How does a GPS signal look ?

MGA Webinar Series # 13

Dr. Dinesh Manandhar, Associate Professor (Project)
Center for Spatial Information Science, The University of Tokyo

14th MAY 2020, 18:00 – 19:00 (JST)

ZOOM Link:
Registration: https://gnss.peatix.com

Introduction

This webinar provides information on GPS L1C/A signal structure, signal generation and its properties like power spectrum, signal power. A software generated signal will be used for demonstration to show its properties like modulation, power spectrum and measurement of these power values using a Tektronix RSA 306B spectrum analyzer.

This webinar will help you to understand and visualize GPS signal. GPS L1C/A signal is a base signal for many other GNSS signals. If you are interested in signal processing, jamming, interference and spoofing (JIS) issues, then this webinar will provide necessary information required to understand JIS mitigation techniques. We will conduct webinar on JIS in near future.

DATE: 14th MAY 2020 (Thursday)
TIME: 18:00 - 19:00 JST (Japan Time)
Registration: https://gpsca.peatix.com
Main Link: https://gnss.peatix.com (Registration is required)

GPS L1C/A Signal Structure

- Carrier Signal
  - It defines the frequency of the signal
  - For example:
    - GPS L1 is 1575.42MHz, L2 is 1227.60MHz and L5 is 1176.45MHz
- PRN (Pseudo Random Noise) Code
  - Randomly generated codes following a particular rule
  - Used to modulate the data and identify each satellite
  - Should have good auto-correlation and cross-correlation properties
- Navigation Data
  - Required to compute distance between the satellite and the receiver
  - Provides satellite orbit related data (ephemeris data)
  - Provides satellite clock related information (clock errors etc)
  - Provides satellite health related information to receiver

GPS L1C/A Signal Structure

- Carrier Signal
  - Frequency : 1575.42MHz

- PRN Code
  - Chip Rate : 1.023MHz
  - Code Period : 1msec
  - No of Chips/Period : 1023

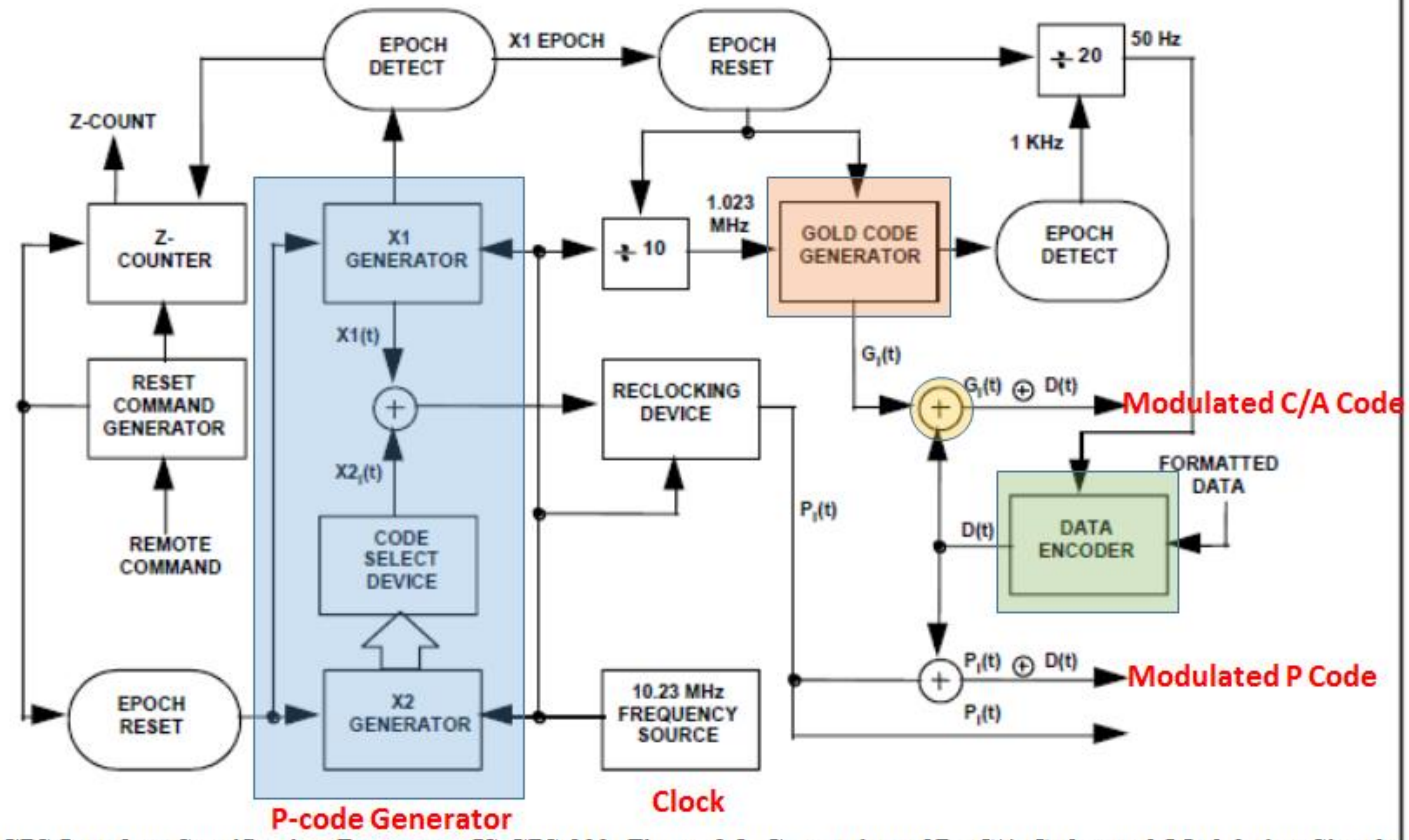
- Navigation Data
  - Data Rate : 50bps (bits per sec)
  - Bit Length : 20msec

- Modulation : BPSK(1)
  - BPSK (Binary Phase Shift Keying)

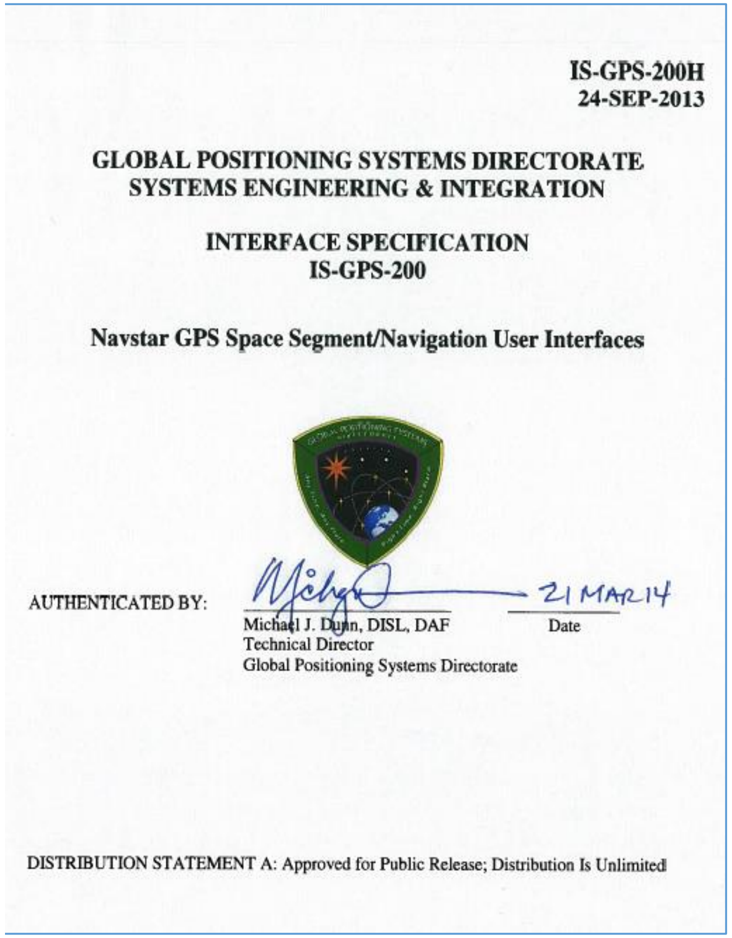
GPS Signals

Band	Frequency, MHz	Signal Type	Code Length msec	Chip Rate, MHz	Modulation Type	Data / Symbol Rate, bps/sps	Notes
L1	1575.42 (10.23*154)	C/A	1	1.023	BPSK	50	Legacy Signal
		C_{Data}	10	1.023	BOC(1,1)	50 / 100	
		C_{Pilot}	10	1.023	TMBOC	No Data	BOC(1,1) & BOC(6,1)*
		P(Y)	7 days	10.23	BPSK		Restricted / Military
L2	1227.60 (10.23*120)	CM	20	0.5115	BPSK	25 / 50	Modulated by TDM of (L2CM xor Data) and L2CL
		CL	1500	0.5115		No Data	
		P(Y)	7days	10.23	BPSK		Restricted / Military
L5	1176.45 (10.23*115)	I	1	10.23	BPSK	50 / 100	Provides Higher Accuracy
		Q	1			No Data	

GPS L1C/A, P Signals



Source: GPS Interface Specification Document, IS-GPS-200, Figure 3-1. Generation of P-, C/A-Codes and Modulating Signals



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INTERFACE SPECIFICATION
IS-GPS-200

Navstar GPS Space Segment/Navigation User Interfaces

AUTHENTICATED BY: Michael J. Dunn, DISL, DAF
Technical Director
Global Positioning Systems Directorate

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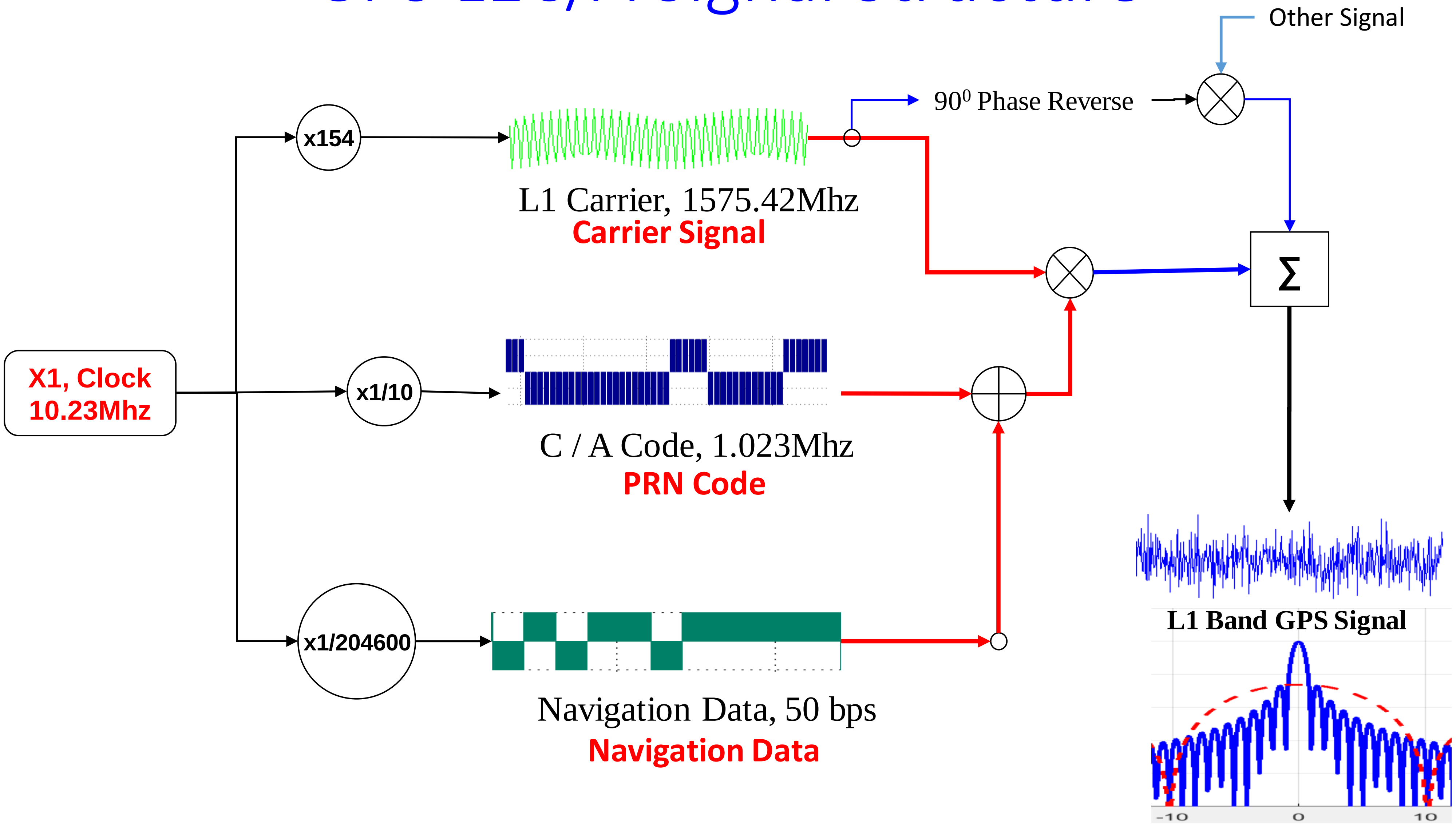
GPS L1C/A Signal Structure



GPS L1 C/A PRN CODE

Table 3-Ia. Code Phase Assignments (sheet 1 of 2)

SV ID No.	GPS PRN Signal No.	Code Phase Selection C/A($G2_i$)***	Code Phase Selection ($X2_i$)	Code Delay Chips C/A	Code Delay Chips P	First 10 Chips Octal* C/A	First 12 Chips Octal P
1	1	2 ⊕ 6	1	5	1	1440	4444
2	2	3 ⊕ 7	2	6	2	1620	4000
3	3	4 ⊕ 8	3	7	3	1710	4222
4	4	5 ⊕ 9	4	8	4	1744	4333
5	5	1 ⊕ 9	5	17	5	1133	4377
6	6	2 ⊕ 10	6	18	6	1455	4355
7	7	1 ⊕ 8	7	139	7	1131	4344
8	8	2 ⊕ 9	8	140	8	1454	4340
9	9	3 ⊕ 10	9	141	9	1626	4342
10	10	2 ⊕ 3	10	251	10	1504	4343
11	11	3 ⊕ 4	11	252	11	1642	
12	12	5 ⊕ 6	12	254	12	1750	
13	13	6 ⊕ 7	13	255	13	1764	
14	14	7 ⊕ 8	14	256	14	1772	
15	15	8 ⊕ 9	15	257	15	1775	
16	16	9 ⊕ 10	16	258	16	1776	
17	17	1 ⊕ 4	17	469	17	1156	
18	18	2 ⊕ 5	18	470	18	1467	
19	19	3 ⊕ 6	19	471	19	1633	4343

* In the octal notation for the first 10 chips of the C/A code as shown in this column, the first digit (1) represents a "1" for the first chip and the last three digits are the conventional octal representation of the remaining 9 chips. (For example, the first 10 chips of the C/A code for PRN Signal Assembly No. 1 are: 1100100000).

** C/A Codes for 34 and 37 are identical.

*** The two-tap coder utilized here is only an example implementation that generates a limited set of valid C/A codes.

⊕ = "exclusive or"

NOTE #1: The code phase assignments constitute inseparable pairs, each consisting of a specific C/A and a specific P code phase, as shown above.

Table 3-Ia. Code Phase Assignments (sheet 2 of 2)

SV ID No.	GPS PRN Signal No.	Code Phase Selection C/A($G2_i$)****	Code Phase Selection ($X2_i$)	Code Delay Chips C/A	Code Delay Chips P	First 10 Chips Octal* C/A	First 12 Chips Octal P
20	20	4 ⊕ 7	20	472	20	1715	4343
21	21	5 ⊕ 8	21	473	21	1746	
22	22	6 ⊕ 9	22	474	22	1763	
23	23	1 ⊕ 3	23	509	23	1063	
24	24	4 ⊕ 6	24	512	24	1706	
25	25	5 ⊕ 7	25	513	25	1743	
26	26	6 ⊕ 8	26	514	26	1761	
27	27	7 ⊕ 9	27	515	27	1770	
28	28	8 ⊕ 10	28	516	28	1774	
29	29	1 ⊕ 6	29	859	29	1127	
30	30	2 ⊕ 7	30	860	30	1453	
31	31	3 ⊕ 8	31	861	31	1625	
32	32	4 ⊕ 9	32	862	32	1712	
65	33***	5 ⊕ 10	33	863	33	1745	
66	34**	4 ⊕ 10	34	950	34	1713	
67	35	1 ⊕ 7	35	947	35	1134	
68	36	2 ⊕ 8	36	948	36	1456	
69	37**	4 ⊕ 10	37	950	37	1713	4343

* In the octal notation for the first 10 chips of the C/A code as shown in this column, the first digit (1) represents a "1" for the first chip and the last three digits are the conventional octal representation of the remaining 9 chips. (For example, the first 10 chips of the C/A code for PRN Signal Assembly No. 1 are: 1100100000).

** C/A codes 34 and 37are identical.

*** PRN sequence 33 is reserved for other uses (e.g. ground transmitters).

**** The two-tap coder utilized here is only an example implementation that generates a limited set of valid C/A codes.

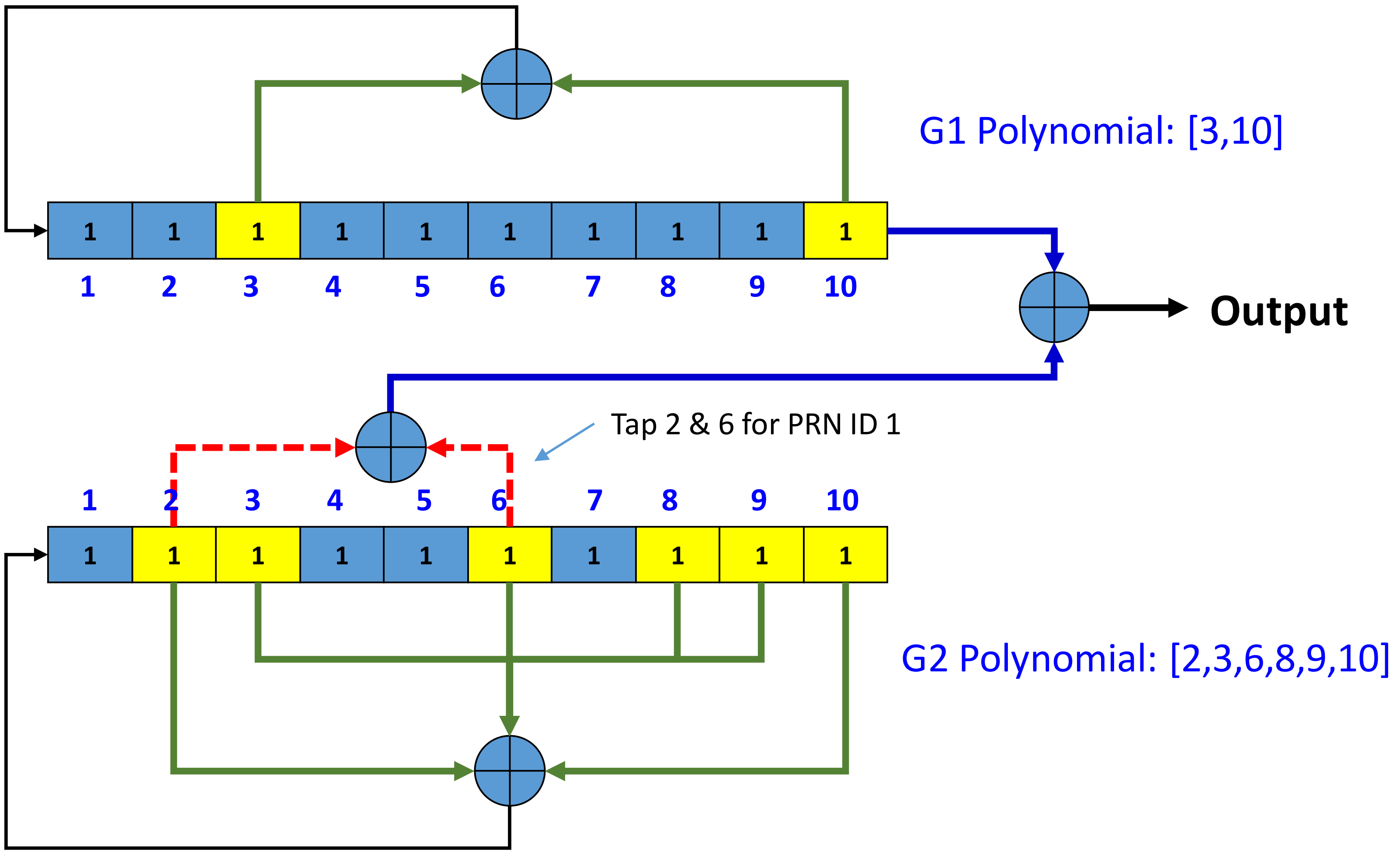
⊕ = "exclusive or"

NOTE #1: The code phase assignments constitute inseparable pairs, each consisting of a specific C/A and a specific P code phase, as shown above.

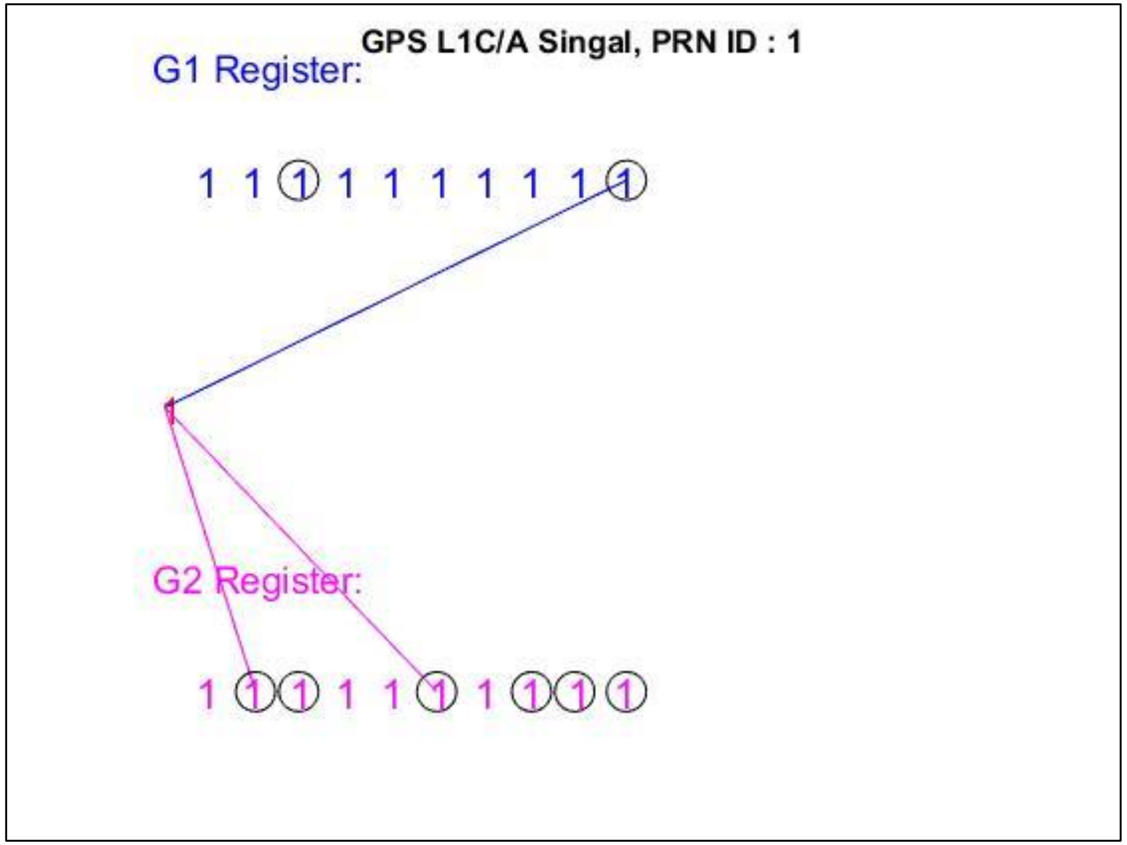
Source: GPS Interface Specification Document, IS-GPS-200,

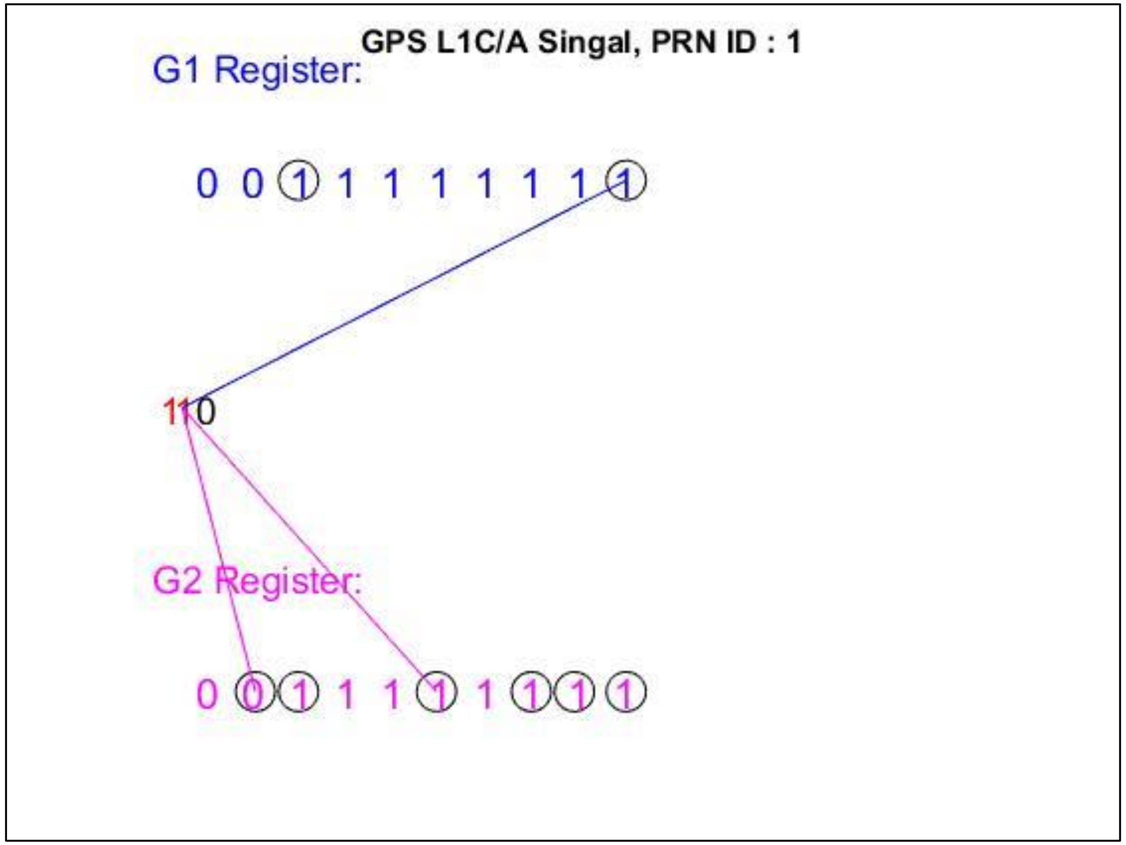
Generation of GPS L1C/A PRN Code

- Based on Gold Codes
- Use two 10 bit registers, G1 and G2
  LFSR (Linear Feed Shift Register)
- All initial bits of registers are set at 1
- Taps 3 and 10 are used for G1
- Taps 2,3,6,8,9,10 are used for G2
- Two additional taps are selected based on PRN ID. See GPS IS document for the list of the taps.
- Example, Taps 2 and 7 are used for PRN ID 1.

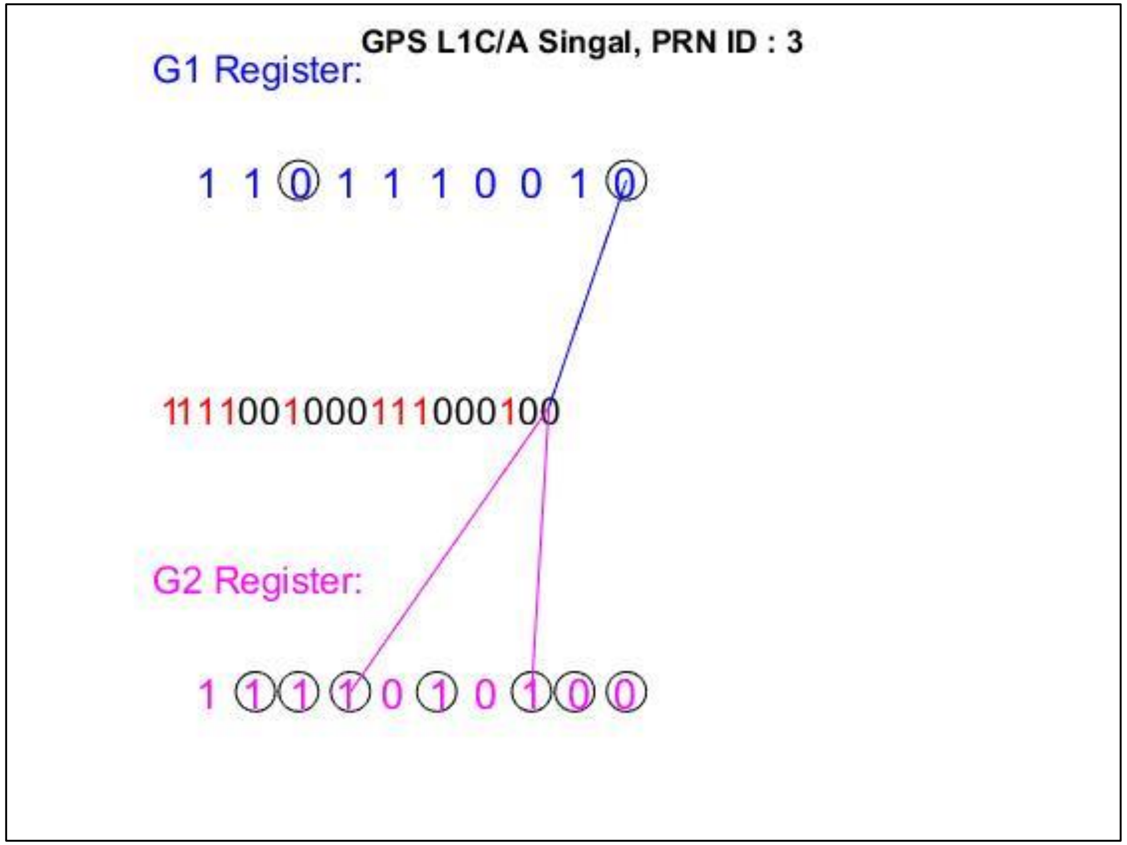


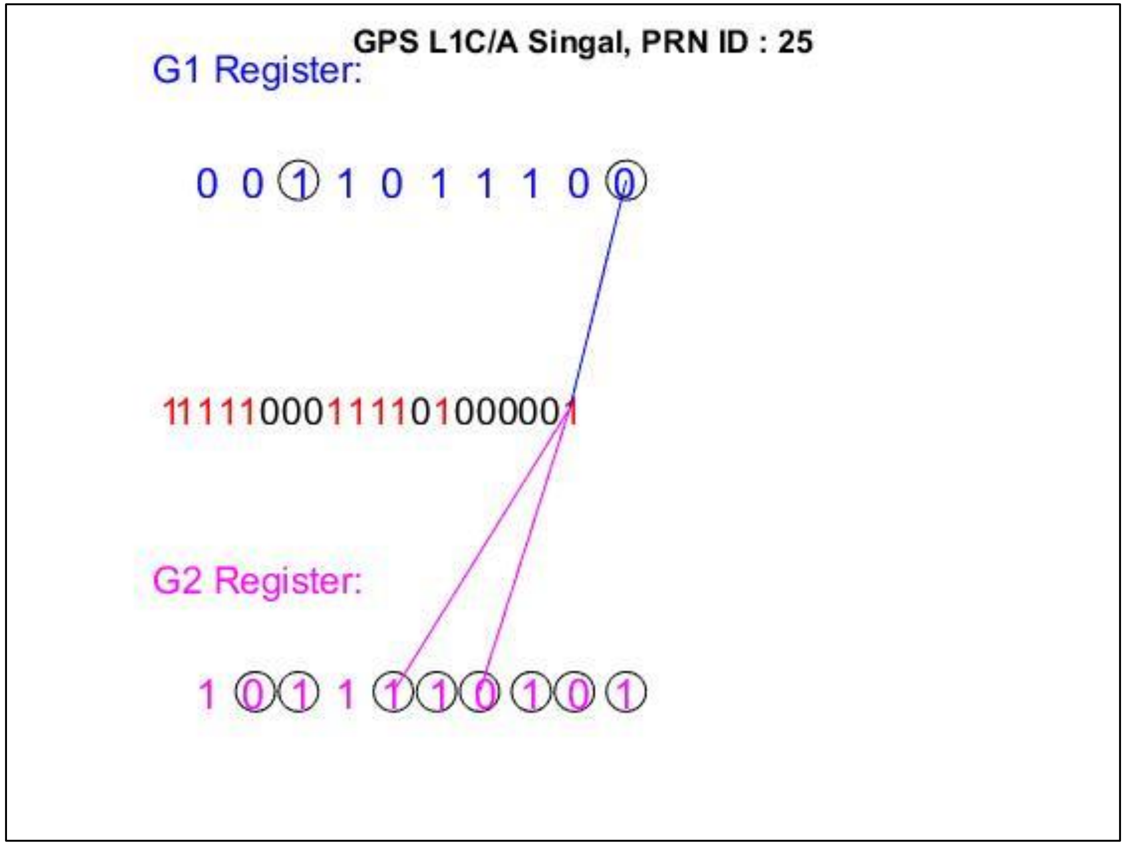
PRN Code Output #1





PRN Code Output #3 and #25





Modulo – 2 Operation

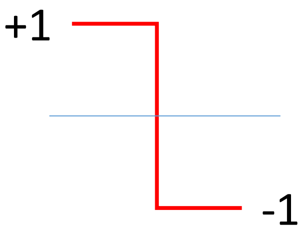
Represent all signals by "+1" or "-1" and use multiplication for Software Approach

0	$\oplus$	0	=	0
0	$\oplus$	1	=	1
1	$\oplus$	0	=	1
1	$\oplus$	1	=	0

1	X	1	=	1
1	X	-1	=	-1
-1	X	1	=	-1
-1	X	-1	=	1

- Either use "0" and "1" or "1" and "-1"
- We need the code representation in "1" and "-1" format

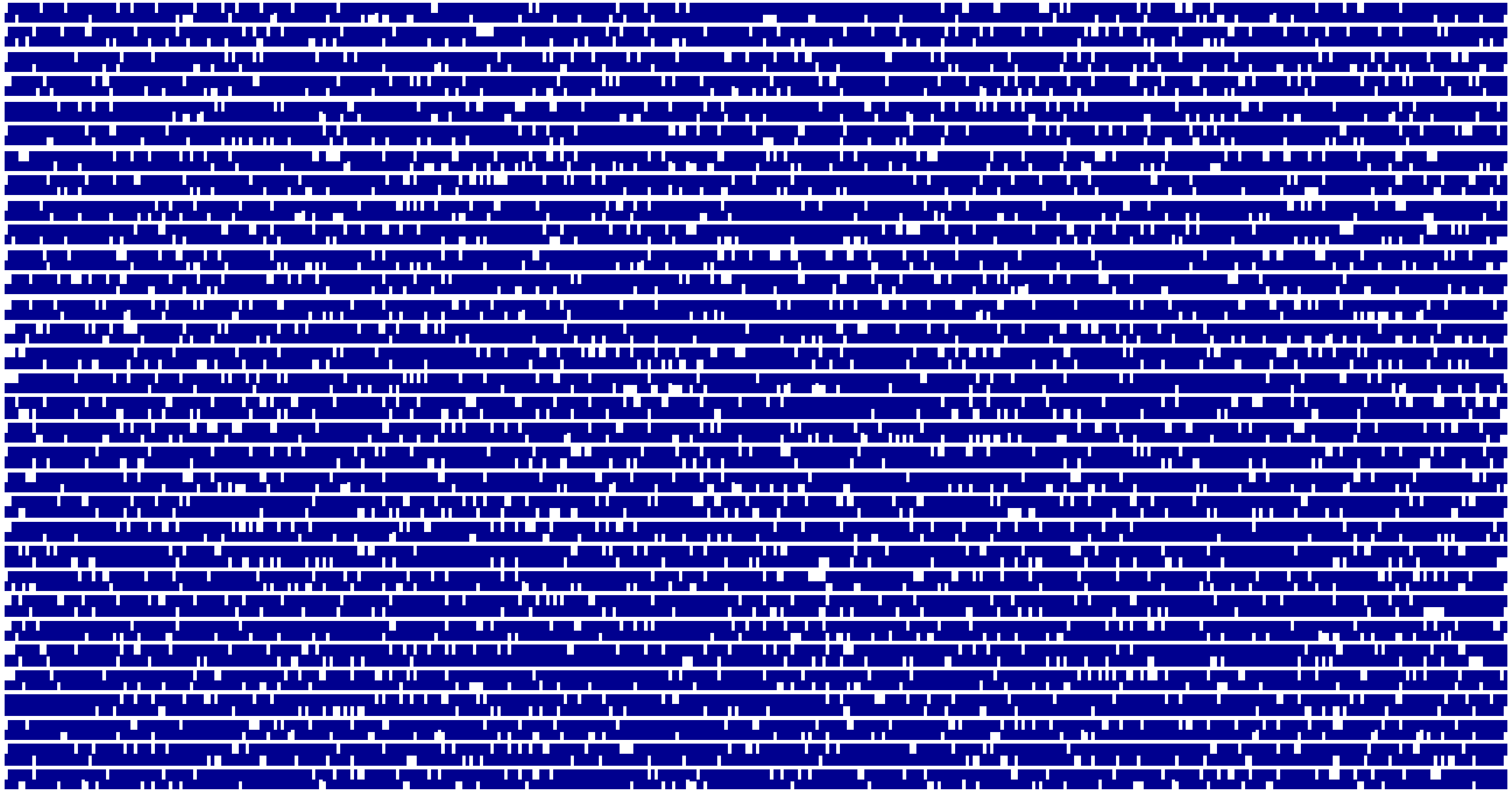
Example:
PRN 1 : 1 1 0 0 1 0 0 0 0 0….. Shall be
-1 -1 1 1 -1 1 1 1 1 1 …………..



- Represent "0" by "1" and "1" by "-1"
- Then multiply for Modulo - 2 operation
  - Simpler for programming
- Digital signal can have only "+1" or "-1"
- "1" or "0" means "ON" and "OFF"

GPS L1 C/A Code of PRN 1 to 32

PRN 1- [
PRN 2- [



PRN 32- [

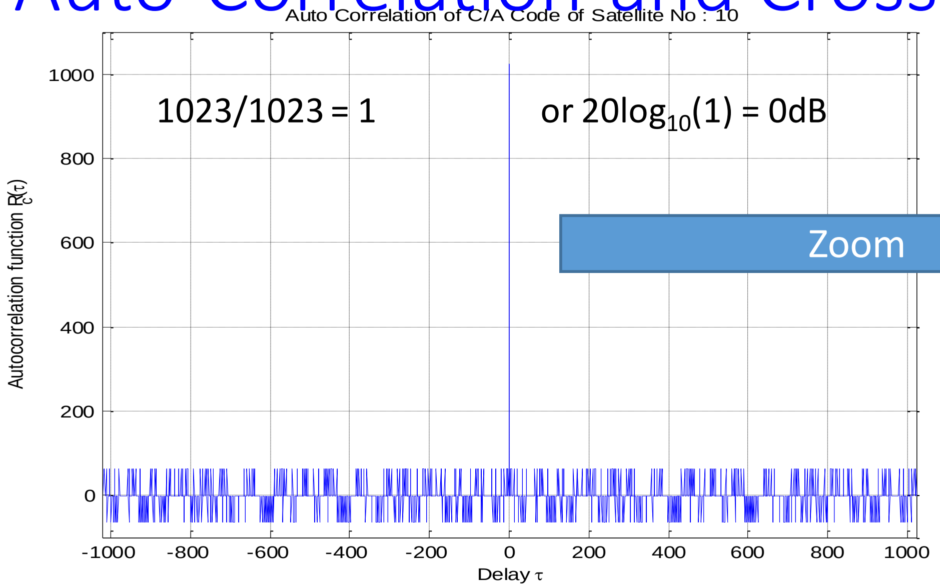
C/A Codes for the First 10bits

PRN 1 : 1100100000
PRN 29 : 1001010111
PRN 32 : 1111001010

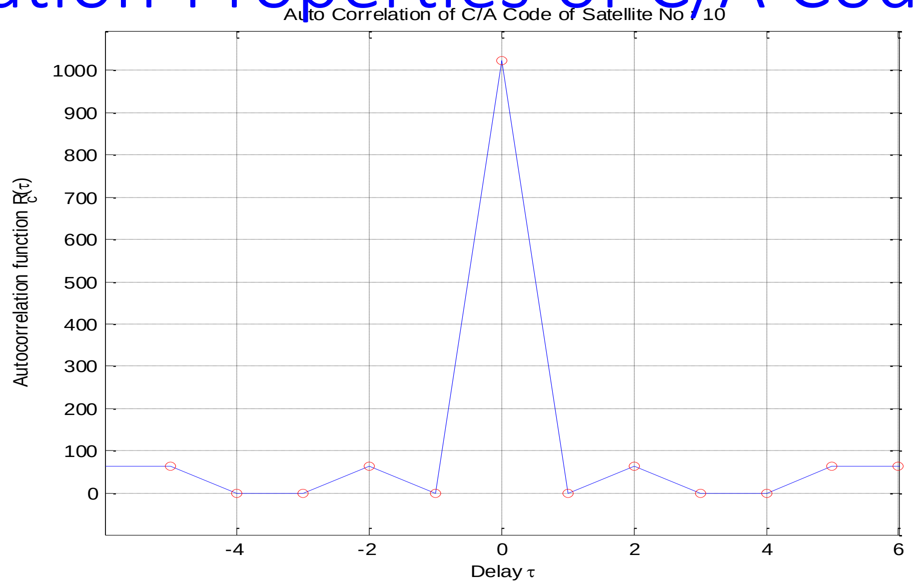
Auto Correlation Property

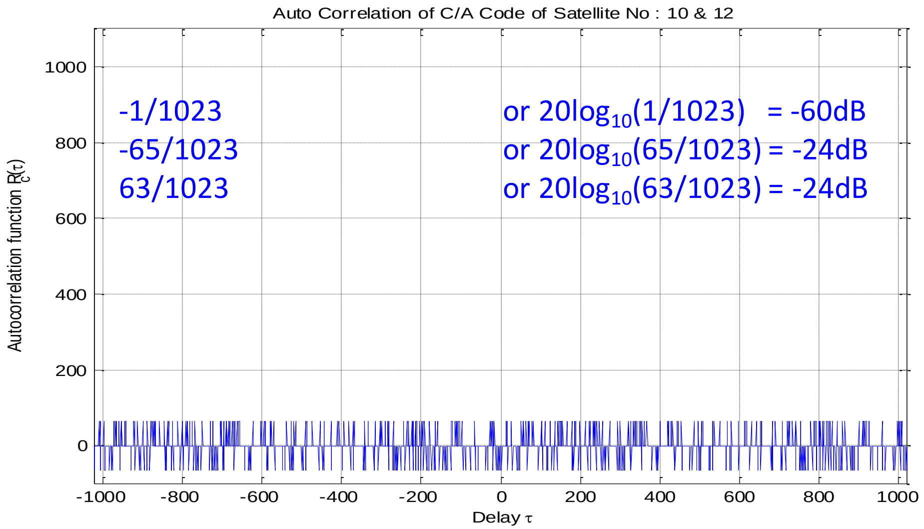
- Auto correlation Property of Gold Code when the shift is an integer multiple of a chip width is :
  - 1
  - -1/N
  - -B(n)/N
  - [B(n)-2]/N
  - Where $B(n) = 1+2^{(n+2)/2}$
    - n = 10 for Gold Code that generates C/A code
  - Example :
    - $N = 2^n-1 = 1023$ for n = 10
    - Auto Correlation Values are
      - 1023/1023 = 1 or $20\log_{10}(1) = 0$dB
      - -1/1023 or $20\log_{10}(1/1023) = -60$dB
      - -65/1023 or $20\log_{10}(65/1023) = -24$dB
      - 63/1023 or $20\log_{10}(63/1023) = -24$dB

Auto-Correlation and Cross-Correlation Properties of C/A Code

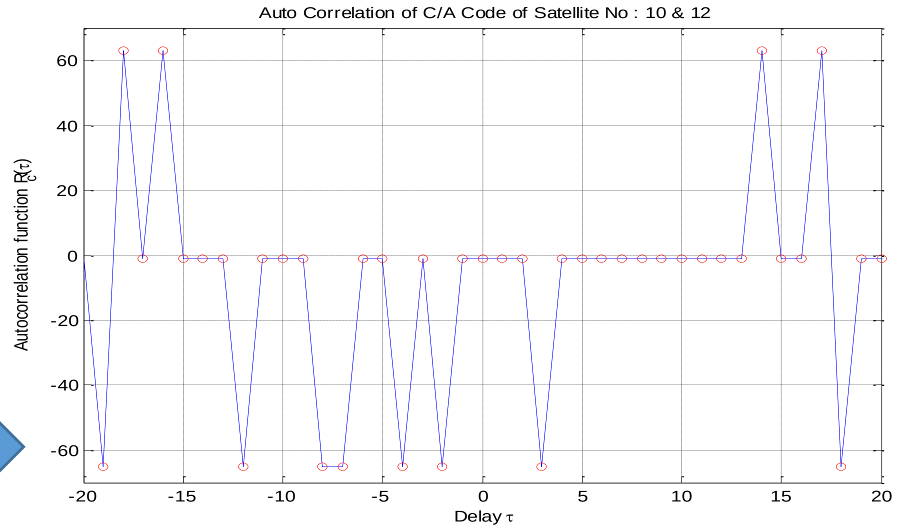


Zoom

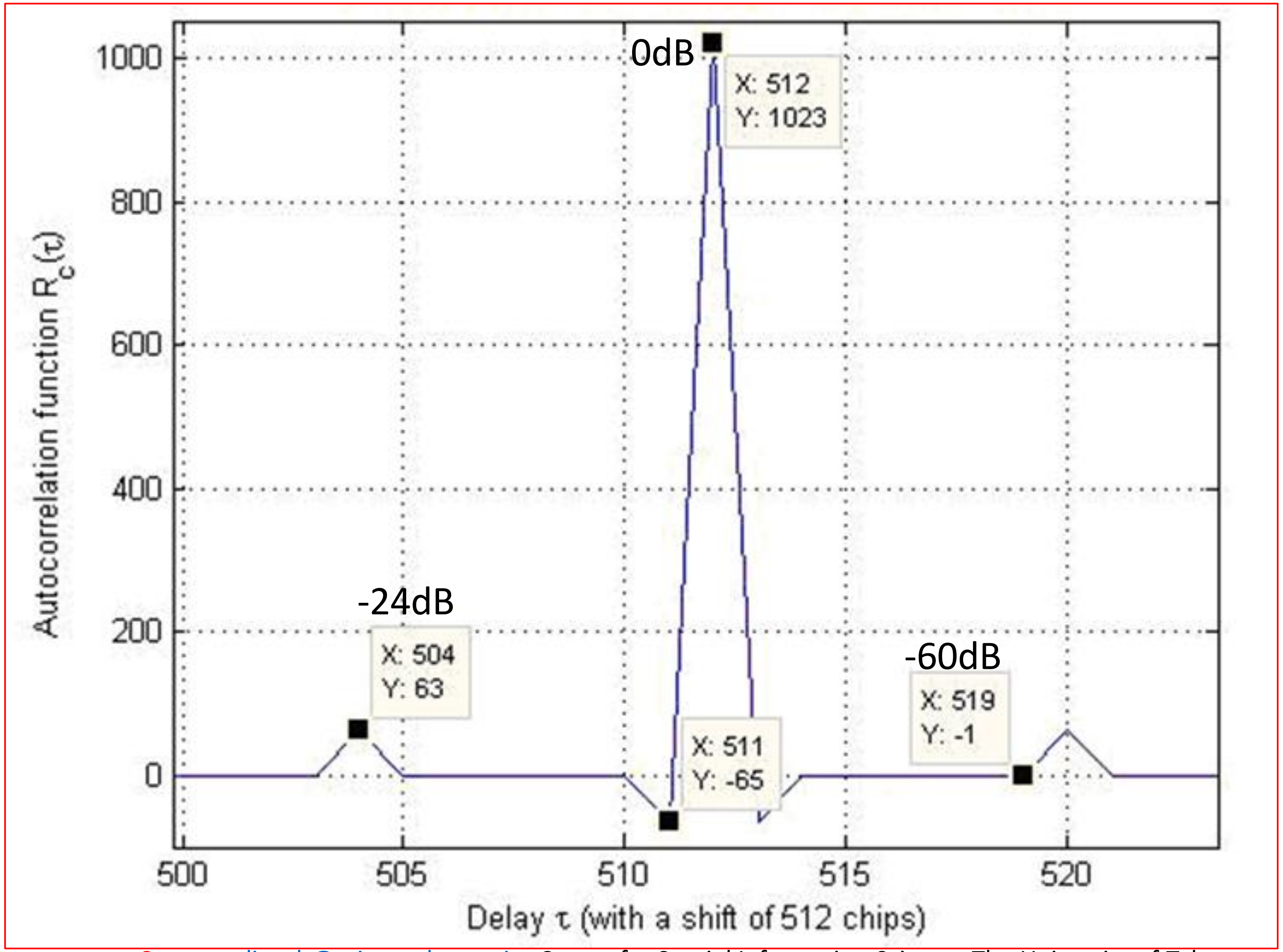




Zoom

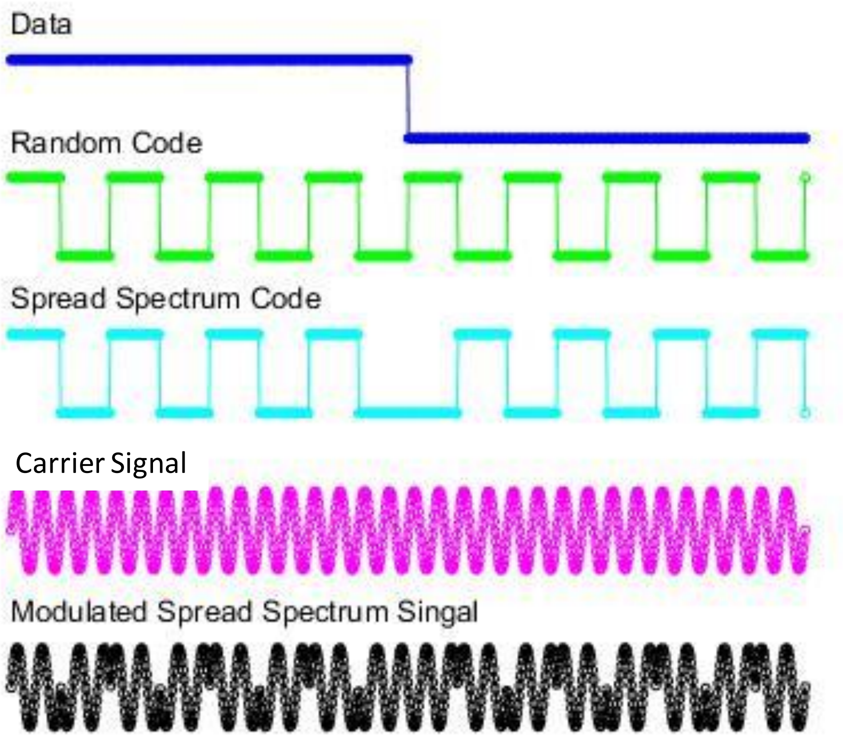


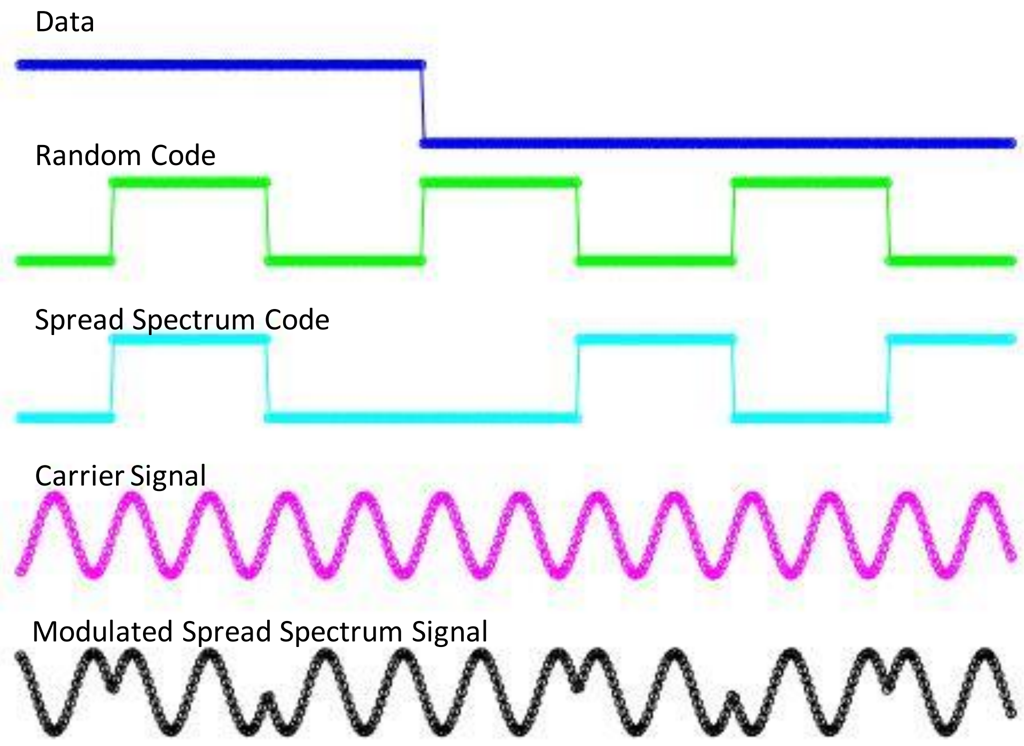
Auto-Correlation and Cross-Correlation Properties of C/A Code



Carrier, Code and Data Modulation Example

BPSK (Binary Phase Shift Keying)





SS : Spread Spectrum
DSSS : Direct Sequence Spread Spectrum
BPSK : Binary Phase Shift Keying

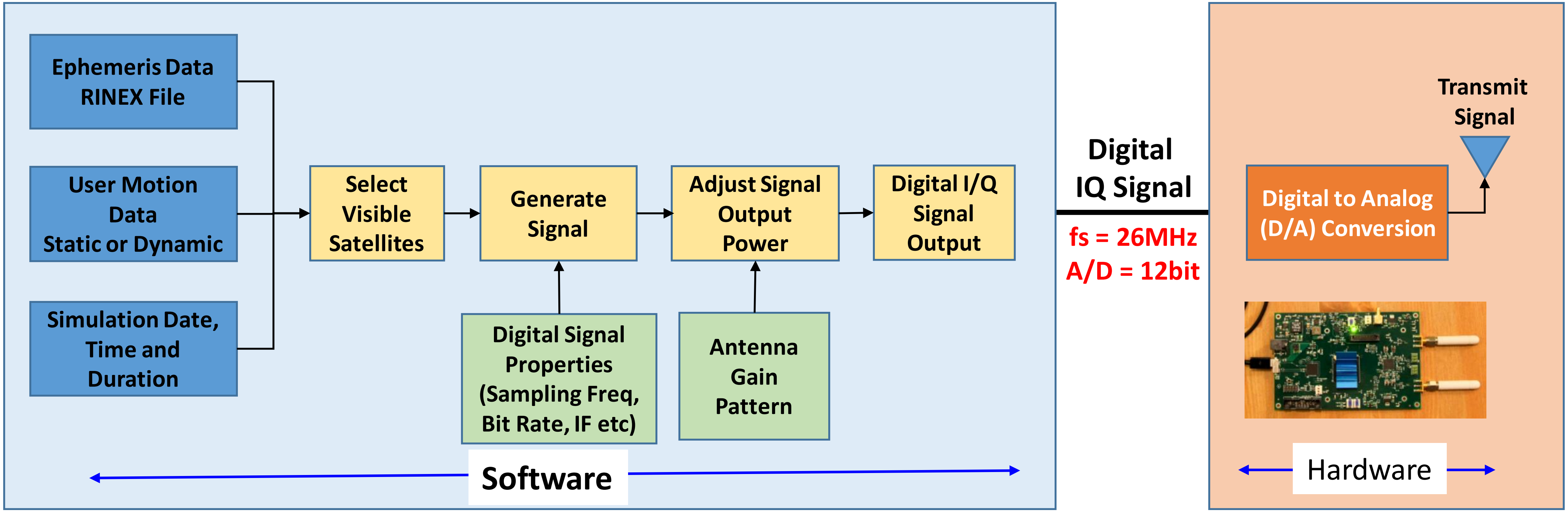
Generate GPS L1C/A Signal

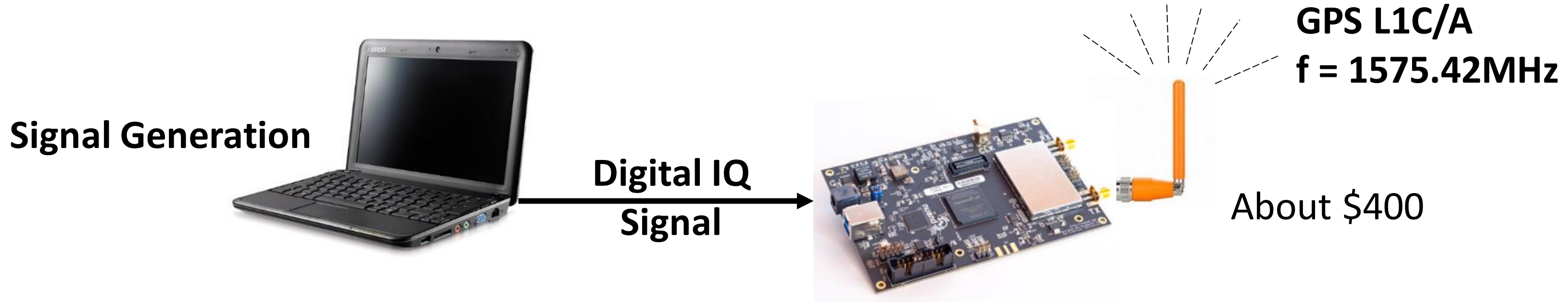
- Carrier Signal
  - Generate Carrier Signal
    - C = A*cos(w*t) = A*cos(2*pi*fc*t)
    - fc = Carrier frequency or center frequency
    - A = amplitude or signal power
- PRN Code
  - Generate as specified in the GPS IS Document
- Navigation Data
  - Generate as specified in the GPS IS Document
  - Data Rate : 50bps
  - 1 word : 30bits
  - 1 sub-frame : 300bits (6 sec)
    - 10 words / sub-frame
  - 1 frame : 1500bits (30 sec)
    - 5 sub-frames/frame

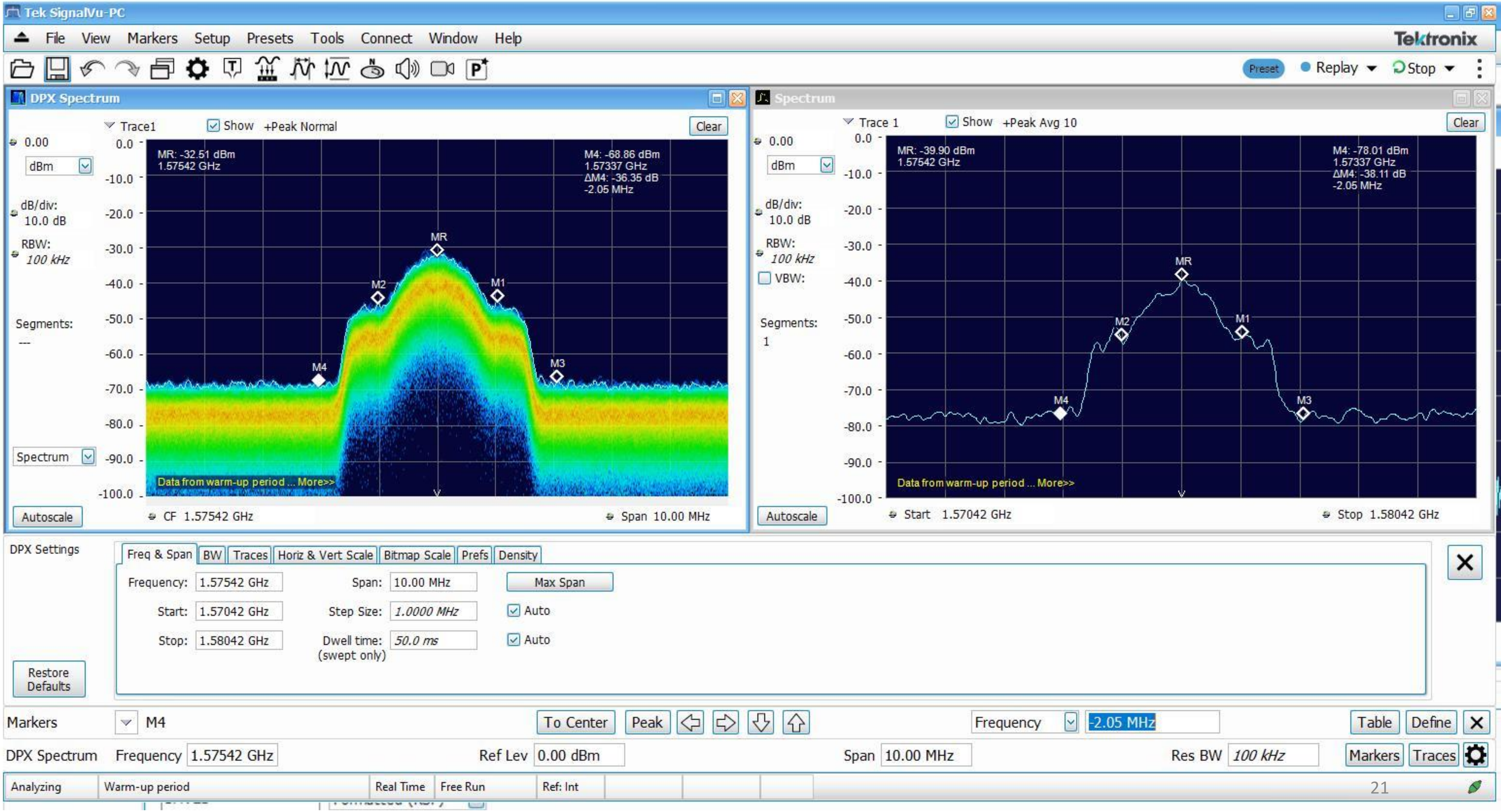
Generate GPS L1C/A Signal

- Generate GPS L1C/A signal in computer
  - Digital IF signal
  - Signal is generated at IF level
    - For example:
      - IF (Intermediate Frequency) : 4MHz
      - Sampling Frequency : 16MHz
      - A/D Resolution : 4bit
- Convert the digital IF signal to analog RF signal
  - Use Software Radio Device
    - Up-convert from IF to RF
      - Generate RF signal at 1575.42MHz (analog signal)
      - Transmit the signal from antenna

Low-Cost GPS Signal Generator






Tek SignalVu-PC
File View Markers Setup Presets Tools Connect Window Help
Tektronix
Preset Replay Stop
DPX Spectrum
Trace1 Show +Peak Normal Clear
MR: -32.51 dBm 1.57542 GHz
M4: -68.86 dBm 1.57337 GHz ΔM4: -36.35 dB -2.05 MHz
Data from warm-up period ... More>>
CF 1.57542 GHz
Span 10.00 MHz
Spectrum
Trace 1 Show +Peak Avg 10 Clear
MR: -39.90 dBm 1.57542 GHz
M4: -78.01 dBm 1.57337 GHz ΔM4: -38.11 dB -2.05 MHz
Start 1.57042 GHz
Stop 1.58042 GHz
DPX Settings
Freq & Span BW Traces Horiz & Vert Scale Bitmap Scale Prefs Density
Frequency: 1.57542 GHz Span: 10.00 MHz Max Span
Start: 1.57042 GHz Step Size: 1.0000 MHz Auto
Stop: 1.58042 GHz Dwell time: 50.0 ms (swept only) Auto
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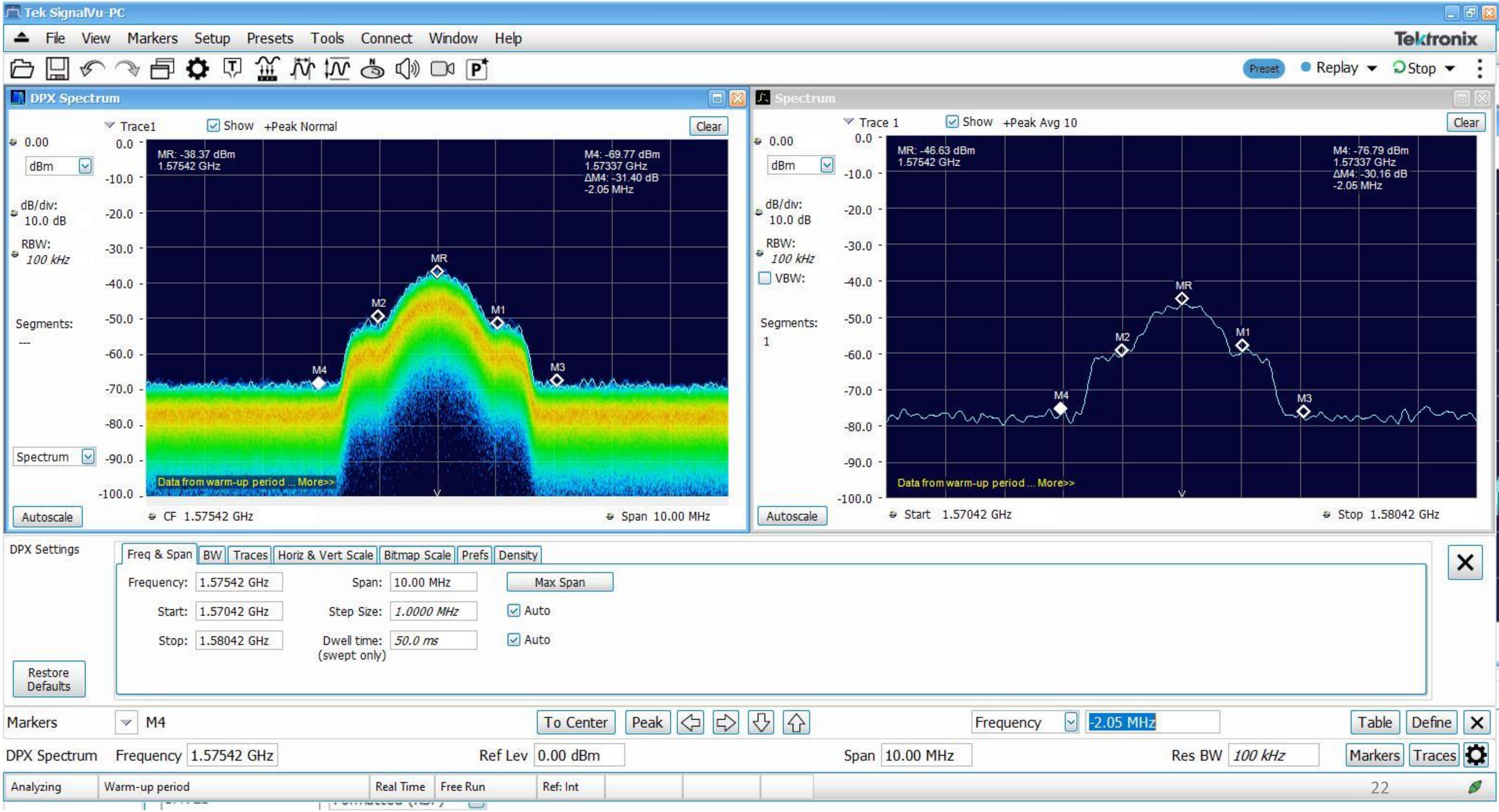
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Trace1 Show +Peak Normal Clear
0.00
dBm
dB/div:
10.0 dB
RBW:
100 kHz
Segments:

Spectrum
Autoscale
MR: -38.37 dBm
1.57542 GHz
M4: -69.77 dBm
1.57337 GHz
ΔM4: -31.40 dB
-2.05 MHz
MR
M1
M2
M3
M4
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Span 10.00 MHz
Spectrum
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VBW:
Segments:
1
MR: -46.63 dBm
1.57542 GHz
M4: -76.79 dBm
1.57337 GHz
ΔM4: -30.16 dB
-2.05 MHz
Start 1.57042 GHz
Stop 1.58042 GHz
DPX Settings
Freq & Span BW Traces Horiz & Vert Scale Bitmap Scale Prefs Density
Frequency: 1.57542 GHz
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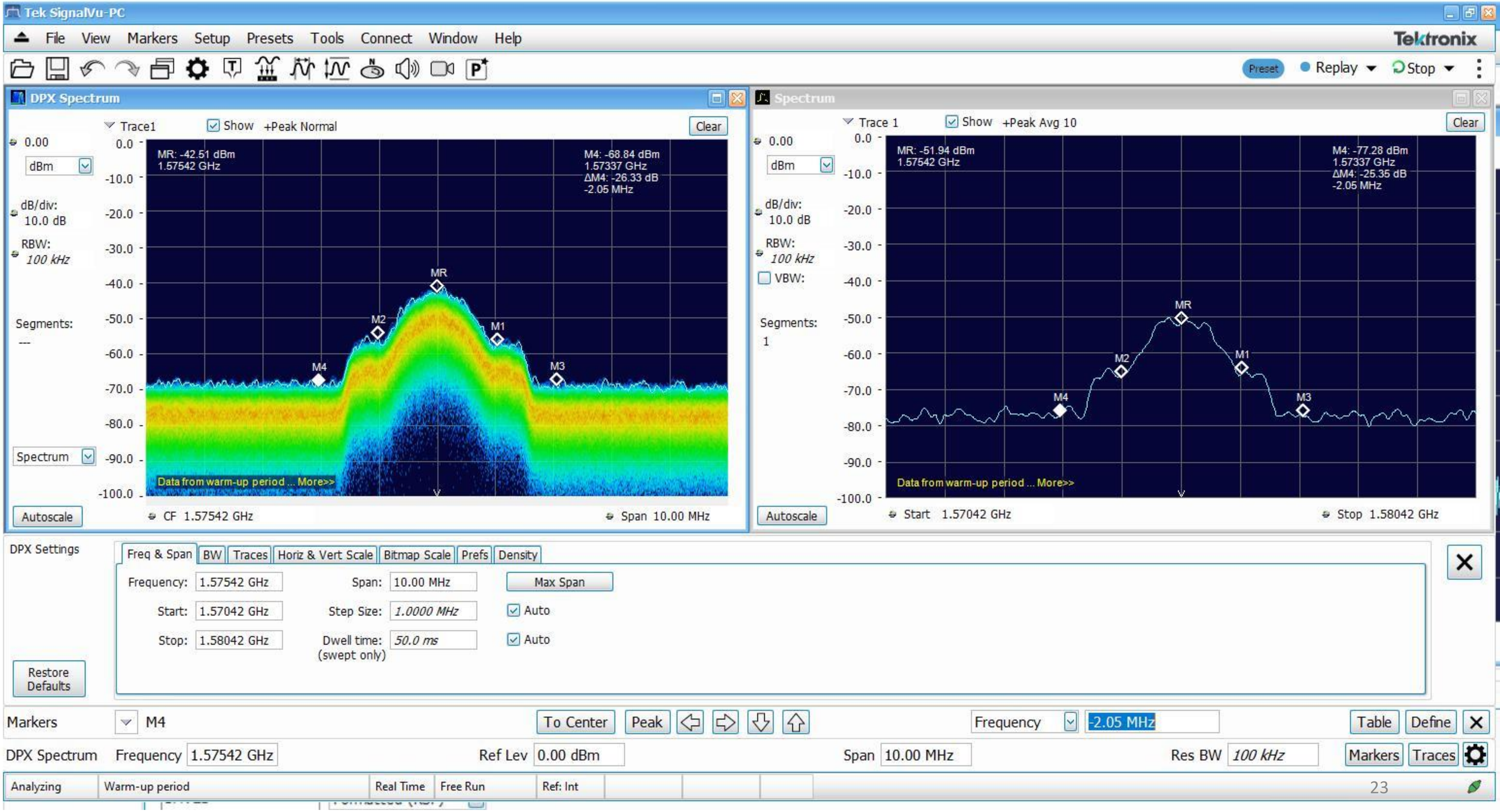
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M3
M4
Data from warm-up period ... More>>
CF 1.57542 GHz
Span 10.00 MHz
Spectrum
Trace 1
Show
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Clear
0.00
dBm
dB/div:
10.0 dB
RBW:
100 kHz
VBW:
Segments:
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Autoscale
MR: -51.94 dBm
1.57542 GHz
M4: -77.28 dBm
1.57337 GHz
ΔM4: -25.35 dB
-2.05 MHz
Data from warm-up period ... More>>
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Stop 1.58042 GHz
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
DPX Settings
Freq & Span
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Traces
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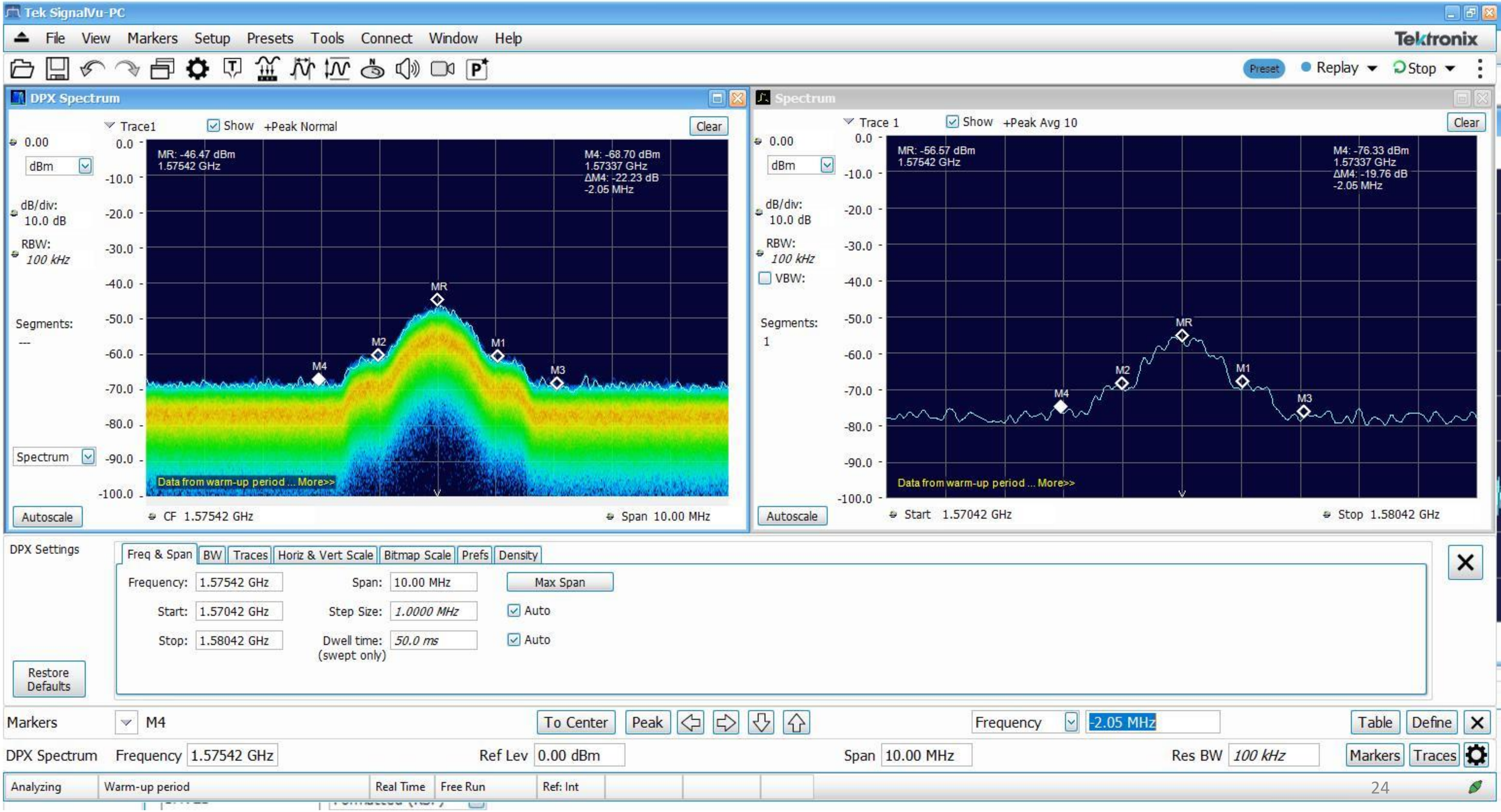
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Clear
0.00
dBm
dB/div:
10.0 dB
RBW:
100 kHz
VBW:
Segments:
1
Autoscale
MR: -56.57 dBm
1.57542 GHz
M4: -76.33 dBm
1.57337 GHz
ΔM4: -19.76 dB
-2.05 MHz
Data from warm-up period ... More>>
Start 1.57042 GHz
Stop 1.58042 GHz
DPX Settings
Freq & Span
BW
Traces
Horiz & Vert Scale
Bitmap Scale
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Start: 1.57042 GHz
Stop: 1.58042 GHz
Span: 10.00 MHz
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Restore Defaults
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Peak
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Analyzing
Warm-up period
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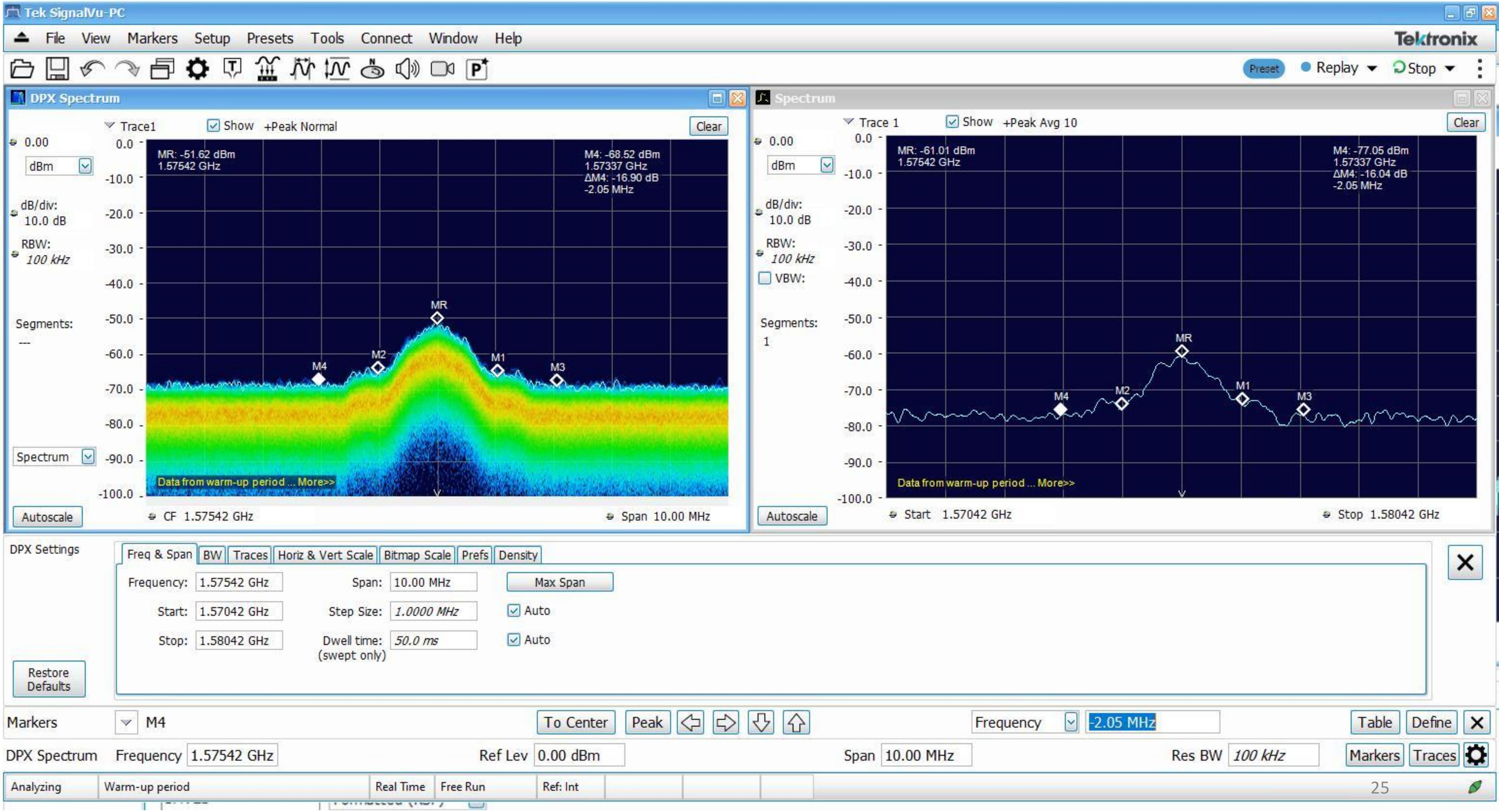
Ref: Int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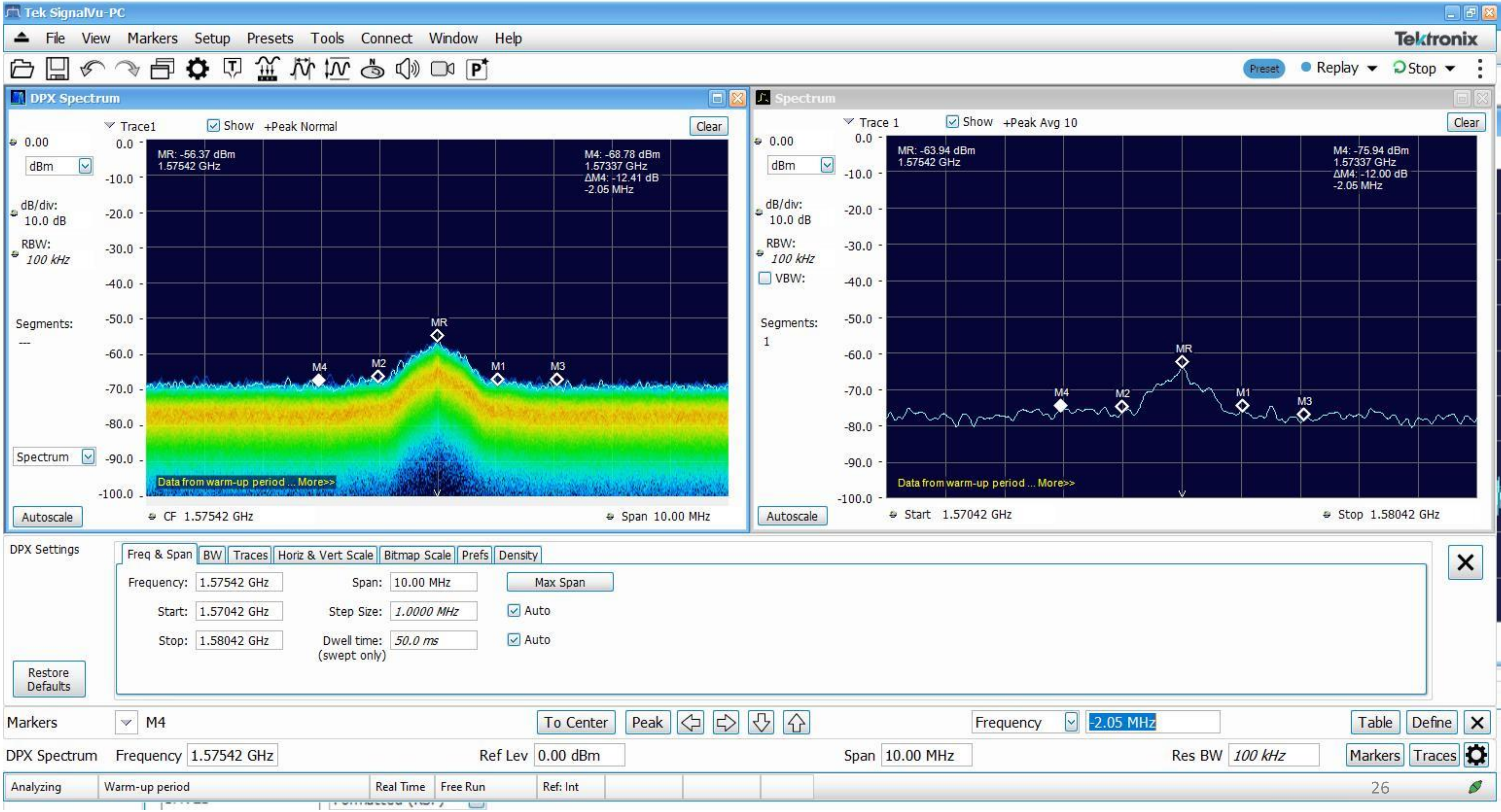
File View Markers Setup Presets Tools Connect Window Help
Tektronix
Preset
Replay
Stop
DPX Spectrum
Trace1
Show
+Peak Normal
Clear
0.00
dBm
dB/div:
10.0 dB
RBW:
100 kHz
Segments:

Spectrum
Autoscale
MR: -51.62 dBm
1.57542 GHz
M4: -68.52 dBm
1.57337 GHz
ΔM4: -16.90 dB
-2.05 MHz
MR
M1
M2
M3
M4
Data from warm-up period ... More>>
CF 1.57542 GHz
Span 10.00 MHz
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
Spectrum
Trace 1
Show
+Peak Avg 10
Clear
0.00
dBm
dB/div:
10.0 dB
RBW:
100 kHz
VBW:
Segments:
1
Autoscale
MR: -61.01 dBm
1.57542 GHz
M4: -77.05 dBm
1.57337 GHz
ΔM4: -16.04 dB
-2.05 MHz
Data from warm-up period ... More>>
Start 1.57042 GHz
Stop 1.58042 GHz
DPX Settings
Freq & Span
BW
Traces
Horiz & Vert Scale
Bitmap Scale
Prefs
Density
Frequency: 1.57542 GHz
Start: 1.57042 GHz
Stop: 1.58042 GHz
Span: 10.00 MHz
Step Size: 1.0000 MHz
Dwell time: 50.0 ms
(swept only)
Max Span
Auto
Auto
Restore Defaults
Markers
M4
To Center
Peak
Frequency
-2.05 MHz
Table
Define
DPX Spectrum
Frequency 1.57542 GHz
Ref Lev 0.00 dBm
Span 10.00 MHz
Res BW 100 kHz
Markers
Traces
Analyzing
Warm-up period
Real Time
Free Run
Ref: Int


Tek SignalVu-PC
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Trace1 Show +Peak Normal Clear
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RBW:
100 kHz
Segments:

Spectrum
Autoscale
MR: -56.37 dBm
1.57542 GHz
M4: -68.78 dBm
1.57337 GHz
ΔM4: -12.41 dB
-2.05 MHz
MR
M4
M2
M1
M3
Data from warm-up period ... More>>
CF 1.57542 GHz
Span 10.00 MHz
Spectrum
Trace 1 Show +Peak Avg 10 Clear
0.00
dBm
dB/div:
10.0 dB
RBW:
100 kHz
VBW:
Segments:
1
Autoscale
MR: -63.94 dBm
1.57542 GHz
M4: -75.94 dBm
1.57337 GHz
ΔM4: -12.00 dB
-2.05 MHz
Data from warm-up period ... More>>
Start 1.57042 GHz
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DPX Settings
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Frequency: 1.57542 GHz
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Stop: 1.58042 GHz
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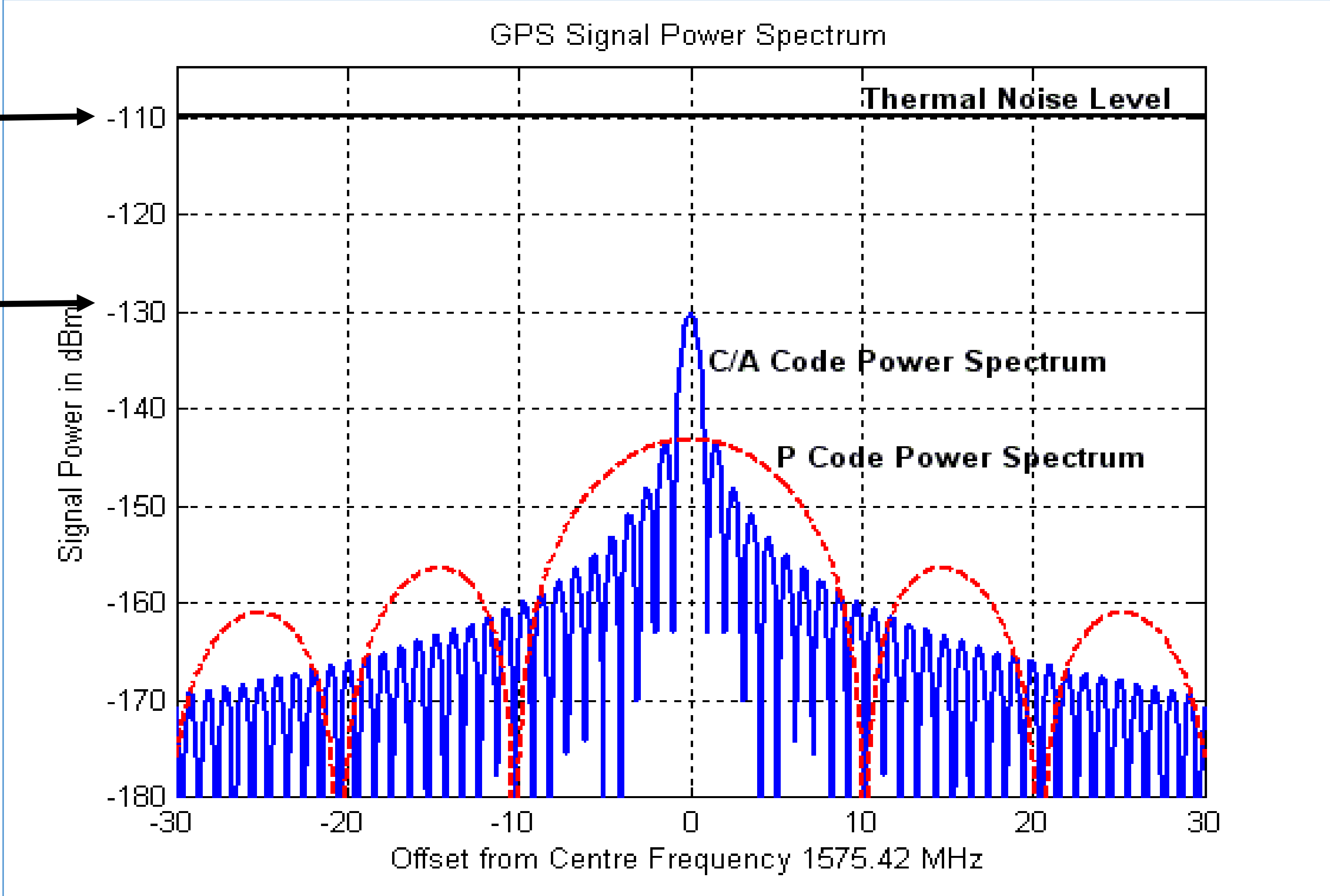
DPX Spectrum Frequency 1.57542 GHz Ref Lev 0.00 dBm Span 10.00 MHz Res BW 100 kHz Markers Traces
Analyzing Warm-up period Real Time Free Run Ref: Int

GPS Signal Power

Noise Power
Any Signal below this noise level can't be measured in a Spectrum Analyzer

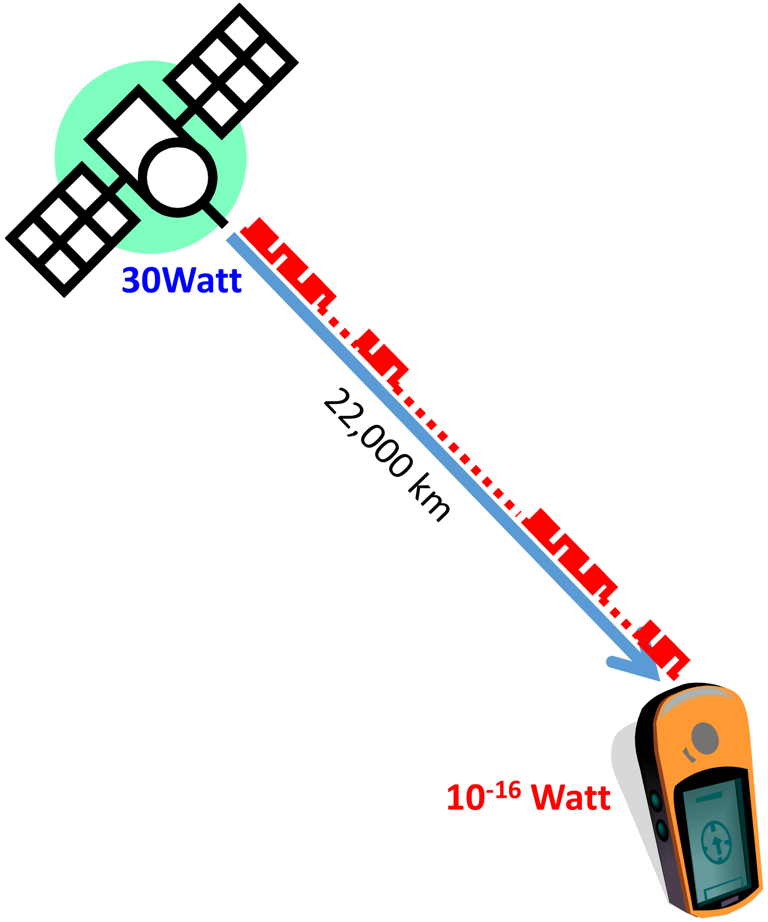
GPS Signal Power at Antenna, -130dBm

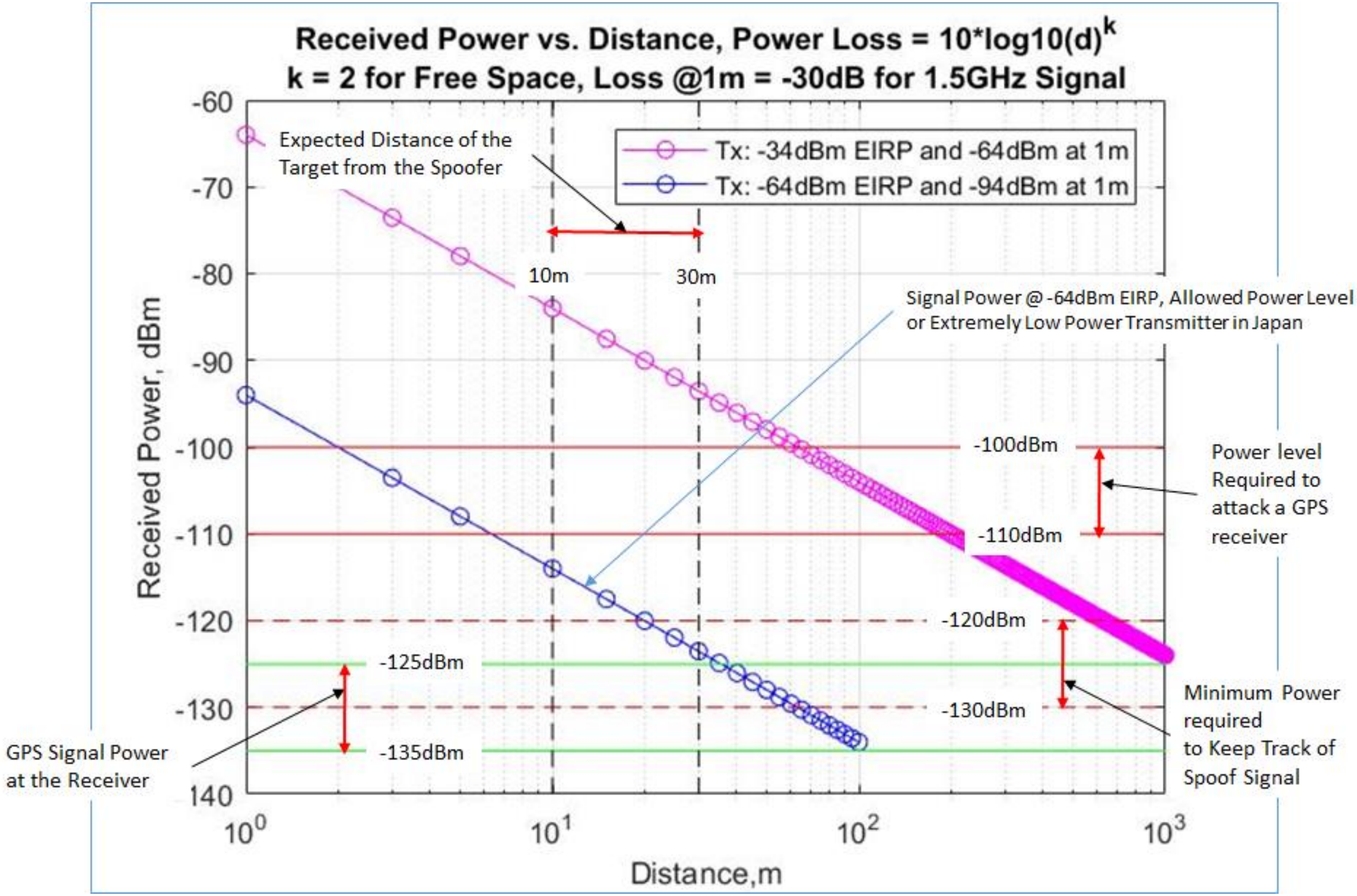
Mobile phone, WiFi, BT etc have power level above -110dBm, much higher than GPS Signal Power

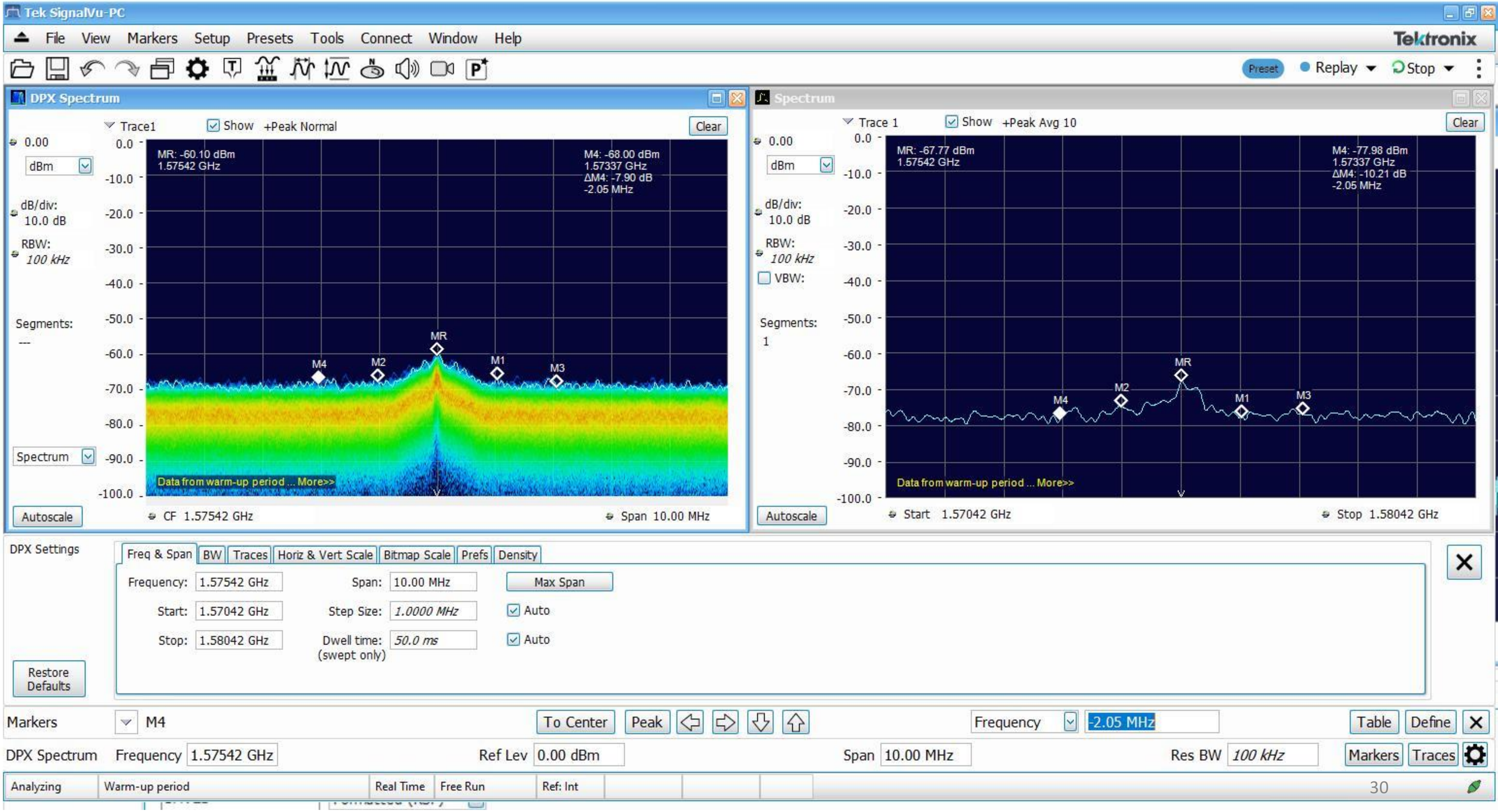


GPS Signal Power, How Strong or How Weak?

- GPS satellites are about 22,000km away
- Transmit power is about 30W
- This power when received at the receiver is reduced by 10^{16} times.
  - The power reduces by 1/distance^2
  - This is similar to seeing a 30W bulb 22,000Km far
- GPS signals in the receiver is about 10^{-16} Watt, which is below the thermal noise




Received Power vs. Distance, Power Loss = 10*log10(d)^k
k = 2 for Free Space, Loss @1m = -30dB for 1.5GHz Signal
Received Power, dBm
Distance,m
Tx: -34dBm EIRP and -64dBm at 1m
Tx: -64dBm EIRP and -94dBm at 1m
Expected Distance of the Target from the Spoofer
10m
30m
Signal Power @ -64dBm EIRP, Allowed Power Level or Extremely Low Power Transmitter in Japan
-100dBm
-110dBm
Power level Required to attack a GPS receiver
-120dBm
-130dBm
Minimum Power required to Keep Track of Spoof Signal
-125dBm
-135dBm
GPS Signal Power at the Receiver
-60
-70
-80
-90
-100
-110
-120
-130
140
10^0
10^1
10^2
10^3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RBW:
100 kHz
Segments:

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Autoscale
MR: -60.10 dBm
1.57542 GHz
M4: -68.00 dBm
1.57337 GHz
ΔM4: -7.90 dB
-2.05 MHz
MR
M4
M2
M1
M3
Data from warm-up period ... More>>
CF 1.57542 GHz
Span 10.00 MHz
Spectrum
Trace 1 Show +Peak Avg 10 Clear
0.00
dBm
dB/div:
10.0 dB
RBW:
100 kHz
VBW:
Segments:
1
Autoscale
MR: -67.77 dBm
1.57542 GHz
M4: -77.98 dBm
1.57337 GHz
ΔM4: -10.21 dB
-2.05 MHz
Data from warm-up period ... More>>
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Stop 1.58042 GHz
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Frequency: 1.57542 GHz
Span: 10.00 MHz
Max Span
Start: 1.57042 GHz
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Auto
Stop: 1.58042 GHz
Dwell time: 50.0 ms
(swept only)
Auto
Restore Defaults
Markers M4 To Center Peak Frequency -2.05 MHz Table Define
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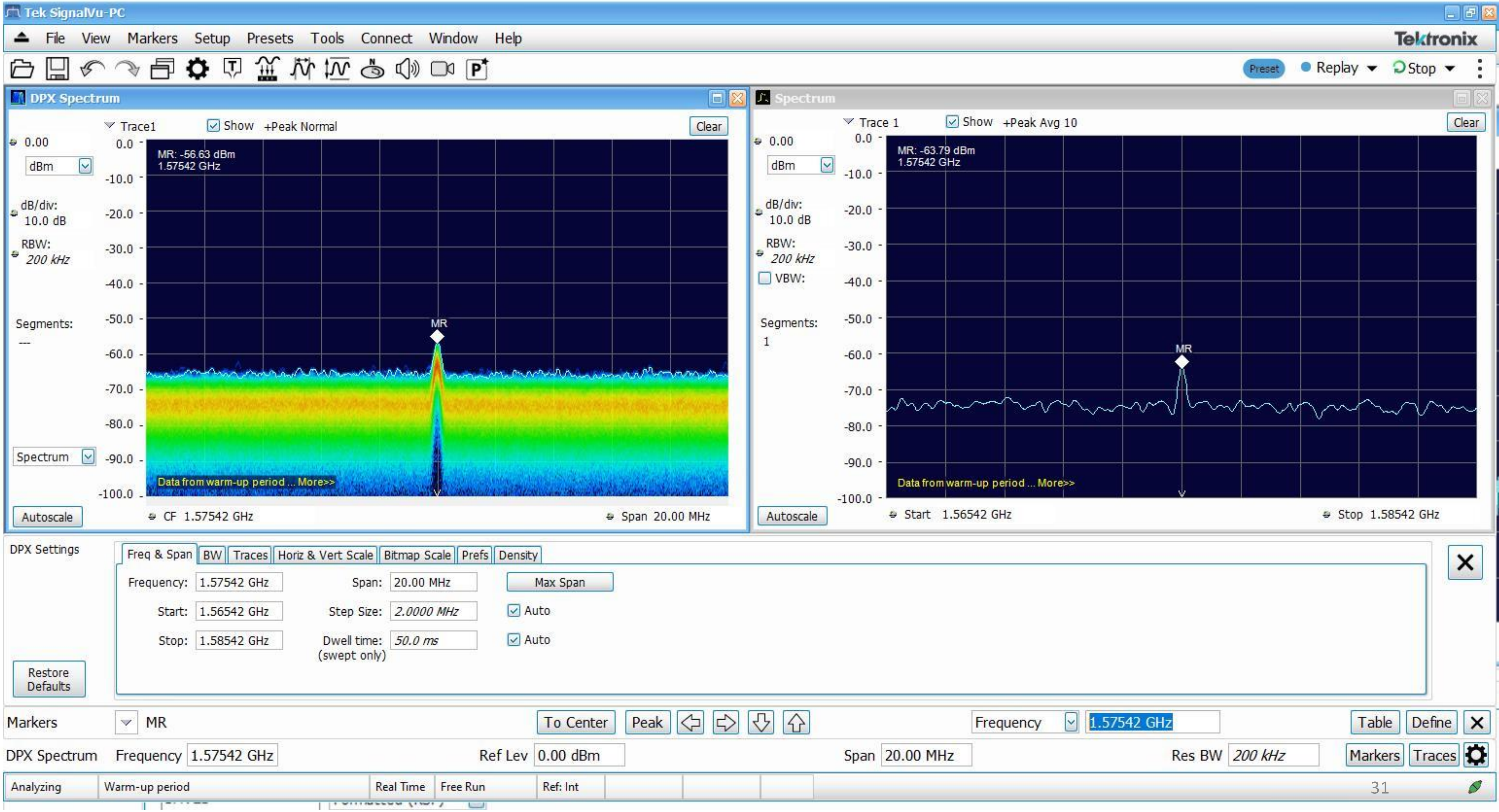
Analyzing Warm-up period Real Time Free Run Ref: Int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Autoscale
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
MR: -56.63 dBm
1.57542 GHz
MR
Data from warm-up period ... More>>
CF 1.57542 GHz
Span 20.00 MHz
Spectrum
Trace 1
Show
+Peak Avg 10
Clear
0.00
dBm
dB/div:
10.0 dB
RBW:
200 kHz
VBW:
Segments:
1
Autoscale
MR: -63.79 dBm
1.57542 GHz
MR
Data from warm-up period ... More>>
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SNR & C/No

- SNR
  - Signal to Noise Ratio, unit is dB
  - S: Signal Power in dBm or dBW
  - N: Noise power in a given bandwidth in dBm or dBW
- C/No
  - Carrier to Noise Density, unit is dB-Hz
  - C: Carrier power in dBm or dBW
  - No: Noise power density in dBm-Hz or dBW-Hz
- SNR = C/No-BW (BW = bandwidth of the Front End)
  - If BW = 4Mhz = 10*log10(4000000) = 66dB
  - If C/No = 48dB-Hz
  - SNR = C/No-BW = 45-66 = -21dB
- C/No from Received Signal Power
  - Noise Density (No) at Room Temperature (290K): -204dBW/Hz
  - Received Power (GPS L1C/A Signal) at Antenna: -158.5dBW or -128.5dBm
  - C/No = -158.5-(-204) = 45.5dB-Hz

Contact Information

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