

# THE USE OF INTERMODULATION TABLES FOR MIXER SIMULATIONS

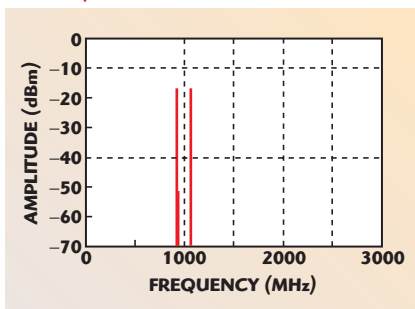
*The use of intermodulation table (IMT) files can lead to accurate prediction of the output frequency content of an up-converting or down-converting mixer in system simulations. For best results, custom IMT files should be constructed from mixer output spectrum measurements made at or close to the desired input signal and local oscillator frequency and power conditions.*

Mixers are nonlinear devices used, among other things, to convert signals from one frequency to another. They are characterized by how much conversion gain or loss they introduce in this translation, and also by how much distortion and noise they introduce. In addition to the desired output frequency signal, mixers produce many other frequencies, due to the nonlinear mixing, or intermodulation of the input signal (RF or IF) frequency and the local oscillator (LO) signal frequency. This article covers the use of intermodulation tables to better model

the broadband frequency output of mixers used as down- or up-converters in communication systems. A system level mixer model, available in Agilent Advanced Design System 1.5 (ADS™) computer-aided-engineering (CAE) software, is used to explore and overcome some of the potential difficulties involved with obtaining ac-

curate predictions of mixer intermodulation product signal levels using such system simulation models. Specifically, the MixerIMT model was used in ADS to predict observations made on a commercial mixer (Mini-Circuits® ZEM-4300MH) before and after customized characterization, using IMT files. The mixer model available in ADS only requires the conversion loss as an input parameter to model the device under investigation, thus predicting only the upper and lower sideband frequency content (see **Figure 1**). On the other hand, the IMT file represents a custom table of mixer intermodulation product levels resulting from given local oscillator (LO) and input signal frequencies and powers. The predicted output signal results in a direct mapping of each input signal with each LO signal. This study is a continuation from previous in-

Fig. 1 Simplified ADS model. ▼



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# TECHNICAL FEATURE

		M × LO															
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
N × SIGNAL	0	99	39	42	46	58	37	65	49	75	62	72	61	70	57	87	60
	1	25	0	39	11	50	16	59	19	59	43	63	52	70	57	73	
	2	68	67	76	67	80	66	82	66	83	72	84	72	82	70		
	3	63	58	65	60	65	55	64	54	66	57	85	54	70			
	4	96	80	96	80	95	82	98	78	90	95	95	95				
	5	93	73	87	72	88	66	85	64	82	75	95					
	6	99	99	99	99	99	99	99	99	99	99						
	7	99	79	99	78	99	78	99	81	99							
	8	99	95	99	95	99	95	99	95								
	9	90	95	90	90	99	99										
	10	99	99	99	99	99	99										
	11	90	99	90	95	90											
	12	99	99	99	99												
	13	90	99	90													
	14	99	99														
	15	99															

SIGNAL LEVEL = -10 dBm  
LO LEVEL = 7 dBm

▲ Fig. 2 Intermodulation table for a double-balanced mixer.<sup>4</sup>

vestigations of a 915 MHz receiver used in the University of South Florida's Wireless Circuits and Systems Design course<sup>1,2</sup>, as well as a recent paper that describes a complete communications systems test bed constructed to identify and resolve issues affecting system simulation accuracy for transmitter and receiver hardware.<sup>3</sup>

## MIXER PRODUCT SIMULATION USING IMT TABLES

The simulation results obtained in a related preceding work<sup>1</sup> use mixer models that produce the desired up-converted RF or down-converted IF at the mixer output, but do not predict the other harmonic and intermodulation (IM) products. Intermodulation products are unwanted signals generated by the mixer and exiting from any port. There are two types of intermodulation products — single-tone and multi-tone.

Single-tone intermodulation products consist of a single input (RF or IF) signal mixing with the LO and generating the following frequencies:

$$f_{\text{OUT}} = |Mf_{\text{LO}} \pm Nf_{\text{RF}}| \quad (1)$$

where

$f_{\text{OUT}}$  = output signal for the mixer  
 $f_{\text{RF}}$  = input signal for the mixer  
 $f_{\text{LO}}$  = LO frequencies for the mixer  
 $M, N$  = integers (0, 1, 2, ...)

Multi-tone intermodulation products consist of two or more input signals mixing with the LO and generating the following frequencies

$$f_{\text{OUT}} = |(\pm M_1 f_{\text{RF1}} \pm M_2 f_{\text{RF2}} \pm M_3 f_{\text{RF3}} \dots \pm N f_{\text{LO}})| \quad (2)$$

where  $M_1, M_2, M_3$  and  $N$  are integers (0, 1, 2, ...). Multi-tone intermodulation

is outside the scope of this article.

The ADS system mixer model MixerIMT can predict multiple IM products at a mixer's output. It requires the use of an IMT file. The IMT file provides information related to the mixer's IM generation properties as a function of single-tone signal and LO mixing order

with their respective relative power level (dBc) to the desired output signal (IF or RF). The frequencies at which to expect IM products are given by Equation 1. An example IMT table is shown in **Figure 2**.

The IMT file ideally applies for a specific reference power level for both  $P_{\text{SIG}}$  (RF or IF) and  $P_{\text{LO}}$  signals. If the input signals power levels vary from the values specified in the IMT table, interpolation is performed. The recommended ranges for which interpolation is applicable are  $P_{\text{SIG}} \leq P_{\text{SIGREF}}$  (dBc) + 3 and  $P_{\text{LO}}$  (dBc) - 10  $\leq P_{\text{LO}} \leq P_{\text{LO}}$  (dBc) + 3.<sup>4</sup> A related consequence is that the Mixer IMT model does not appear useful for predicting 1 dB conversion gain compression in mixer simulations. Further study is needed to explore accuracy of such extrapolations of mixer product amplitude simulations.

In the example IMT file shown

- Each position in the IMT table is occupied by the amplitude in dBc relative to the desired output frequency (IF or RF) expected at the mixer output.
- The vertical column number  $N$  (0, 1, 2 to 15) shows the harmonic number of either input signal used.
- The horizontal row number  $M$  (0, 1, 2 to 15) shows the harmonic number of the LO signal used.
- Notice that a 0 appears in the table at the position of the fundamental signal ( $N = 1, M = 1$ ). The frequency corresponding to this position could be either the sum or difference frequency (i.e.  $|f_{\text{LO}} \approx f_{\text{SIG}}|$ ), or the IF frequency for a down-converter.
- All other entries are specified in dBc relative to the power at the mixer output at the fundamental sum or difference frequency. The power level is assumed lower at this frequency un-

less the numeric entry is negative, which represents a power level higher than the fundamental sum or difference frequency.

- In row  $M = 1$ , column  $N = 3$ , the data is 11. This shows for an input signal at -10 dBm and an LO signal of +7 dBm there will be an IM product at  $|3f_{\text{signal}} \pm 1f_{\text{LO}}|$ , with a power level of 11 dB below the signal at the desired sum or difference frequency.
- Notice that there are missing entries in the IMT. These missing entries have assigned values of 99 dB below the fundamental reference.

The simulator assigns identical values for sum and difference frequencies at the mixer output. This is consistent with the conventional assumption of a symmetrical mixer as far as output spectrum amplitudes are concerned. To the extent that a real mixer is non-symmetric, this assumption generates unavoidable errors in the simulations as will be shown in the examples below.

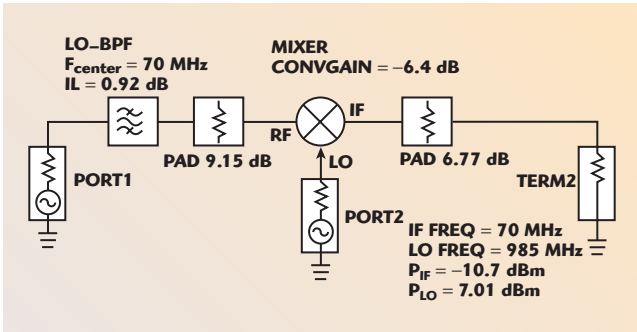
The frequencies corresponding to the IMT file content are sometimes referred as a "spur table" (see **Appendices A** and **B**). These spur tables show the expected frequencies at the mixer output. Each cell shows the frequency corresponding to the intermodulation of the LO harmonic and RF harmonic represented by the occupied row and column number.

For example, the fundamental sum and difference frequencies for the given down-converter example are 70 MHz and 1900 MHz, respectively, which can be seen by looking at the cell corresponding to  $M = 1; N = 1$  in the tables. Because of the symmetrical mixer requirement discussed, the IMT file does not allow for separate entries for these two frequencies. The same is true for any pair of frequencies occupying the same cell position.

## MIXER IM PRODUCT CHARACTERIZATION MEASUREMENTS

Unfortunately, "one size does not fit all" when it comes to IMT files. Hence, the use of the IMT file example in an attempt to predict the output spectrum of the ZEM4300 mixer will be useful only in showing the frequencies at which IM products can be expected, but with very inaccurate amplitudes. Therefore, for the MixerIMT model to

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▲ Fig. 3 Harmonic balance test bench schematic (up-converter configuration).

**TABLE I**

**SPECTRUM ANALYZER SETTINGS**

Attenuation (dB)	0
Reference level (dBm)	-10
Resolution BW (kHz)	100
Sweep Time (ms)	20
Span (MHz)	1

**TABLE II**

**COMPARISON BETWEEN MEASUREMENT AND SIMULATED RESULTS FOR UP-CONVERTER EXAMPLE (f<sub>LO</sub> = 985 MHz, f<sub>IF</sub> = 70 MHz)**

Frequency (MHz)	Measurement (dBm)	Simulated (dBm)	Measurement - Simulated
70	-64.41	-64.41	0
140	-62.53	-62.53	0
210	-80.35	-80.35	0
775	-61.55	-61.55	0
845	-72.72	-70.02	-2.70
915	-16.11	-16.11	0
985	-27.28	-27.28	0
1055	-16.36	-16.11	-0.25
1125	-70.02	-70.02	0
1195	-61.43	-61.55	-0.12
1830	-64.23	-61.43	-2.80
1900	-49.14	-49.14	0
1970	-36.45	-36.45	0
2040	-52.74	-49.14	-3.60
2110	-61.43	-61.43	0
2815	-69.45	not predicted	
2885	-25.22	-25.22	0
2955	-47.96	-47.96	0

be useful, files must be available that properly represent the specific mixer model to be used under the desired operating signal and LO frequencies and powers. Here, the construction of custom IMT files for a given mixer is briefly described.

## UP-CONVERTER MIXER CHARACTERIZATION

The measurements involved two signal sources, test accessories and a spectrum analyzer (SA). The configuration is reflected in the simulation schematic, as shown in **Figure 3**, with the load at the right side of the network replaced with the SA, a bandpass filter and three attenuators pads around the mixer (10 dB – RF, 3 dB – LO, 6 dB – IF). The IF signal was generated by a HPESG D4000A

signal generator (P<sub>IF</sub> = 3.2 dBm) and the LO signal was generated by a HP8753D VNA (P<sub>LO</sub> = 10.80 dBm). This set-up presented an input power of -10.07 dBm at the RF port of the mixer, and an input power of 7.01 dBm at the LO port. The loss of both the 6 dB pad and the output cable, as measured separately with the HP8753D network analyzer, was taken into account at each IM product frequency when calculating the output

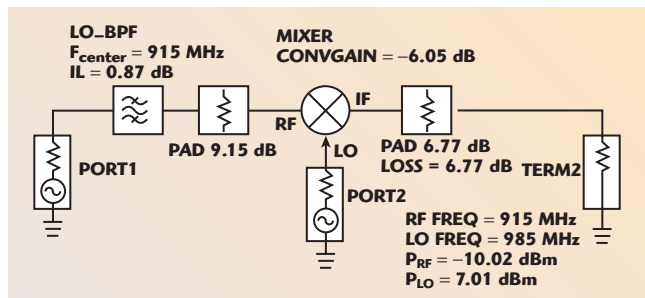
power from the mixer IF port measured remotely with a HP8595E spectrum analyzer. The settings of the SA are shown in **Table 1**.

The measured results for IM products observed for this up-converting mixer are listed in **Table 2**, along with the simulation results.

The conversion loss was determined from a subset of these measurements to be 6.04 dB. It was found important to specify the conversion loss in the mixer model as determined from the same measurement data set used to construct the IMT file in order to obtain the best simulation/measurement consistency. For various reasons, the conversion loss measurements, made in different ways, typically vary by several tenths of a decibel difference between results while obtained for the same mixer.<sup>5</sup>

## DOWN-CONVERTER MIXER CHARACTERIZATION

The measurement procedure was essentially the same as that described above, this time using the configuration of **Figure 4**. A 915 MHz bandpass filter was used along with the same three attenuators pads around the mixer (10 dB – RF, 3 dB – LO, 6 dB – IF). The RF signal was generated by the HPESG D4000A signal generator (P<sub>RF</sub> = 4.8 dBm) and the LO signal was generated by the HP8753D VNA (P<sub>LO</sub> = 10.80 dBm). This set-up presented an input power of -10.02 dBm at the RF port of the mixer, and an input power of 7.01 dBm at the LO port. The loss of both the 6 dB pad and the output cable is taken into account when calculating the output power from the IF port at each IM product frequency, based on the remotely measured product levels observed on the HP8595E SA. The conversion loss was measured to be 6.05 dB. The settings of the SA are the same as for the up-



▲ Fig. 4 Harmonic balance test bench schematic (down-converter configuration).

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**TABLE III**

**COMPARISON BETWEEN MEASUREMENT AND SIMULATED RESULTS**  
( $f_{LO} = 985 \text{ MHz}$ ,  $f_{RF} = 915 \text{ MHz}$ )

Frequency (MHz)	Measurement (dBm)	Simulated (dBm)	Measurement - Simulated
70	-16.07	-16.07	0
140	-59.65	-59.65	0
845	-59.35	-59.35	0
915	-35.56	-35.56	0
985	-27.72	-27.72	0
1055	-49.93	-49.93	0
1760	-71.85	-71.85	0
1830	-68.00	-68.00	0
1900	-23.83	-16.07	-7.76
1970	-41.84	-41.84	0
2040	-43.66	-43.66	0
2745	-84.72	-84.72	0
2815	-68.42	59.35	-9.07
2885	-51.77	-49.93	-1.84
2955	-32.97	-32.97	0

converter case. The measured results are shown in **Table 3**, along with the simulation results obtained.

## SIMULATION OF MIXER IM PRODUCTS USING CUSTOM IMT FILES

### Up-converter Simulation

The measured results obtained for the up-converting mixer configuration were used to generate the custom IMT file for the ZEM-4300MH mixer shown in **Figure 5**. It is important to mention that since the IMT file only allows one value for either the sum or difference frequency, the highest power level between the two was chosen. The file, once generated, needs to reside in the data folder, then pointed to from the mixer model itself prior to simulation. The simulated results are shown in **Figure 6**. The comparison between measurement and simulated results is facilitated by the tabulation given in Table 2. Note that for most frequencies exact agreement is possible. Those frequencies where discrepancies are indicated correspond to sum (or difference) frequencies whose corresponding difference (or sum) frequency pair had higher observed amplitude. Note that these pairs are easily identified in the simulated results column of the table by looking for pairs of frequencies with the exact same predicted power level.

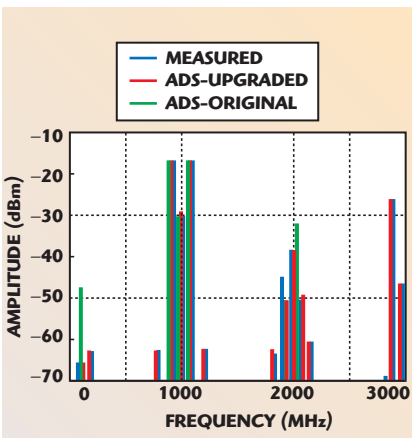
### Down-converter Simulation

A custom IMT file for the ZEM-4300MH mixer in the down-converter configuration was constructed from measured results. This file is shown in **Figure 7**. A simulation was

N x SIGNAL	M x LO															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	99	11.17	20.34	31.85	99	99	99	99	99	99	99	99	99	99	99	99
1	48.3	0	33.03	9.11	99	99	99	99	99	99	99	99	99	99	99	99
2	46.42	53.91	45.32	53.34	99	99	99	99	99	99	99	99	99	99	99	99
3	64.24	45.44	99	99	99	99	99	99	99	99	99	99	99	99	99	99
4	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
5	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
6	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
7	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
8	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
9	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
10	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
11	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
12	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
13	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
14	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
15	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99

SIGNAL LEVEL = -10.07 dBm  
LO LEVEL = 7.01 dBm  
 $f_{IF} = 70 \text{ MHz}$   
 $f_{LO} = 985 \text{ MHz}$

▲ Fig. 5 Custom measurement based IMT for ZEM 4300 mixer in up-converter configuration.



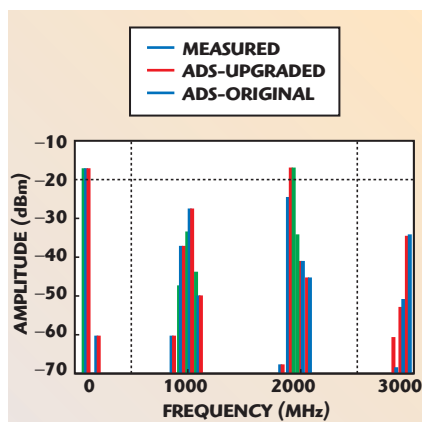
▲ Fig. 6 Measured and simulated results using generic and custom IMT files for an up-converter mixer.

N x SIGNAL	M x LO															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	99	11.65	25.77	16.9	99	99	99	99	99	99	99	99	99	99	99	99
1	19.49	0	33.86	27.59	99	99	99	99	99	99	99	99	99	99	99	99
2	51.93	43.28	43.58	99	99	99	99	99	99	99	99	99	99	99	99	99
3	68.65	55.78	99	99	99	99	99	99	99	99	99	99	99	99	99	99
4	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
5	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
6	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
7	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
8	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
9	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
10	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
11	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
12	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
13	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
14	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
15	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99

SIGNAL LEVEL = -10.02 dBm  
LO LEVEL = 7.01 dBm  
 $f_{RF} = 915 \text{ MHz}$   
 $f_{LO} = 985 \text{ MHz}$

▲ Fig. 7 Custom measurement based IMT for ZEM 4300 mixer in down-converter configuration.

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▲ Fig. 8 Measured and simulated results using generic and custom IMT files for a down-converter mixer.

performed using the schematic previously shown, and instructing the mixer model to reference this file. The simulated results are shown graphically in **Figure 8**. The comparison between measurement and simulated results are more clearly summarized in Table 5. Again the remaining discrepancies are due to sum and difference frequency pairs that had different observed amplitudes. Note that the discrepancy at 1900 MHz (whose corresponding difference frequency pair is 70 MHz) is significant as the observed signal level is fairly high ( $-23$  dBm or  $-7.8$  dBc) and the error is on the order of 30 percent.

## CONCLUSION

The use of intermodulation table (IMT) files can lead to accurate prediction of the output frequency content of an up-converting or down-converting mixer. For best results, custom IMT files should be constructed from accurate mixer output spectrum measurements made at or close to the desired input signal and local oscillator frequency and power conditions. Still, discrepancies can occur due to the inability of current IMT file mixer models to assign different amplitudes to sum and difference frequency components. The ability of a system mixer model, such as the ADS MixerIMT, to extrapolate beyond the specific measurement conditions used to characterize the IMT file is one aspect of on-going

work in this area by this research group. Also, IMT file mixer models may not be useful for simulating all parameters of interest such as system gain compression, in which case a different system mixer model can be used to produce the desired simulation. In short, CAE system mixer models are useful, but care must be taken to use them properly and understand their limitations and range of validity.

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## APPENDIX A

SPUR TABLE FOR THE IM PRODUCT DIFFERENCE FREQUENCIES IN MHz ( $F_{OUT} = |N F_{RF} - M F_{LO}|$ ) FOR LO = 985 MHz AND RF = 915 MHz

$N \times RF$	$M \times LO$										
	0	1	2	3	4	5	6	7	8	9	10
0	0	985	1970	2955	3940	4925	5910	6895	7880	8865	9850
1	915	70	1055	2040	3025	4010	4995	5980	6965	7950	8935
2	1830	845	140	1125	2110	3095	4080	5065	6050	7035	8020
3	2745	1760	775	210	1195	2180	3165	4150	5135	6120	7105
4	3660	2675	1690	705	280	1265	2250	3235	4220	5205	6190
5	4575	3590	2605	1620	635	350	1335	2320	3305	4290	5275
6	5490	4505	3520	2535	1550	565	420	1405	2390	3375	4360
7	6405	5420	4435	3450	2465	1480	495	490	1475	2460	3445
8	7320	6335	5350	4365	3380	2395	1410	425	560	1545	2530
9	8235	7250	6265	5280	4295	3310	2325	1340	355	630	1615
10	9150	8165	7180	6195	5210	4225	3240	2255	1270	285	700

## APPENDIX B

SPUR TABLE FOR THE IM PRODUCT SUM FREQUENCIES IN MHz ( $F_{OUT} = |N F_{RF} + M F_{LO}|$ ) FOR LO = 985 MHz AND RF = 915 MHz

$N \times RF$	$M \times LO$										
	0	1	2	3	4	5	6	7	8	9	10
0	0	985	1970	2955	3940	4925	5910	6895	7880	8865	9850
1	915	1900	2885	3870	4855	5840	6825	7810	8795	9780	10765
2	1830	2815	3800	4785	5770	6755	7740	8725	9710	10695	11680
3	2745	3730	4715	5700	6685	7670	8655	9640	10625	11610	12595
4	3660	4645	5630	6615	7600	8585	9570	10555	11540	12525	13510
5	4575	5560	6545	7530	8515	9500	10485	11470	12455	13440	14425
6	5490	6475	7460	8445	9430	10415	11400	12385	13370	14355	15340
7	6405	7390	8375	9360	10345	11330	12315	13300	14285	15270	16255
8	7320	8305	9290	10275	11260	12245	13230	14215	15200	16185	17170
9	8235	9220	10205	11190	12175	13160	14145	15130	16115	17100	18085
10	9150	10135	11120	12105	13090	14075	15060	16045	17030	18015	19000