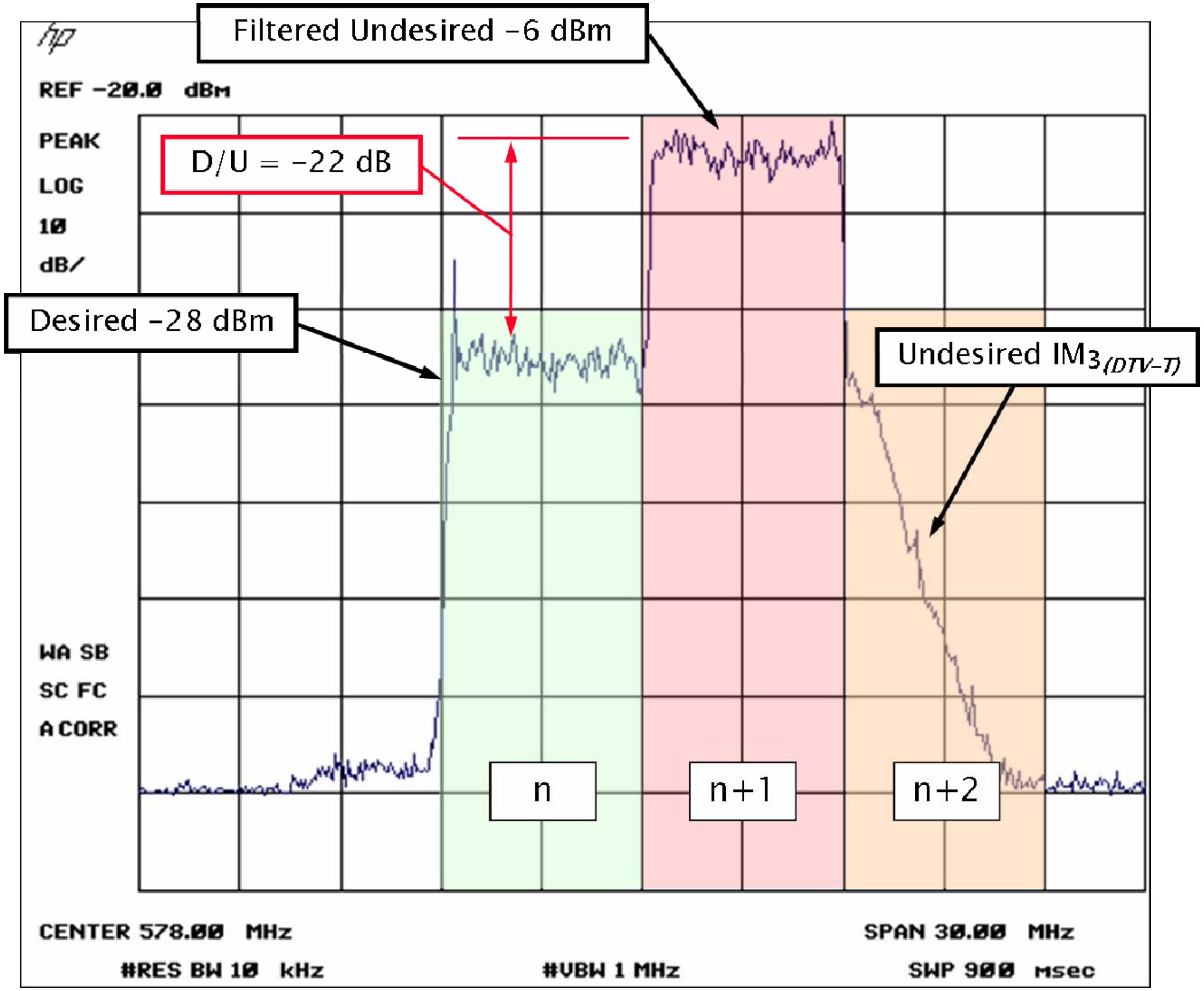

Figure 18: n= -28 dBm; Undesired Signal at n+1; Significant $IM_{3\ (DTV-T)}$ Configuration

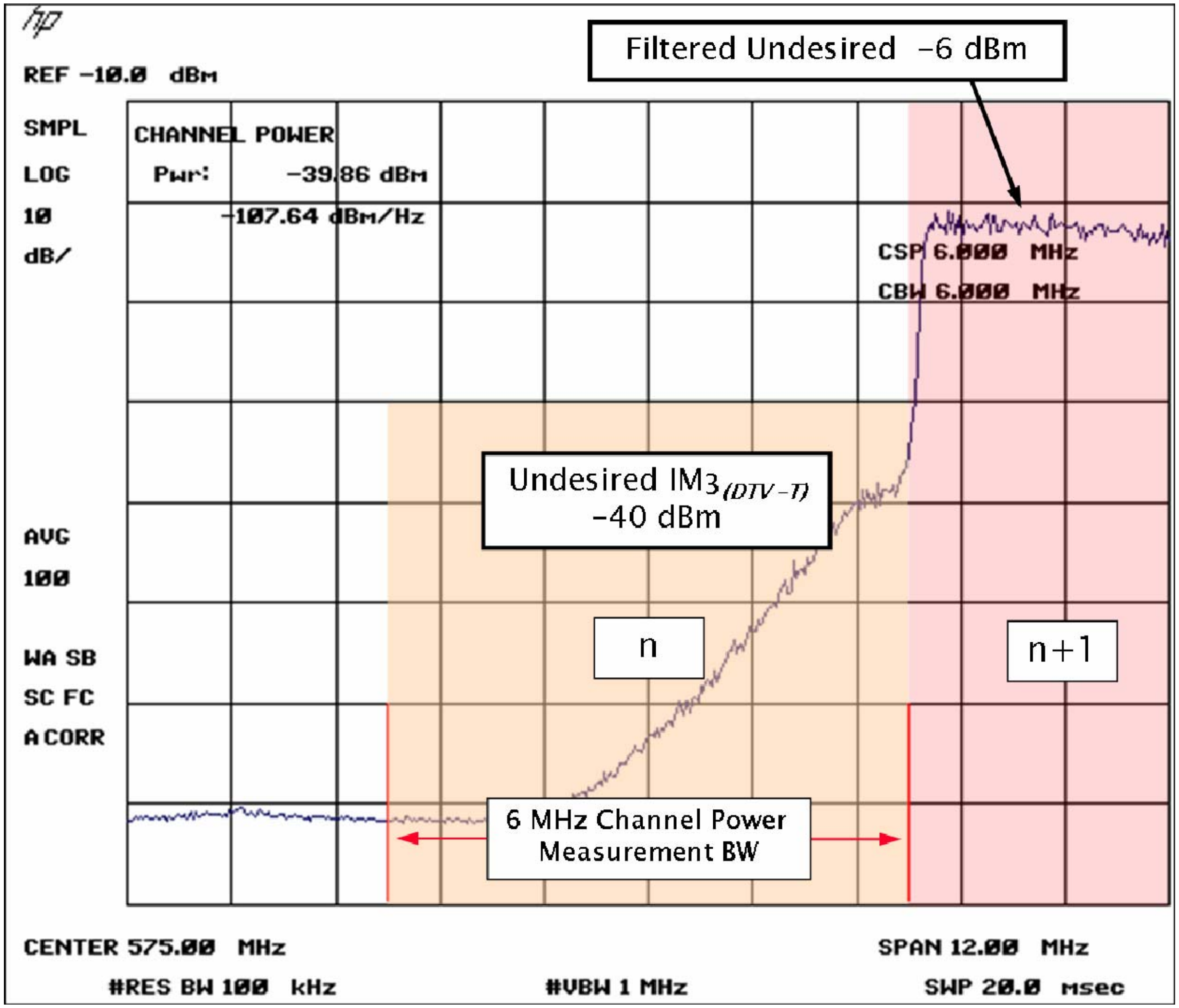

Figure 19: $IM_{3\ (DTV-T)}$ Level Present in Desired Channel n

Undesired Signal at n+1; Significant $IM_{3\ (DTV-T)}$ Configuration