Title: Forecasting Analog MEMS Microphones with TFDEA

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Abstract

The improvements in the Signal-to-Noise Ratio (SNR) and Acoustic Overload Point (AOP) of analog MEMS microphones are considered between 2004 and 2015. Using output-oriented TFDEA, the SNR and AOP are forecasted (as output parameters), assuming microphone surface area and volume are TFDEA input parameters. Technological State-of-the-Art frontier surfaces are generated.

2015

Forecasting Analog MEMS Microphones with TFDEA

PORTLAND STATE UNIVERSITYETM-532; FALL 2015

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Introduction

Technology forecasting techniques are used to predict future technical features and capabilities of products and systems. These techniques are also used to estimate the approximate timeframe in which technological advancements will take place in these products and systems. This paper uses TFDEA [1] to explore the technological Rate-of-Change (RoC) in analog MEMS microphones. Today, MEMS microphones are commonly used in smartphones, tablets, hearing aids, and within automobiles. The market for MEMS microphones now exceeds $1.2 billion[2]. As the technical performance of MEMS microphones continues to improve, the applications in which the microphones are used is expanding, including far field and directional microphone array systems [3]. This paper focuses on the Signal-to-Noise Ratio (SNR), and Acoustic Overload Point (AOP) characteristics of analog MEMS microphones.

Literature Review

A brief review of microphone transducers

A transducer is a device which converts one type of energy or signal into another[4]. A microphone is a transducer which converts sound pressure into an electrical signal. Although somewhat historically disputable [5], the first microphone transducer can be credit to Alexander Graham Bell, who in 1876 filed US Patent 174,465 for a device which stretched an electrical wire between two moving armature transmitters/receivers [5], as depicted in Figure 1.

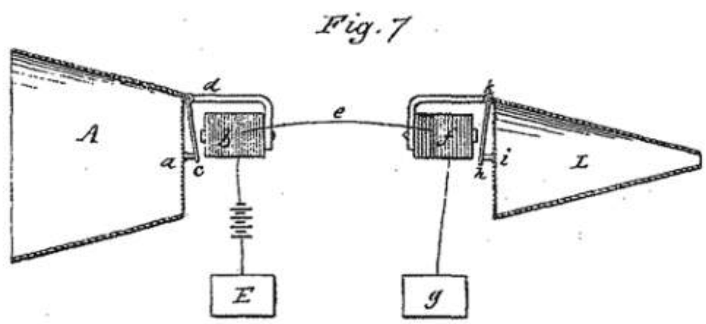

Figure 1 From Alexander Graham Bell's 1876 patent [6]

The carbon microphone was invented by David Edward Hughes in 1878 [7], but was later perfected and patented as the "carbon-button" microphone in the United States by Thomas Edison in 1886 [7]. This microphone consisted of two electrodes separated by loose granules of carbonized anthracite coal. In response to incoming sound waves, one electrode would compress the granules, changing the resistance between the two electrode plates, producing an electrical signal analogous to the incoming sound pressure (Figure 2). Because of the ease of manufacture and reliability of the carbon-button microphone, the design was the basis for telephone microphones for over a century[7].

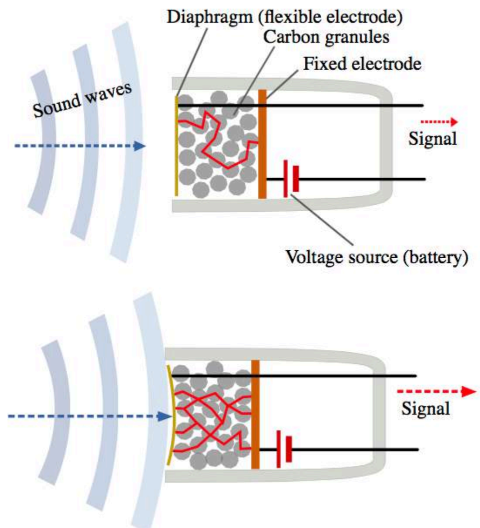

Figure 2 Carbon-Button Microphone [8]

Condenser Microphones

Condenser microphones (also known as capacitive microphones) were first developed in 1917 by E.C. Wente at Bell Laboratories [7]. There are many different styles of condenser microphones, but fundamentally they all rely upon the same technological implementation: incoming sound pressure waves flex a diaphragm which makes up one plate of a capacitor. As the diaphragm flexes, the capacitance changes, resulting in a change in electrical potential. This change in potential is proportional to the pressure of the incoming sound wave, and constitutes the output electrical signal of the microphone (Figure 3).

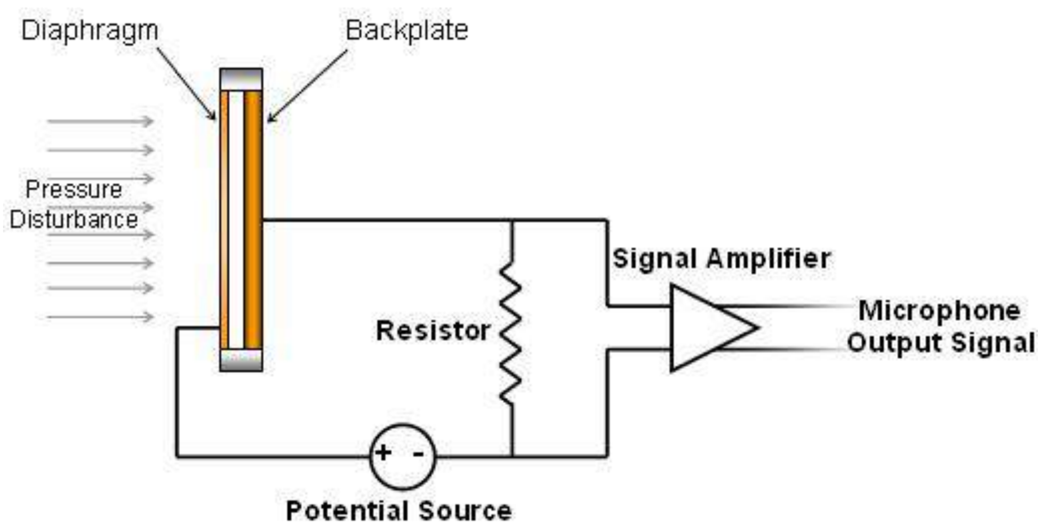

Figure 3 Battery Powered Condenser Microphone Diagram[9]

MEMS Microphones

MEMS (Micro-Electrical-Mechanical-Systems) microphones are condenser microphones, where the capacitor consists of two silicon plates [10]. MEMS microphones are typically used in applications where small size, affordability, and reliability are important[10]. MEMS microphones are also capable of being being directly surface mounted to circuit boards alongside and at the same time as other semiconductor components, via automatic "pick and place" manufacturing techniques[11], making them easy to manufacture into products. The market for MEMS microphones has reach $1.2 billion in 2015[2], with almost $900 million coming their placement inside smartphones, tablets, and wearables.

Technology Forecasting

Technology forecasting attempts to predict the future characteristics and feature enhancements of current technologies and systems. Technology forecasting also attempts to predict the approximate timeframe in which these new characteristics and enhancements will be realized. The practice of technology forecasting increased substantially during the early era of the Cold War [12], when the U.S. military needed to make long range plans during an era of rapid technological advancement. Various technology forecasting techniques have been developed since then including trend curve and extrapolation techniques, particularly S-Curve/Logistic Curve modelling [13]. So called "structured judgment"[13], methods (such as Delphi) have been developed to harness the opinions of fields of experts. Stochastic forecasts [14] provide a "probabilistic trend" into the future for a particular technology, with a probability distribution along the predicted path.

TFDEA

TFDEA is a technology forecasting technique which considers multiple technological attributes instead of the typical single characteristic often considered by extrapolation and regression techniques [1]. It extends DEA (data envelopment analysis), by producing a technological rate of change parameter for the technology under consideration[1]. TFDEA provides for specifying a variable number of "input" technological features, which influence a variable number of "output" technological features. It can be used to predict the future state-of-the-art "surface" of the technology being considered.

Methodology

Data Collection

Analog MEMS microphone manufacturers publish specifications detailing their products in documents known as datasheets. The datasheet will include specifications on the microphone's size and shape, it's electrical power requirements, electrical wiring diagrams, and the microphone's functional performance specifications. In this study, datasheets were collected from the following major manufacturers: Knowles, Cirrus Logic, STM, and InvenSense. According to[15], Knowles controlled 59% of the MEMS microphone market share in 2015. The

Analog MEMS datasheet data was tabulated into a spreadsheet compatible for TFDEA analysis. It is provided in Table 7 in the Appendix section.

Model Parameters

Structural Characteristics

Of the multiple features of analog MEMS microphones, the features chosen for this study were structural characteristics (surface area, volume), and two functional characteristics (Signal-to-Noise ratio and AOP). The data table provided in Table 7 in the Appendix section reflects this – only these parameters were recorded. The surface area of an analog MEMS microphone represents the amount of space the microphone will occupy on a circuit board. As MEMS microphones are typically used in space constrained applications [10], minimizing the surface area of the microphone is generally desirable. The microphone “footprint” is typically of rectangular shape [16]. The MEMS microphone silicon diaphragm and associated circuitry is housed in chamber, the height of which, considered with the surface area, defines the volume of the microphone.

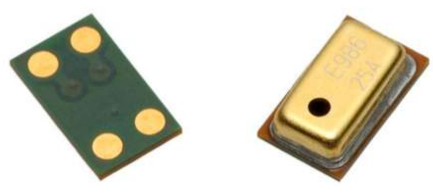

Figure 4 Analog MEMS Example [16]

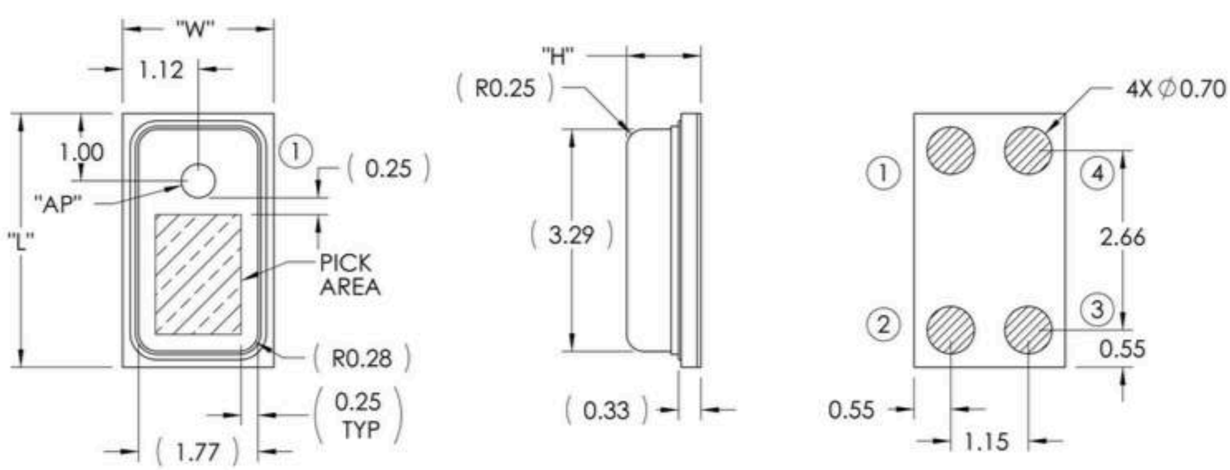

Figure 5 Structural Characteristics Example Dimensions [16]

Functional Characteristics

The Signal-to-Noise ratio and Acoustic Overload Point (AOP) are two functional characteristics of analog MEMS microphones. The AOP is "..the highest acoustic sound pressure level (SPL) that the microphone can tolerate" [17]. It is specified in units of dB SPL. If the microphone is subject to a sound pressure level which exceeds its rating, the electrical output signal from the microphone is likely to be highly distorted and unrepresentative of the sound source. Therefore, the higher the AOP rating of the microphone, the greater the sound pressures it can handle (it can handle louder sounds). The Signal-to-Noise ratio (SNR) "…specifies the ratio of a reference signal to the noise level of the microphone output"[17]. The SNR is calculated by by first measuring the electrical output signal of the microphone in a silent (anechoic) environment. Ideally, the output of the microphone in such an environment would be an electrical signal with no energy, but due to electrical self-noise the microphone will output a very low level random noise signal. The energy of this signal is the "noise floor", or EIN (equivalent input noise), measured in dB. The microphone is then subjected to a 94dB SPL 1kHz sine reference sound. The SNR is the difference in amplitude, in decibels, between the electrical signal output from the microphone when subjected to the reference sound and the microphone noise floor [17]. A higher SNR is desirable.

TFDEA Model Configuration

The TFDEA model used in this study was configured according to the parameters listed in Table 1.

Orientation	Output Oriented
Input Parameters	Surface Area (mm^2); Volume (mm^3)
Output Parameters	Signal-to-Noise Ratio (SNR); Acoustic Overload Point (AOP)

Table 1 TFDEA Model Configuration

An output-oriented TFDEA model is chosen to maximize output parameters, given fixed input parameters [18]. As such, in this study, the model is configured to maximize SNR and AOP (the output parameters) assuming the surface area and volume (the input parameters) of the analog MEMS microphone are held constant. The model parameters were chosen this way to consider the microphone structural characteristics as inputs, and functional characteristics as outputs (Figure 6).

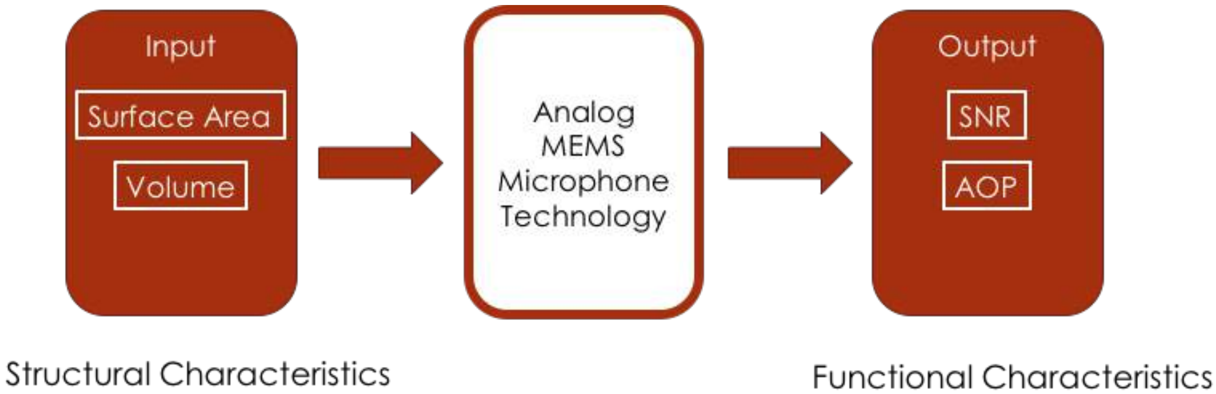

Figure 6 TFDEA Model

Frontier Year

Figure 7 shows the number of available DMUs (Decision Making Units) for the TFDEA model in each year, from 2004 to 2015. Because the number of available DMUs was sparse in 2004-2008, the model was tested against frontier years 2009-2014.

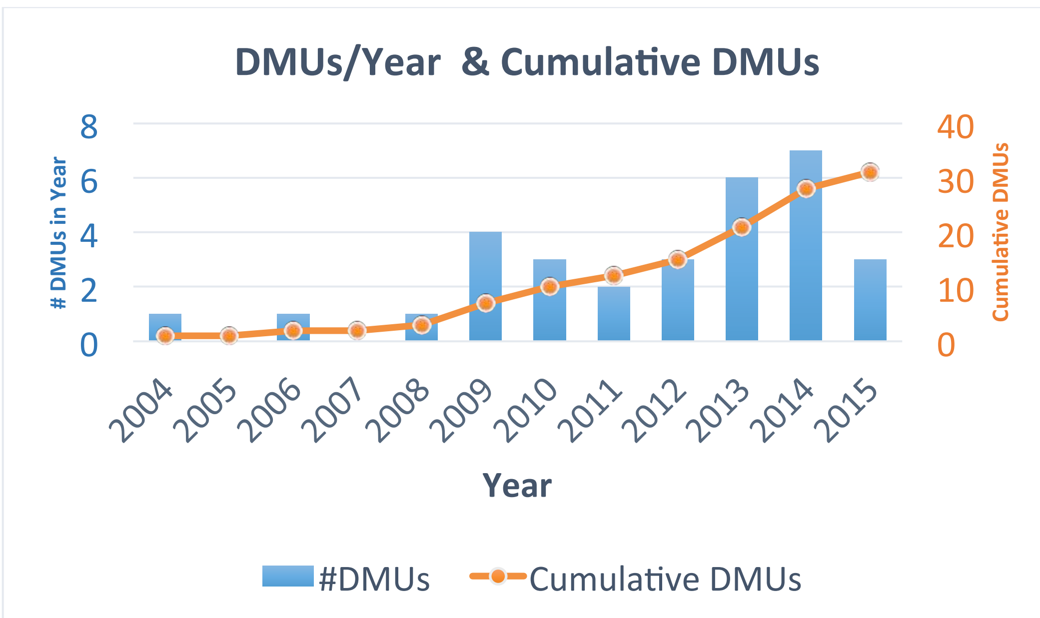

Figure 7 DMUs/Year & Cumulative DMUs

The TFDEA model was configured and tested by utilizing the Portland State University – Extreme Technology Analytics TFDEA web application [19]. The web application accepts .csv file as input for upload. The application provides the means to select the appropriate row/column for frontier year, input and output parameters, and model orientation. The tool provides output plots and tabulated data spreadsheets.

Results

The results of the TFDEA forecasting models for frontier year 2009:2014 are attached in the Appendix section. The MAD (Mean Absolute Deviation) and RoC (Rate of Change) for frontier year 2009-2014 are presented in Table 2 and Figure 8.

Frontier Year	Learning Period	Validation Period	Avg RoC	MAD[years]
2009	2004-2009	2009-2015	1.038023257	2.66
2010	2004-2010	2010-2015	1.031302007	2.058517618
2011	2004-2011	2011-2015	1.019032523	0.985470309
2012	2004-2012	2012-2015	1.014213361	1.46283912
2013	2004-2013	2013-2015	1.018937643	0.869135041
2014	2004-2014	2014-2015	1.014492323	3.089464815

Table 2 TFDEA Calculated MAD and RoC - Frontier Year 2009:2014

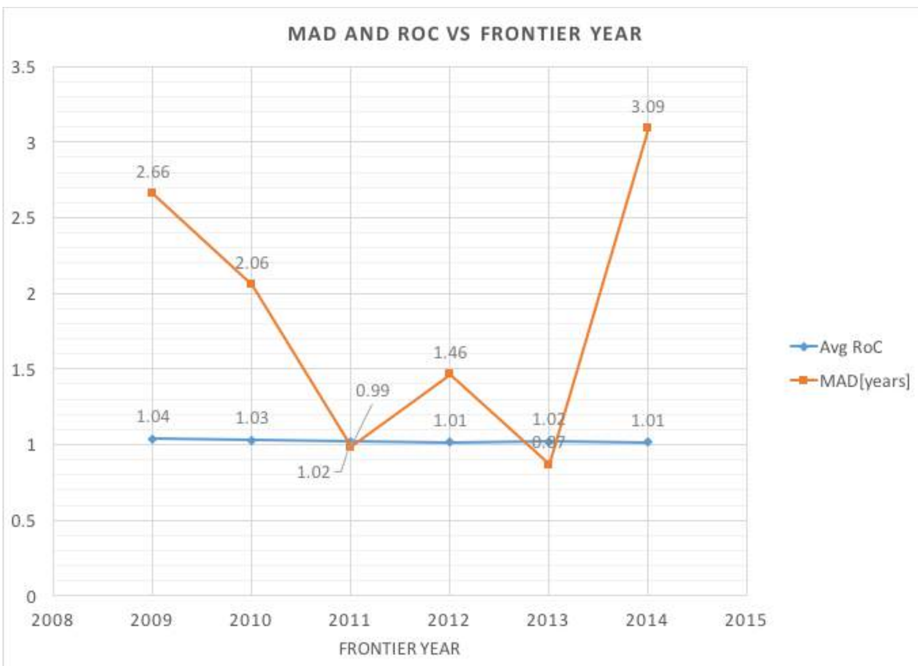

Figure 8 MAD and RoC vs Frontier Year 2009:2014

Discussion

As depicted in Table 2 and Figure 8, the TFDEA MAD shows general improvement between frontier year 2009:2013. The improving performance of the model can be attributed to the increasing number of total DMUs available to the forecasting model, as depicted in Figure 7. The TFDEA model also indicates a relatively steady rate-of-change (RoC) of approximately 1.5%-3.5% between frontier years 2009:2014.

The TFDEA model shows a sharp increase in MAD in frontier year 2014 of 3.09 years. Reexamining the SNR specifications of all DMUs under test reveals that in 2015, one microphone had a specified SNR of 70dB – 4dB greater than all other microphones (Table 3 & Figure 9).

Index	Year (Fractional)	SNR (dB)	AOP	Area (mm^2)	Volume (mm^3)	Manufacturer	Product Name
29	2015.136111	70	124	12	14.4	InvenSense	ICS-40720

Table 3 - 70dB SNR Outlier Microphone

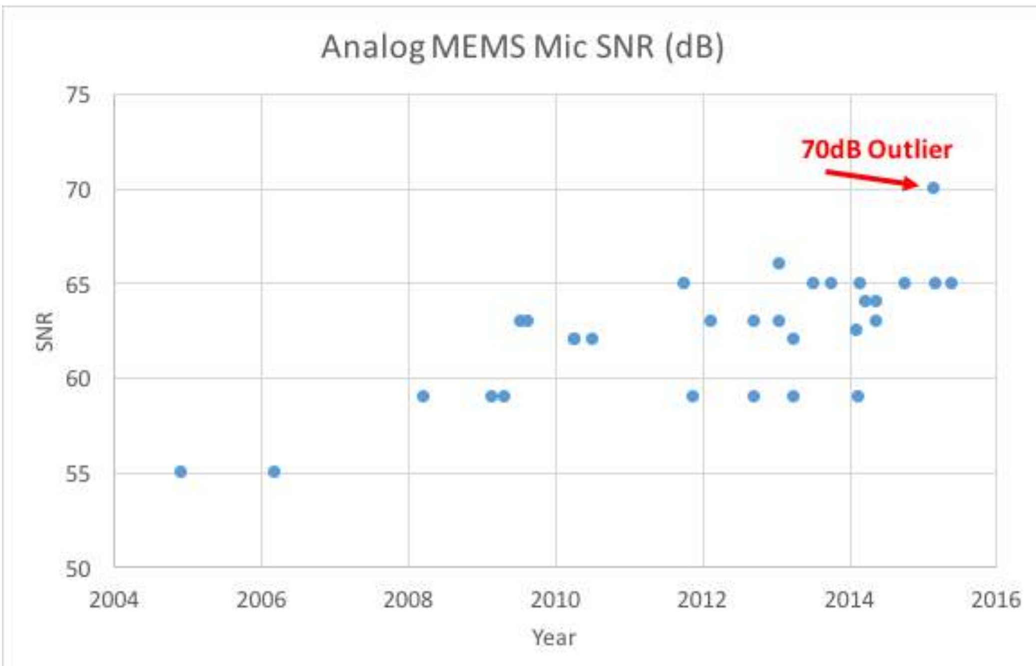

Figure 9 - Emphasizing 70dB SNR Microphone vs All Other Microphones as Outlier

This microphone represents a significant SNR performance increase versus all other microphones considered by the TFDEA forecasting model, and explains the sharp increase in MAD for frontier year 2014.

Forecasting

Forecasting of microphone SNR and AOP performance was performed to predict SNR and AOP performance in year 2016.

Forecasting SNR

Forecasting for SNR is performed by not including the 70dB SNR outlier discussed previously.

In the collection of DMUs, the best SNR (excluding the outlier) is 66dB. This value is considered the SOA. This sample is found in year 2014, even though the DMU collection includes samples from year 2015. Only 3 DMU datasheets could be found from year 2015 which may explain why none had at least a SOA SNR of 66dB.

The forecast is performed by utilizing the average RoC of frontier year 2014 (the latest frontier year available from the TFDEA analysis), and the SOA SNR of 66dB. Because the RoC frontier year is 2014, the expected 2015 SNR is predicted first. The forecast is performed by multiplying the SOA SNR in the DMU collection by the 2014 average RoC to yield the predicted 2015 SNR. This result is then multiplied by the 2014 average RoC again to yield the predicted 2016 SNR (Table 4).

Step 1	SOA SNR in DMU collection	Average RoC (Frontier Year 2014)	Predicted 2015 SNR
	66dB (from2014)	1.01499	66.98dB

Step 2	Predicted 2015 SNR	Average RoC (Frontier Year 2014)	Predicted 2016 SNR
	66.98dB	1.01499	67.99dB

Table 4 SNR Forecast

This forecast predicts that the 2015 SNR should be 66.98dB. The collection of DMUs from 2015 available for this analysis only had SNR values of 65dB (excluding the outlier), indicating they are behind the SOA. Extending this forecasting analysis to 2016 shows the 2016 predicted SNR is 67.99dB.

Forecasting AOP

In the collection of DMUs the best AOP is 131dB SPL. This sample is found in year 2013 and is considered the SOA.

The forecast is performed by utilizing the average RoC of frontier year 2014 (the latest frontier year available from the TFDEA analysis), and the SOA AOP of 131dB SPL. Because the RoC frontier year is 2014, the expected 2015 AOP is predicted first. The forecast is performed by multiplying the SOA AOP in the DMU collection by the 2014 average RoC to yield the predicted 2015 AOP. This result is then multiplied by the 2014 average RoC again to yield the predicted 2016 SNR (Table 4).

Step 1	SOA AOP in DMU collection	Average RoC (Frontier Year 2014)	Predicted 2015 AOP
	131dB (from2013)	1.01499	132.96dB SPL

Step 2	Predicted AOP in 2015	Average RoC (Frontier Year 2014)	Predicted 2015 AOP
	132.96dB SPL	1.01499	134.96 dB SPL

Table 5 AOP Forecast

This forecast predicts that the 2015 AOP should be 132.96dB SPL. The collection of DMUs from 2015 available for this analysis only had SNR values of 124dB SPL, indicating they are behind the SOA. Extending this forecasting analysis to 2016 shows the 2016 predicted AOP is 134.96 dB SPL.

State of the Art Frontiers

The previous forecasting analysis can be shown graphically by plotting the State of the Art frontier "surfaces". It is interesting to plot the recent DMUs on top of these surfaces to graphically see how each DMU compares to the State-of-the-Art.

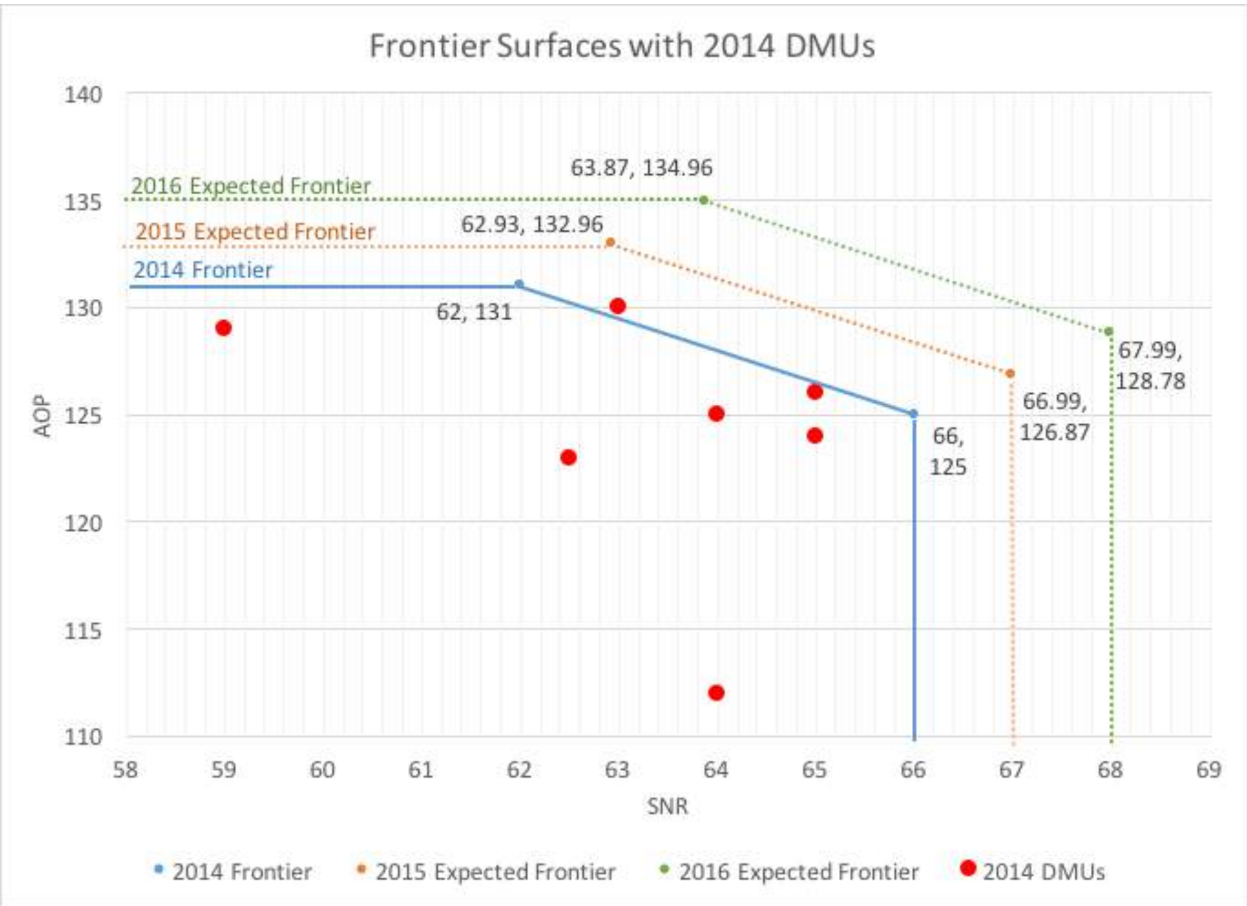

Figure 10 Frontier Surfaces with 2014 DMUs

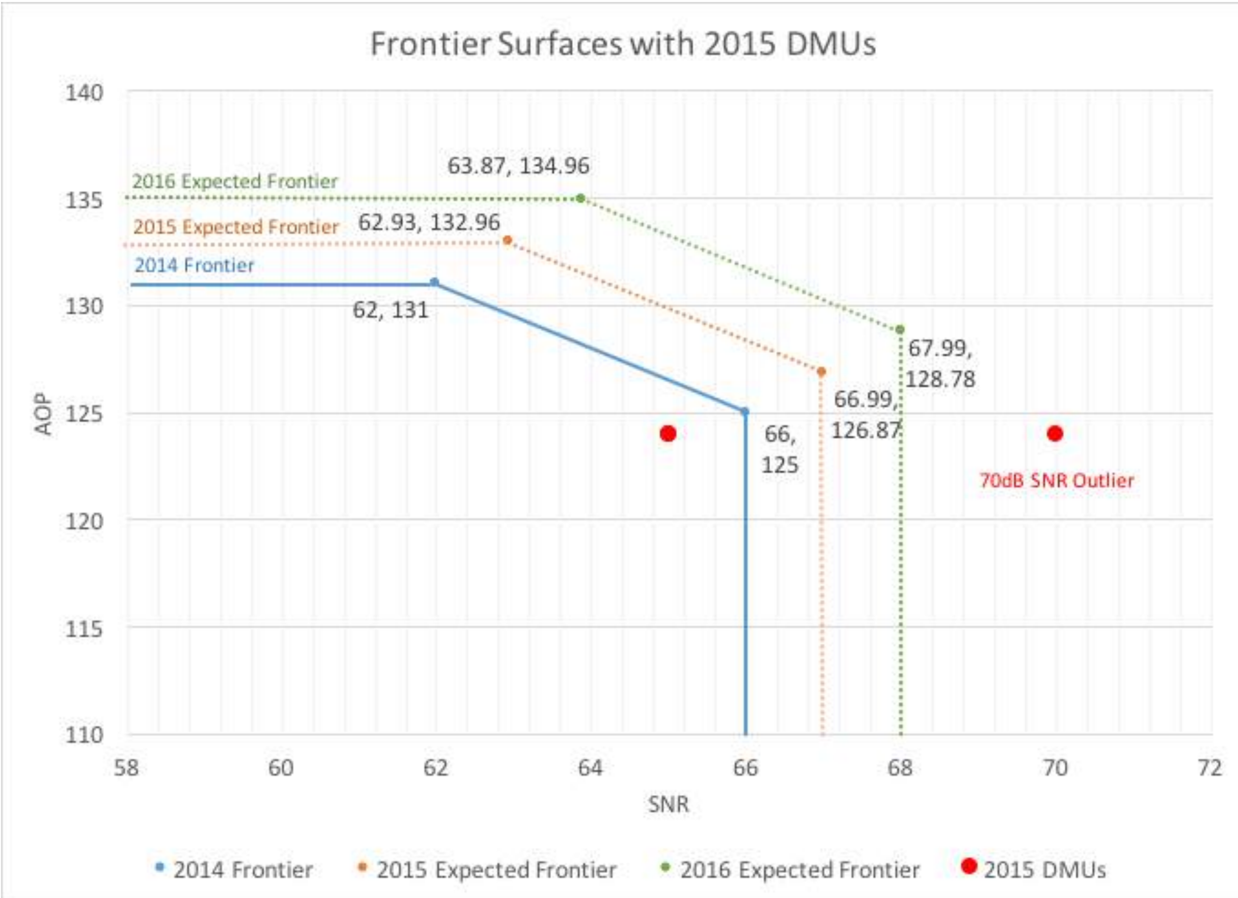

Figure 11 Frontier Surfaces with 2015 DMUs

Conclusion

This research effort used TFDEA to attempt to forecast the future functional characteristics of analog MEMS microphones to year 2016, specifically focusing on signal-to-noise ratio (SNR) and Acoustic Overload Point (AOP). Microphones from years 2009 to 2015 were considered by the TFDEA models. This analysis resulted in a prediction of ~68dB SNR and ~135dB SPL AOP in year 2016, based upon an average Rate-of-Change (RoC) of technical performance of ~1.5% in frontier year 2014. The analysis did not consider a 2015 microphone with a datasheet stated SNR of 70dB, as this value represents an increase in performance of approximately ~6% from microphones in 2014, far in excess of the 1.5% RoC from 2014. The analysis from this paper suggest this SNR is unlikely in year 2015.

Considerations for Future Work

Three future research topics are suggested to extend the analysis in this paper.

1. The InvenSense ICS-40720 microphone should be independently tested to validate the datasheet stated SNR of 70dB. This value is far beyond the stated SNR of other analog

MEMS microphones of the era. Based upon the forecasting in this paper, this SNR seems uncharacteristically high. Independent testing would verify if the ICS-40720 does indeed offer the SOA SNR of 70dB, or if this value is not truly representative of the microphone's performance

2. Additional silicon condenser style MEMs microphone performance can be monitored and projected into the future beyond 2016. Such a research effort would represent a continuation of this paper's work.
3. A new MEMS microphone relying upon a different sound pressure to electrical signal transduction technique (piezoelectricity) will soon be released [20]. Unlike condenser style microphones where the transduction method relies upon variations in electrical capacitance, piezoelectric transduction is accomplished by harnessing the piezoelectric effect – the generation of charge in response to mechanical pressure [21]. The data sheet for this microphone indicates SOA SNR performance (excluding the ICS-40720 outlier). As these microphones utilize a totally different transduction method, it is possible as the technology matures they will offer superior performance to silicon condenser style mics. As these microphones have yet to be sold on the market, there is an opportunity to track their performance enhancements over time, starting from the first model of the first generation.

Parameter	Performance
Signal-to-Noise Ratio	68 dB
Acoustic Overload Point	128 dBSPL

Table 6 Vesper VM101 SNR and AOP[22]

Appendix

TFDEA Forecast Plots – Frontier Years 2009:2014

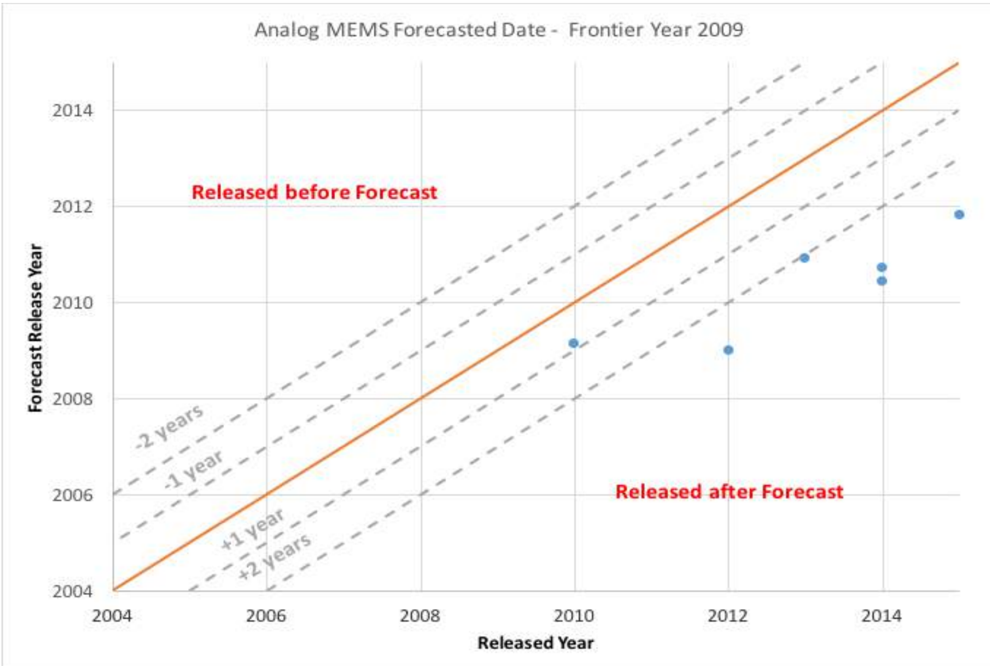

Figure 12. TFDEA Forecast with Frontier Year 2009

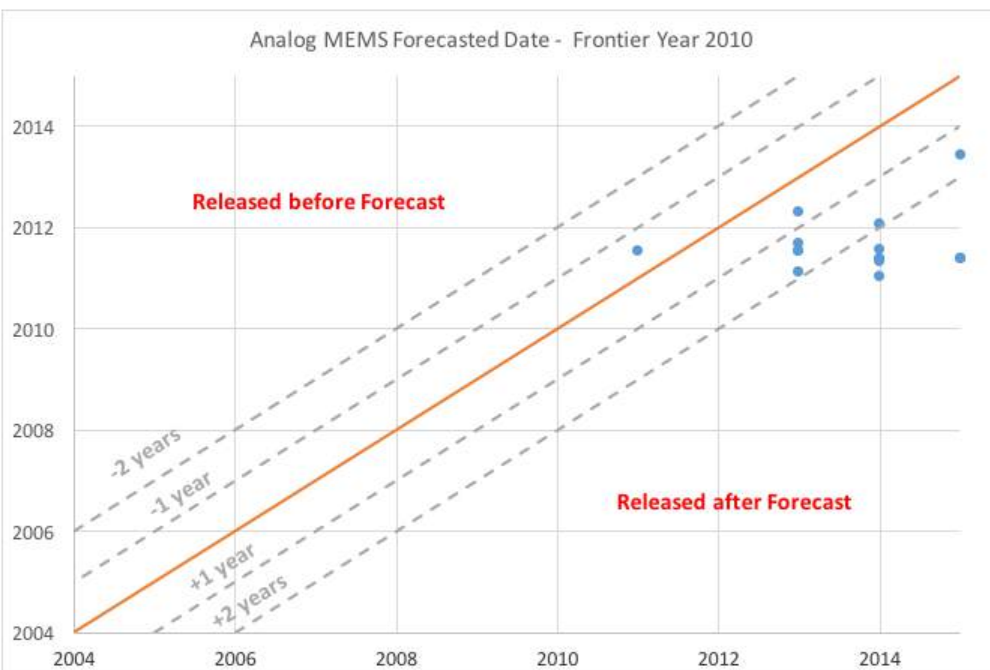

Figure 13. TFDEA Forecast with Frontier Year 2010

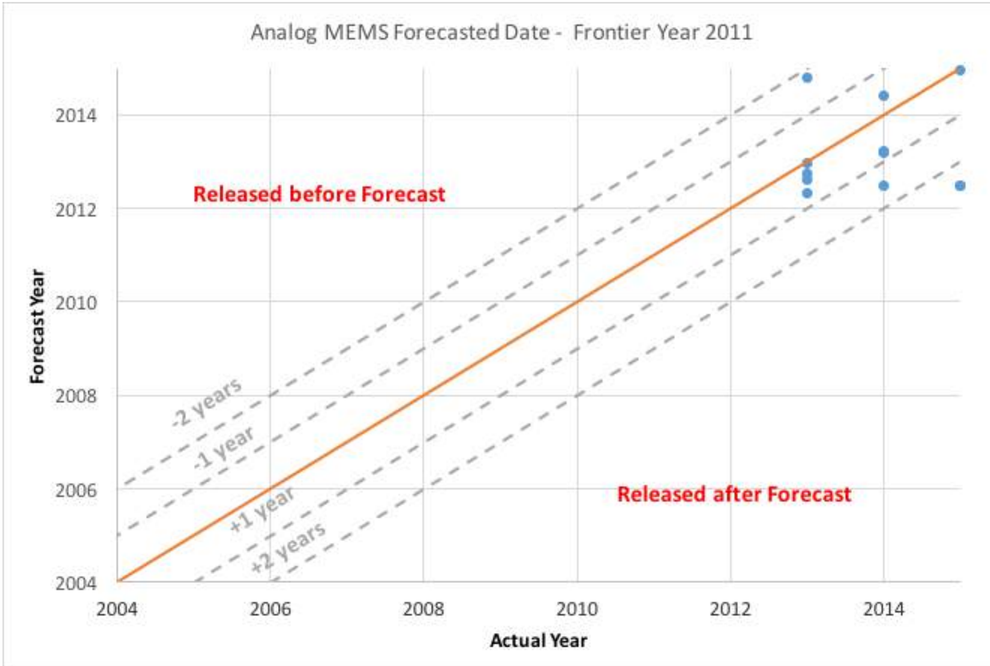

Figure 14. TFDEA Forecast with Frontier Year 2011

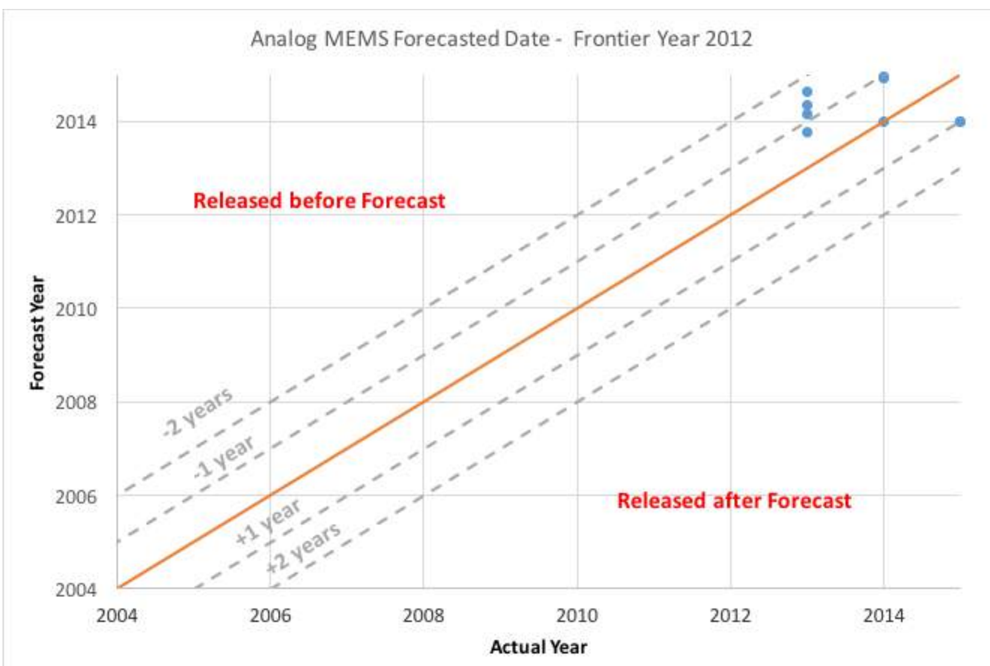

Figure 15 TFDEA Forecast with Frontier Year 2012

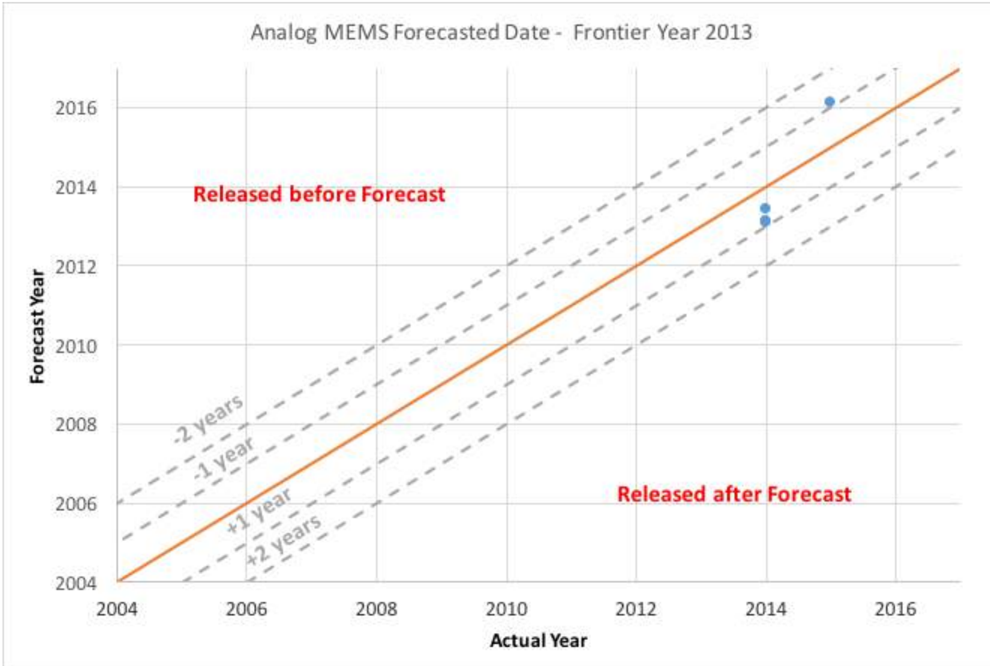

Figure 16 TFDEA Forecast with Frontier Year 2013

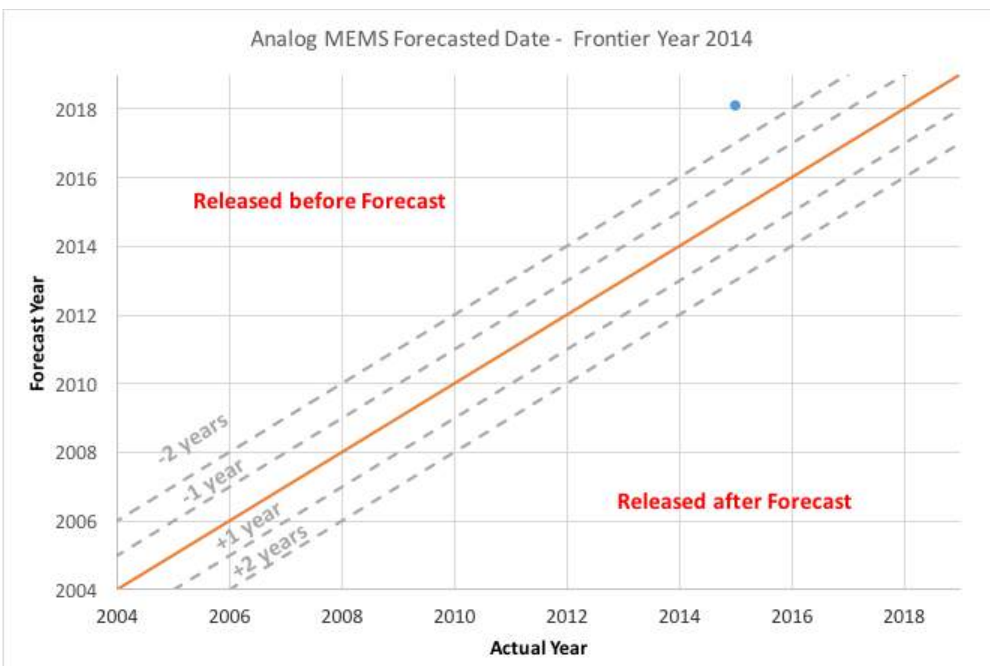

Figure 17. TFDEA Forecast with Frontier Year 2014

Analog MEMS Tabulated Data

Index	Year	Year	SNR	AOP	Area	Volume	Manufacturer	Product Name

	(Fractional)	(int)	(dB)	(dBSPL)	(mm^2)	(mm^3)		
1	2004.916667	2004	55	100	23.124	38.1546	Knowles	SP0102BE3
2	2006.183333	2006	55	100	17.7472	22.184	Knowles	SPM0208HD5
3	2008.216667	2008	59	115	17.7472	14.907648	Knowles	SPM0404HE5H-PB
4	2009.127778	2009	59	122	11.092	12.2012	Knowles	SP0410HR5H-PB
5	2009.311111	2009	59	115	11.092	12.2012	Knowles	SPU0414HR5H-SB
6	2009.519444	2009	63	118	11.28	12.408	Knowles	SPU0410LR5H-QB
7	2009.619444	2009	63	115	17.7472	22.184	Knowles	SPM0408LE5H-TB
8	2010.25	2010	62	120	17.7472	17.7472	InvenSense	INMP401
9	2010.25	2010	62	120	8.375	7.37	InvenSense	INMP404
10	2010.5	2010	62	120	8.375	7.37	InvenSense	INMP405
11	2011.75	2011	65	120	8.375	7.37	InvenSense	INMP504
12	2011.861111	2011	59	115	8.4224	9.26464	Knowles	SPQ0410HR5H-B
13	2012.119444	2012	63	118	11.28	12.408	Knowles	SPU1410LR5H-QB
14	2012.694444	2012	63	118	11.28	12.408	Knowles	SPU0410LR5H-1
15	2012.694444	2012	59	122	11.092	12.2012	Knowles	SPU0410HR5H-1
16	2013.044444	2013	63	125	11.092	11.092	STM	MP33AB01
17	2013.044444	2013	66	125	11.092	11.092	STM	MP33AB01H
18	2013.25	2013	62	131	17.7472	17.7472	InvenSense	INMP411
19	2013.25	2013	59	115	8.4224	9.26464	Knowles	SPQ1410HR5H-B
20	2013.5	2013	65	124	8.375	8.2075	InvenSense	INMP510
21	2013.752778	2013	65	123	8.375	8.2075	Knowles	SPA2629LR5H-B
22	2014.094444	2014	62.5	123	5.0875	4.57875	Knowles	SPV1840LR5H-B
23	2014.127778	2014	59	129	7.75	7.75	Knowles	SPW2430HR5H-B
24	2014.152778	2014	65	126	11.28	12.408	Cirrus	WM7132P
25	2014.222222	2014	64	125	8.375	8.2075	STM	MP23AB02B
26	2014.372222	2014	63	130	17.7472	62.1152	InvenSense	ICS-40300
27	2014.375	2014	64	112	8.375	8.2075	InvenSense	ICS-40310
28	2014.766667	2014	65	124	9.275	9.0895	InvenSense	ICS-40180
29	2015.136111	2015	70	124	12	14.4	InvenSense	ICS-40720
30	2015.180556	2015	65	124	9.275	9.0895	Knowles	SPH1611LR5H-1
31	2015.388889	2015	65	124	9.275	9.275	Knowles	SPH1642HT5H-1

Table 7. Tabulated Microphone Data

Analog MEMS Surface Area, Volume, SNR, AOP Plots

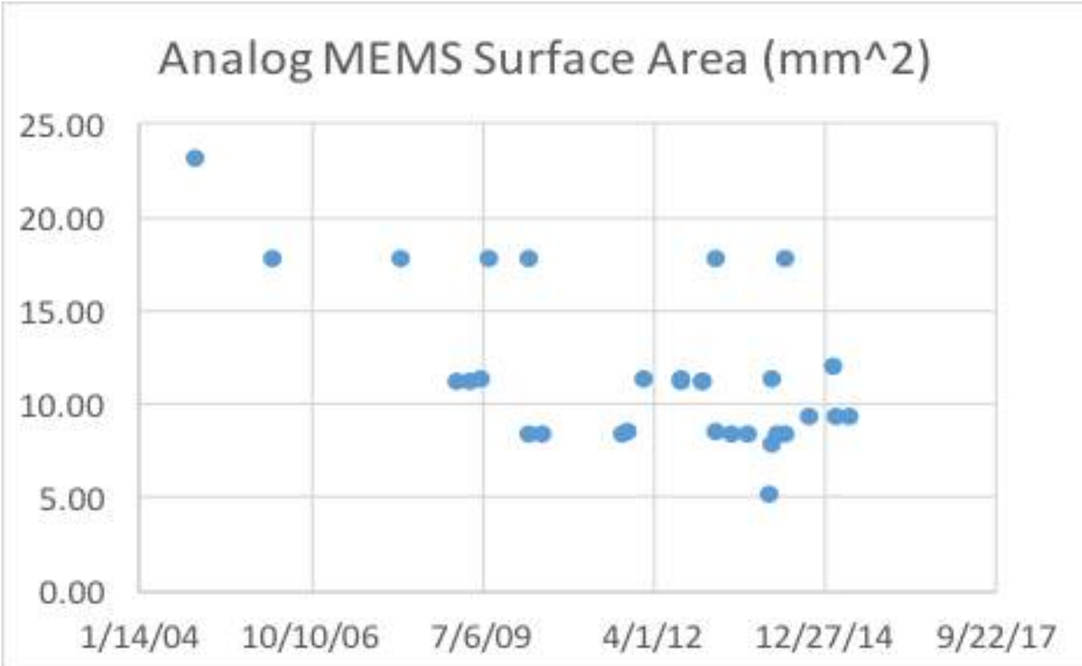

Figure 18 Analog MEMS Microphone Surface Area

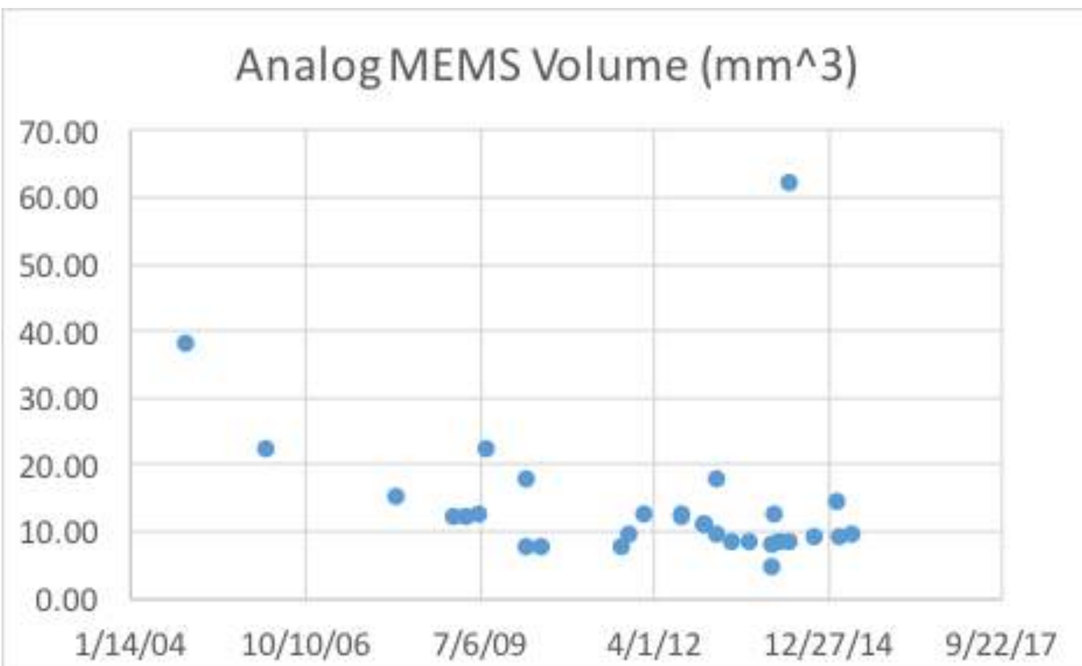

Figure 19 Analog MEMS Microphone Volume

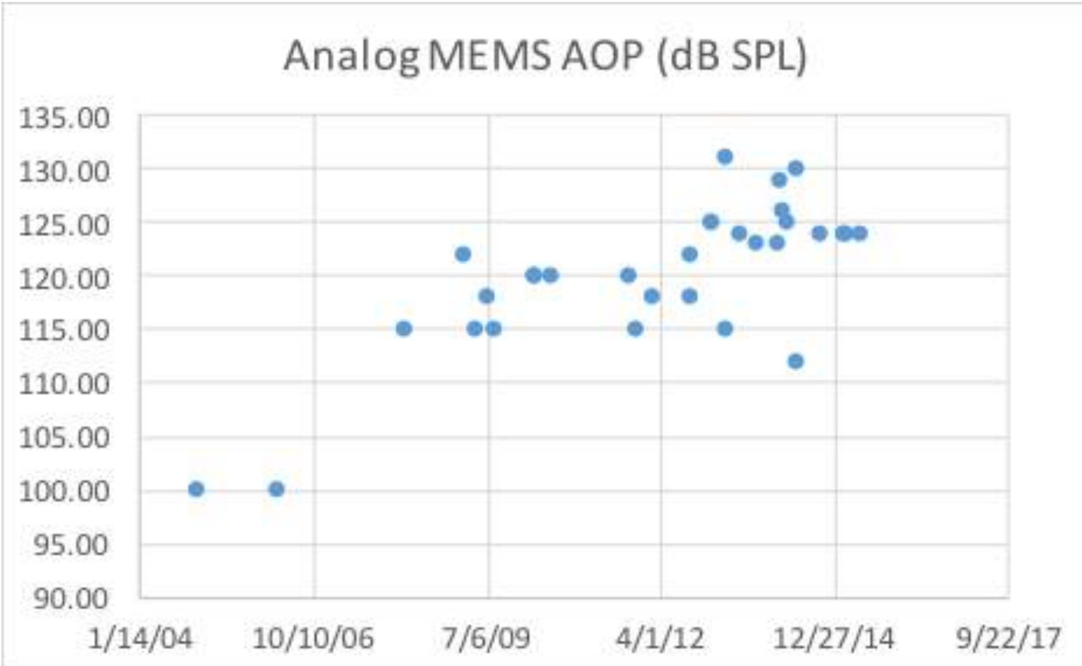

Figure 20 Analog MEMS Microphone AOP

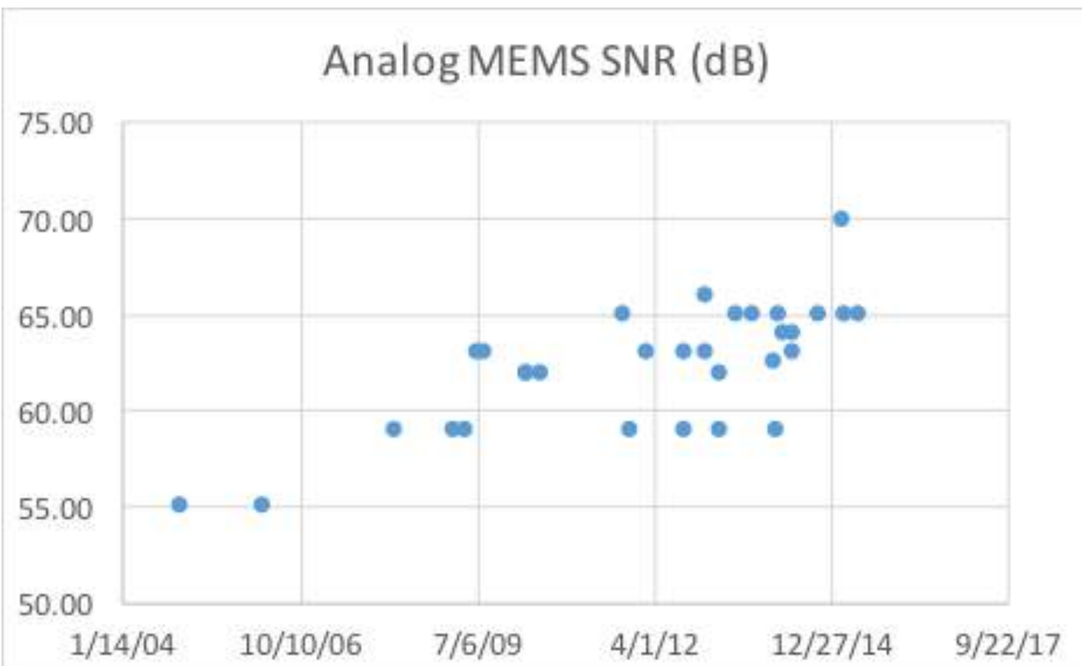

Figure 21 Analog MEMS Microphone SNR

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