# Methods for Quantifying Mid-Frequency Active Sonar in the SOCAL Range Complex

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## Executive Summary

A new method was developed to provide better metrics for quantifying Mid-Frequency Active Sonar (MFAS) occurrence and levels, and was applied to passive acoustic monitoring data collected in the Southern California (SOCAL) Range Complex. MFAS signals are composed of both tones and frequency swept ‘pings’, often with multiple pings grouped closely in time as packets. These packets often occur repeatedly at intervals >20 s over periods of hours as wave train events with gaps between events >1 h. The new approach uses a higher received level packet detection threshold (130 $dB_{pp}$ re 1 µPa) than previous analyses, which limits the detection range to about 20 km, reducing the number of overall detections but also reducing the false detection rate. The new method calculates MFAS packet peak-to-peak (PP) received levels, but additional metrics, not included in previous analyses, are computed such as root-mean-square (RMS) levels, sound exposure levels (SEL) and signal duration. Furthermore, the results from this new method were provided as a comprehensive review over the five-year monitoring period in the SOCAL Range Complex, showing longer term trends than the previous individual reports.

MFAS was recorded in the SOCAL Range Complex from March 2009 to January 2014 using High-frequency Acoustic Recording Packages (HARPs) at three sites: (1) Site M, located in the eastern Santa Cruz Basin, north of San Clemente Island (SCI), (2) Site H, located in the western San Nicolas Basin, west of SCI, and (3) Site N, located in the East Cortez Basin, south of SCI. Site M had the lowest MFAS activity compared to the two sites south. Only 10 wave train events of MFAS were detected at site M; whereas, site H had 151 events and site N had 310 events. On average, wave train events consisted of over 100 MFAS packets with most packet durations < 4 s. In 2009, a few events were comprised of over 1,000 packets, although most events had less than 600 packets, and throughout 2013 the number of MFAS packets per event appeared to decrease at sites H and N.

Cumulative SEL (CSEL) for each wave train event was calculated as the sum of the packet SELs. This provides a measure of the total energy emitted during an event, a useful metric for marine mammal impact studies. Site N had the highest CSELs with values approaching 180 dB re 1 $\mu Pa^2$-s and site H had some CSELs over 170 dB re 1 $\mu Pa^2$-s, but site M had only two events with levels over 160 dB re 1 $\mu Pa^2$-s.

Further enhancements to this new approach for quantifying MFAS activity will be developed in conjunction with marine mammal impact studies. For example, efficiencies can be gained by reducing the number of analysts needed to define wave train events by implementing computer automated methods, and additional parameters, such as packet frequency content, will be measured to investigate if these are important factors for potential marine mammal impact.

## Introduction

Mid-frequency active sonar (MFAS) is used for anti-submarine warfare (ASW) training in the Southern California (SOCAL) Range Complex. Both simulated and real MFAS has been shown to elicit behavioral response in free-ranging marine mammals (Tyack *et al.*, 2011; Melcón *et al.*, 2012; Goldbogen *et al.*, 2013). Additional work is needed to understand the potential impact of MFAS on the behavior of marine mammals in areas of naval training.

Passive Acoustic Monitoring (PAM) recordings allow both animal sounds and sonar pings to be quantified and used in statistical models for impact studies. PAM has been used in the SOCAL Range Complex to monitor the acoustic behavior of marine mammals and the occurrence of MFAS (Hildebrand *et al.*, 2010b; Hildebrand *et al.*, 2010a; Hildebrand *et al.*, 2011; Hildebrand *et al.*, 2012; Kerosky *et al.*, 2013); however, the metrics used for MFAS in previous reports are too general to be used for detailed impact studies, requiring a new more comprehensive approach.

A new method to quantifying MFAS is detailed below and applied to recordings from previous SOCAL Range Complex reports. The results provide a basis to further develop useful metrics for impact studies of MFAS on free-ranging marine mammal behavior over long periods.

## Methods

*Passive Acoustic Monitoring*

The SOCAL Range Complex is an area offshore of Southern California, roughly between Dana Point and San Diego extending west and south, used to train, equip and maintain combat-ready naval forces. The SOCAL Range Complex has been monitored for marine mammal sounds and MFAS since 2009 using passive High-frequency Acoustic Recording Packages (HARPs - Wiggins and Hildebrand, 2007) primarily at three offshore deepwater (~1,000 m) sites (Figure 1 and Table 1). HARPs provide long-term (months), wide-band (10 Hz – 100 kHz) records of underwater sounds. These records are processed and analyzed to detect sounds of interest such as animal calls and sonar. Detections can then be evaluated for spatial-temporal patterns, as well as evaluated for correlations to other sounds or events.

All HARP hydrophones are laboratory-calibrated for frequency response to provide sound pressure received level units in µPa. Select hydrophones are validated at the U.S. Navy's TRANSDEC hydrophone calibration facility. All hydrophones have a maximum received level limit. For MFAS in this study, the HARP received level limit was typically 171 dB re 1 µPa peak-peak (pp); however, a few of the more recent deployment hydrophones had a lower limit set at 161 $dB_{pp}$ re 1 µPa.

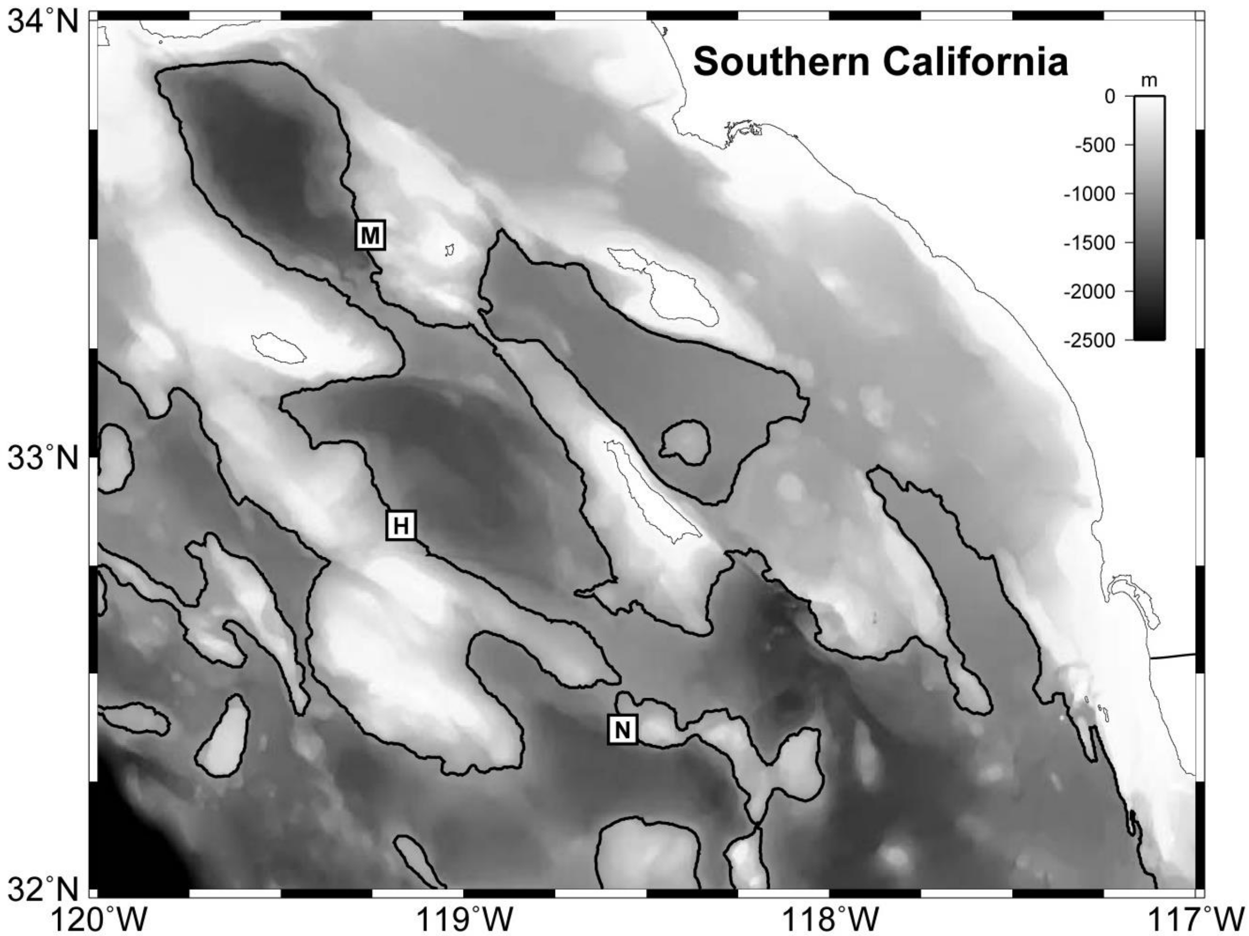

Figure 1. Three HARP long-term deployment sites (white squares) designated M, H, and N. Dark colors are deep, light colors are shallow, the thick contour is at 1,000m, and the thin contour is the coastline.

Table 1. SOCAL HARP deployment site locations.

| Site Name | Latitude | Longitude | Depth |
|---|---|---|---|
| M | 33° 30.92’N | 119° 14.96’W | 920 m |
| H | 32° 56.54’N | 119° 10.22’W | 1,000 m |
| N | 32° 22.18’N | 118° 33.77’W | 1,250 m |

Analyzed PAM periods at HARP sites M, H, and N start in March 2009 and continue to January 2014 (Table 2) with analyses on marine mammals and anthropogenic sounds reported in approximately one year increments: SOCAL 32-37 (Hildebrand *et al.*, 2010a; Hildebrand *et al.*, 2010b), SOCAL 38-41 (Hildebrand *et al.*, 2011), SOCAL 44-45 (Hildebrand *et al.*, 2012), SOCAL 46-47 (Kerosky *et al.*, 2013), and SOCAL 48-50 (Debich *et al.*, in preparation). Typically, two of the three sites were analyzed for these reports.

Table 2. SOCAL HARP PAM periods for sites M, H, and N. **Bold** periods were analyzed for MFAS, *italicized* periods had an instrument malfunction, and the remaining periods have not been analyzed.

| Deployment Name | Site M Monitoring Period | # Hours | Site H Monitoring Period | # Hours | Site N Monitoring Period | # Hours |
|---|---|---|---|---|---|---|
| SOCAL 32 | **03/11/09 – 05/04/09** | **1296** | 03/14/09 – 05/07/09 | 1320 | **03/14/09 – 05/07/09** | **1320** |
| SOCAL 33 | **05/17/09 – 07/08/09** | **1248** | 05/19/09 –06/13/09 | 600 | **05/19/09 – 07/12/09** | **1296** |
| SOCAL 34 | **07/27/09 – 09/16/09** | **1224** | 07/23/09 – 09/15/09 | 1296 | **07/22/09 – 09/15/09** | **1320** |
| SOCAL 35 | **09/25/09 – 11/17/09** | **1272** | 09/25/09 – 11/18/09 | 1320 | **09/26/09 – 11/19/09** | **1296** |
| SOCAL 36 | **12/05/09 – 01/24/10** | **1200** | 12/06/09 – 01/29/10 | 1296 | **12/06/09 – 01/26/10** | **1224** |
| SOCAL 37 | **01/30/10 – 03/25/10** | **1296** | 01/30/10 – 03/22/10 | 1248 | **01/31/10 – 03/26/10** | **1296** |
| SOCAL 38 | **04/10/10 – 07/12/10** | **2232** | 04/10/10 – 07/22/10 | 2472 | **04/11/10 – 07/18/10** | **2352** |
| SOCAL 40 | **07/22/10 – 11/07/10** | **2592** | 07/23/10 – 11/08/10 | 2592 | **07/23/10 – 11/08/10** | **2592** |
| SOCAL 41 | **12/05/10 – 04/24/11** | **3360** | 12/06/10 – 04/17/11 | 3192 | **12/07/10 – 04/09/11** | **2952** |
| SOCAL 44 | **05/11/11 – 10/02/11** | **2712** | **05/11/11 – 10/12/11** | **2952** | *05/12/10 – 09/23/11* | *3216* |
| SOCAL 45 | **10/27/11 – 03/18/12** | **3432** | **10/16/11 – 03/05/12** | **3024** | 10/16/11 – 02/13/12 | 2904 |
| SOCAL 46 | **03/24/12 – 07/22/12** | **2904** | 03/25/12 – 07/21/12 | 2856 | **03/25/12 – 08/05/12** | **3216** |
| SOCAL 47 | *08/10/12 –12/19/12* | *3168* | **08/10/12 – 12/20/12** | **3192** | **08/10/12 – 12/06/12** | **2856** |
| SOCAL 48 | 12/20/12 – 04/25/13 | 3048 | **12/21/12 – 04/30/13** | **3144** | **12/20/12 – 05/01/13** | **3192** |
| SOCAL 49 | **04/30/13 – 09/05/13** | **3048** | 05/01/13 – 09/07/13 | 3096 | **05/02/13 – 09/11/13** | **3144** |
| SOCAL 50 | **09/10/13 - 01/06/14** | **2856** | **09/10/13 – 01/07/14** | **2832** | *09/10/13 – 01/07/14* | *2880* |

*Mid-Frequency Active Sonar*

There are different types of MFAS signals ranging in frequency between 1-10 kHz. These signals are composed of pulses of both continuous wave (CW) single-frequency tones and frequency modulated (FM) sweeps grouped in packets with durations from <1 s to >5 s. Packets can be composed of singular or multiple pulses and are transmitted repetitively as wave trains with inter-packet-intervals typically >20 s. Figure 2 shows an example synthetic spectrogram of a four-pulse FM-CW-FM-CW packet.

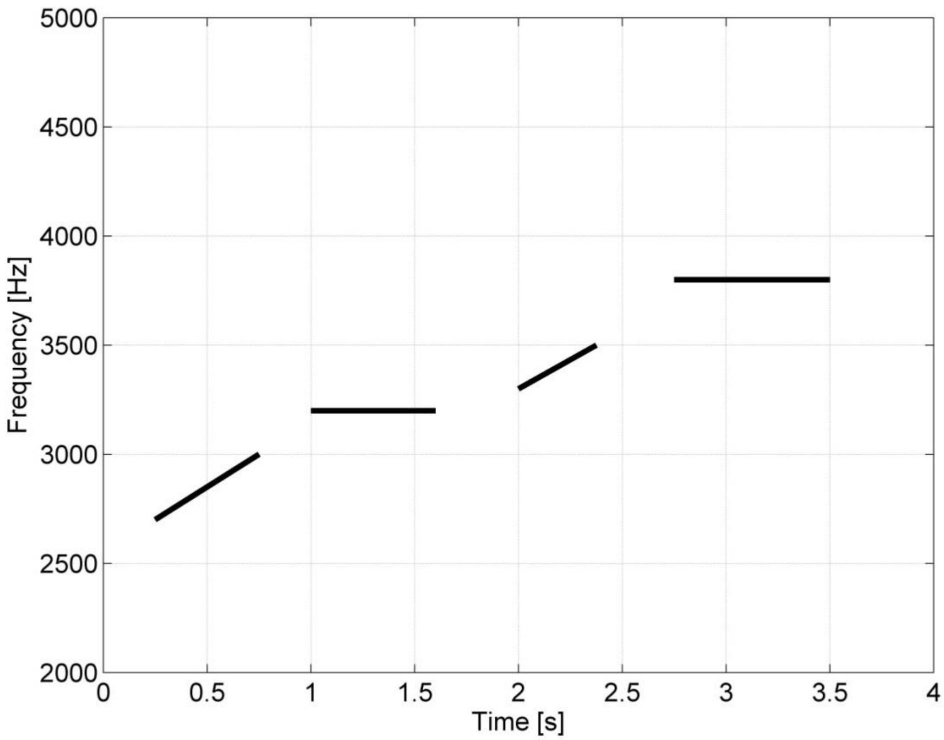


Figure 2. Example synthetic spectrogram of a four-pulse MFAS packet composed of two FM sweeps and two CW tones. MFAS packets typically are repeated at intervals >20 s forming a wave train.

One of the most common types of MFAS, known as 3.5 kHz, is a directional signal produced by the US Navy's hull mounted AN/SQS 53C system with a reported root-mean-square (RMS) source level of 235 $dB_{rms}$ re 1 µPa @ 1m, and was one of the sonar types used during the Bahamas mass-stranding incident (Evans and England, 2001). Based on PAM recordings from the SOCAL Range Complex, 3.5 kHz sonar appears to be the most common type and was the focus of our past investigations; however, higher frequency MFAS, for example from AN/SSQ-62 Directional Command Activated Sonobuoy System (DICASS) sonobuoys (6.5 - 9.5 kHz), occurs in SOCAL and should be studied in future work.

Based on an ad hoc study of MFAS characteristic in the SOCAL Range Complex between mid-April and mid-May 2010 at site N, pulse frequencies for the 3.5 kHz MFAS were mostly between 2.5 kHz and 4.5 kHz and number of pulses per packet ranged from one to four. The most common packet type was a single FM sweep followed by a single CW tone lasting 1-2 s.

*MFAS Detection and Filtering Process*

There were four main steps to detecting individual MFAS packets in the HARP recordings: (1) analysts define MFAS bouts, (2) execute automated detector on analyst-defined bouts, (3) filter detected packets, and (4) evaluate detections and generate resultant plots.

In the first step, analysts evaluated Long-Term Spectral Averages (LTSA – Wiggins and Hildebrand, 2007) and corresponding short-term spectrograms from data with a reduced effective bandwidth up to 5 kHz. Reducing the bandwidth, or decimating the original data to a lower sample rate, reduces computational needs allowing for faster and more efficient processing. During the analysts' review of the recordings, start and end times of wave trains of MFAS packets were noted and saved. These start and end times define a bout of MFAS and can last a few minutes to many hours. Typically, analyst-defined bouts can have low signal-to-noise ratios (SNRs) because human analysts are well-suited for recognizing low SNR patterns. This is especially true because the signals are presented in spectrogram format, which essentially show the recordings through high-resolution bandpass filters. Because of this low threshold, it is unlikely that any high SNR event were missed.

The bout start and end times were used to read segments of waveforms upon which a simple time series energy detector was executed. The segments were first bandpass filtered between 2.4 and 4.5 kHz with an elliptic filter. The energy detector finds all samples in the segment that are above a threshold of 121 $dB_{pp}$ re 1 µPa. Starting with the first sample above the threshold, a waveform from 0.1 s before to 10.0 s after that sample was extracted from the segment for analysis. From this sub-segment waveform, maximum pp received level (RL) along with sound exposure level (SEL) and date/time of packet occurrence were measured and saved. A second threshold, 10 dB lower than the max $RL_{pp}$ was used to define the duration of the waveform that was then used to measure packet $RL_{rms}$; whereas, SEL was measured over the whole 10.1 s. Additionally, the cumulative SEL (CSEL) was calculated by summing the SEL measurements of each packet over the complete wave train. CSEL provides a measure of total energy emitted during a wave train event.

A 20 s delay after the max $RL_{pp}$ sample was used before searching for the next sample above the 121 $dB_{pp}$ re 1 µPa threshold and extracting the next waveform for packet analysis. The delay greatly reduced false triggering on MFAS signal reverberation from the preceding pulse packet and was shorter than most or all wave train inter-packet-intervals. This packet detection process was repeated throughout the analysts' defined bouts for the deployments listed in Table 2. The detections were grouped by deployment.

The third step reduced the number of detected packets based on various filtering criteria. The first filter discarded duplicate detections from overlapping analysts' defined bouts, which occurred only rarely. Next, all packet detections with maximum $RL_{pp}$ <130 $dB_{pp}$ re 1 µPa were removed. Even though this filter was only 9 dB greater than the simple energy detector threshold, its effect was significant and typically reduced the number of packet detections for a deployment by at least 50%. This threshold was chosen to limit the source distance of off-axis received MFAS packets to ~20 km (Table 3).

Table 3. Minimum received level estimation from MFAS AN/SQS 53C source at 20 km range and assumed directivity based on published source level and 3.5 kHz transmit frequency.

| | |
|---|---|
| 235 $dB_{rms}$ re 1 µPa @ 1m | Source Level (Evans and England, 2001) |
| | |
| + 9 dB | RMS to PP conversion |
| - 25 dB | Directivity (assumption) |
| - 86 dB re @ 1m | Spreading loss @ 20km range ($20\log_{10}(R[m])$) |
| - 3 dB | Absorption @ 3.5kHz & 20km (0.15 dB/km – Ainslie and McColm, 1998) |
| | |
| 130 $dB_{pp}$ re 1 µPa | Off-axis (minimum) received level |

Additional filters primarily removed outliers and resulted in about a 5% reduction in the number of packet detections. These filters removed packet detections with RMS durations <0.25 s and >9.9 s, differences in $RL_{pp}$ and $RL_{rms}$ > 25 dB, and after grouping detections into wave trains with gaps >1 hr, wave trains were removed that were shorter than 5 min or with fewer than 10 packet detections.

Detector and filter performance was evaluated by plotting wave train time series of $RL_{pp}$ for each packet aligned with an LTSA of the wave train. False detections were minimal because of the relatively high detection threshold of 130 $dB_{pp}$ re 1 µPa.

## Results

Almost five years of recordings from March 2009 to January 2014 were used to detect packets and wave trains of MFAS with $RL_{pp}$ ≥130 $dB_{pp}$ re 1 µPa in the SOCAL Range Complex. Site M, which is at the northern extent or slightly beyond the Range Complex, had by far the fewest number of wave trains and packets detected compared to the two southern sites (Table 4 and Figure 3). The southern-most site, N, had the greatest number of wave trains and packets detected, even after accounting for the difference in effort at site H, with numbers at site N about 9% greater for wave trains and ~ 27% more for packets than at site H. On average, there were over 100 packets detected for each wave train at sites H and N.

Table 4. MFAS detector results for HARP sites in the SOCAL Range Complex. Total effort for each site in hours (years) and number of wave trains and packets detected.

| Site | Period Analyzed Hours (Years) | Number of Wave Trains | Wave Trains per year | Number of Packets | Packets per year |
|---|---|---|---|---|---|
| M | 30,672 (3.5) | 10 | 2.9 | 836 | 239 |
| H | 15,144 (1.7) | 151 | 88.8 | 16,509 | 9,711 |
| N | 28,056 (3.2) | 310 | 96.9 | 39,327 | 12,290 |

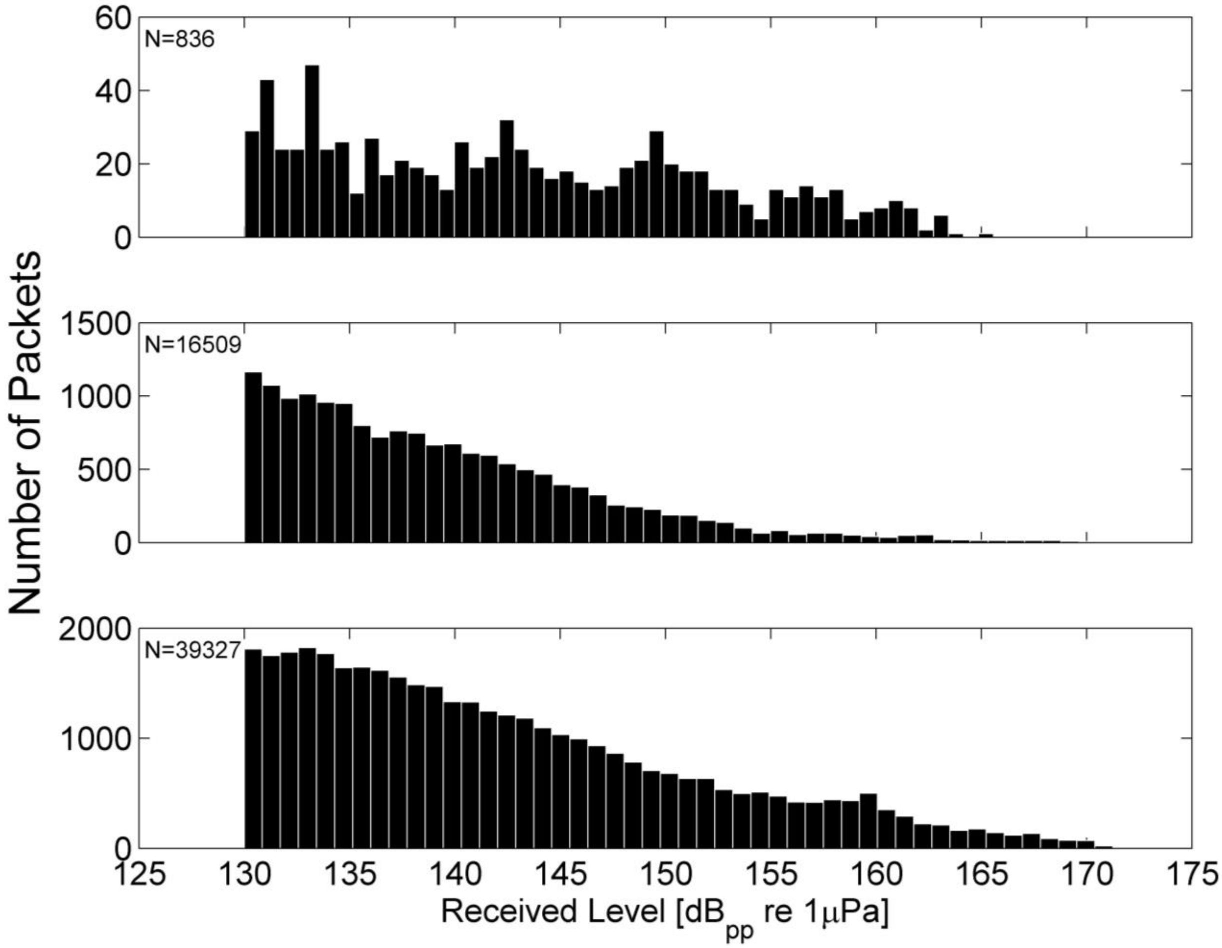


Figure 3. MFAS packet maximum received level distributions for sites M (top), H (middle), and N (bottom). The total number of packets detected (after data filtering) at each site is given in the upper left corner of each panel. Note the vertical axes are at different scales.

To show how MFAS activity was distributed over time, the number of packets for each wave train at each site was plotted over the five year study period (Figure 4). Only a few wave trains per year occur at site M; whereas, sites H and N have greater activity throughout the year with some periods of highly concentrated MFAS activity. Furthermore, it appears the number of wave trains with large numbers of packets decreased during 2013.

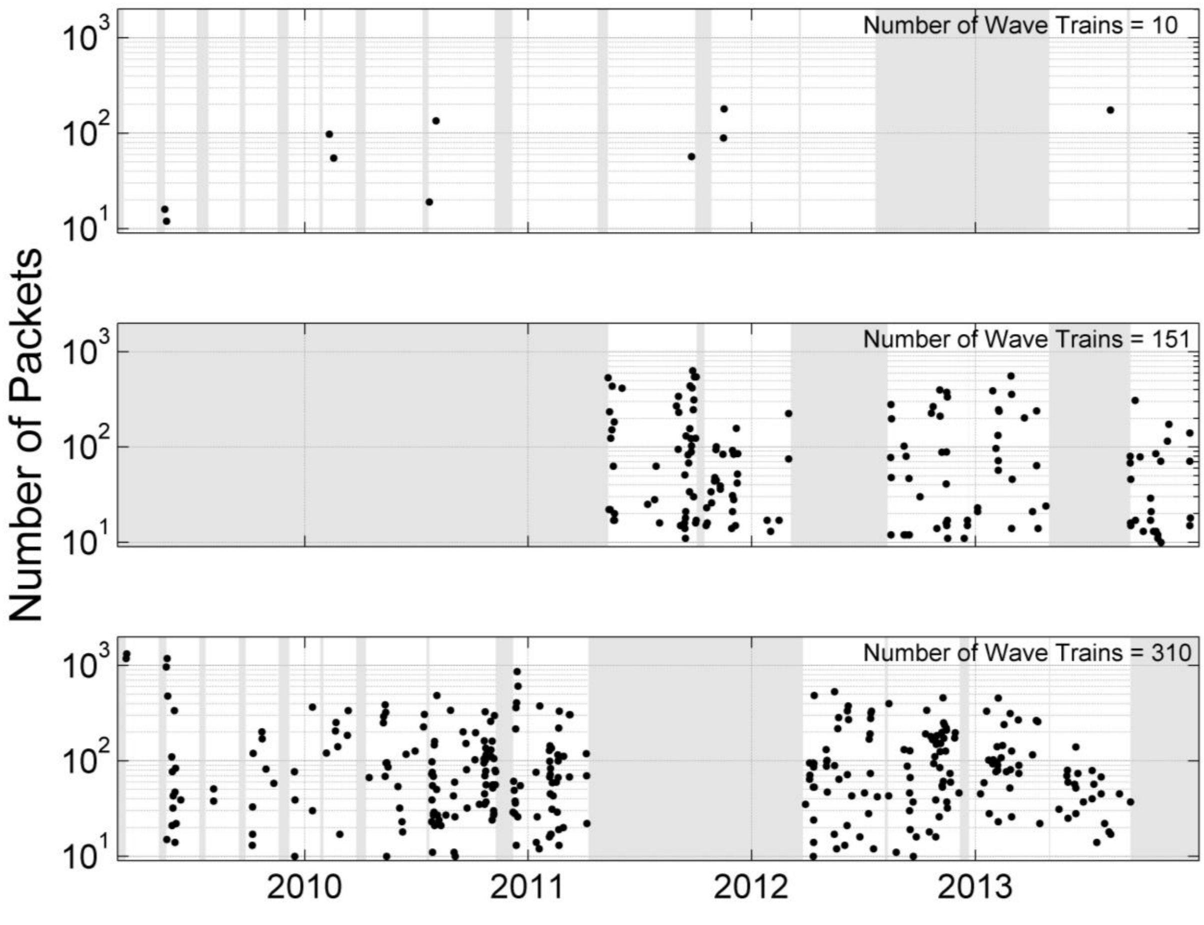


Figure 4. Number of MFAS packets (black dots) in each wave train over the five year study period for site M (top), site H (middle), and site N (bottom). Light gray regions are periods that were not analyzed (see Table 1). Note the vertical axes are logarithmic base-10 from 10 to 2,000.

CSEL, the total energy emitted in each wave train, was plotted over the study period (Figure 5). The CSEL typically appears to be higher at site N than the other two sites, approaching 180 dB re 1μPa$^2$-s in some instances. Site H has a few wave train events with CSEL over 170 dB re 1μPa$^2$-s, but site M has only two events over 160 dB re 1μPa$^2$-s.

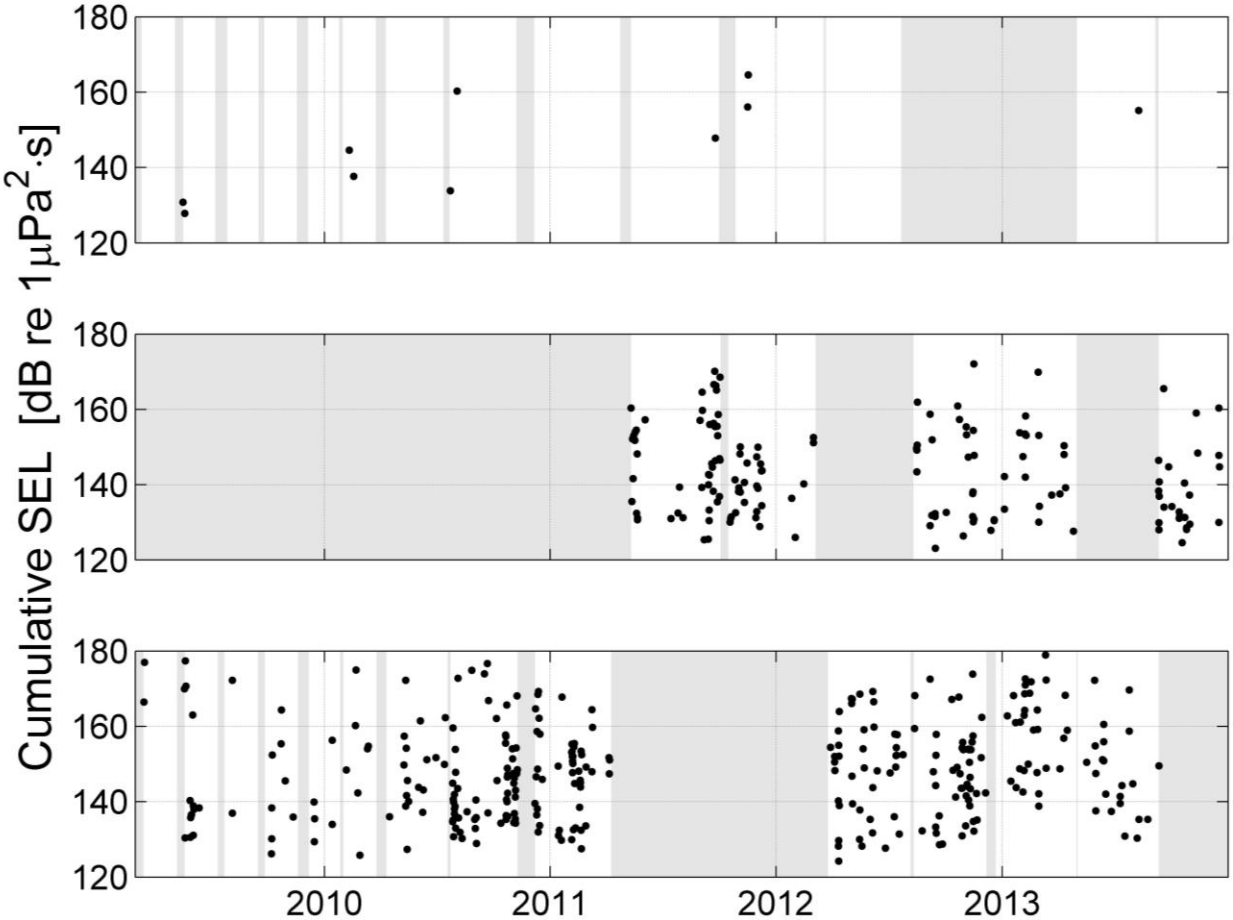


Figure 5. Cumulative SEL (CSEL) for each wave train over the five year study period for site M (top), site H (middle), and site N (bottom). Light gray regions are periods that were not analyzed (see Table 1).

Another metric that may prove useful for study of potential MFAS impact on marine mammal is packet RMS duration because sound exposure time has been shown to be important with temporary threshold shift (TTS) and permanent threshold shift (PTS) in marine mammals. Distributions of the packet RMS durations show most packets are less than 4 s and the majority of the packets are less than 2 s.

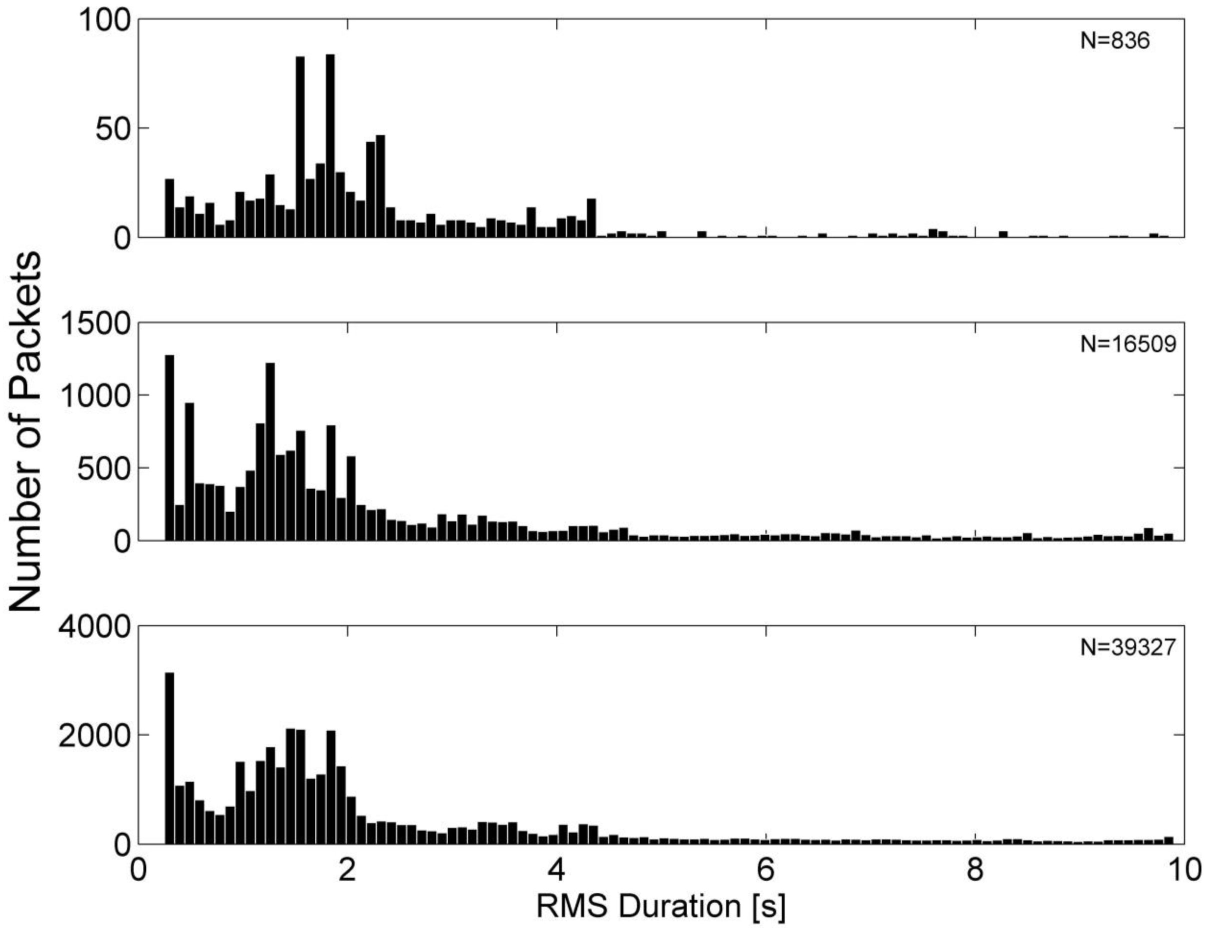


Figure 6. Packet RMS duration distribution for sites M (top), H (middle), and N (bottom). The total number of packets detected (after filtering) is given in the upper right corner of each panel. Note the vertical axes are at different scales.

## Discussion

Previous reports on MFAS usage in the SOCAL Range Complex showed a lower level of activity at site M than at sites H and N, as in this report; however, only RL distribution plots similar to Figure 3 and cumulative RL distribution plots were shown, providing a relative-quantitative comparison between sites. The detection threshold for the earlier reports was so low that packets from sources at large but unknown ranges were counted and the likelihood of false detections with a low threshold was higher than for the $RL_{pp}$ ≥130 $dB_{pp}$ re 1 µPa threshold used in this report.

In the previous reports, temporal plots of MFAS activity were provided as cumulative hours per week and hourly bins per day over the specific reporting period. These plots provide a metric for relative MFAS activity at each site, but not between sites because they are based on the analysts' defined bouts, which have a detection threshold lower than the automated methods used. For example, it is possible to have similar temporal MFAS activity at site M and H, but with RL distributions lower for site M, which may result in less impact at site M due to the lower received and sound exposure levels than site H.

In the new approach, hourly, daily, and weekly time bins of analysts' defined bouts are not used. Instead, packets detected with a higher threshold (130 $dB_{pp}$ re 1 µPa) and filtered are counted and cumulative SEL are grouped by individual wave train events and plotted over multiple years. While counting the number of packets in each wave train can have the same problem with comparing MFAS activity between sites as the cumulative hours per week approach, cumulative SEL takes into account the received level and the number of packets for each wave train event, which provides a better measure of the total energy emitted over the event.

## Conclusion

The MFAS metrics and results developed in this report will be used in future studies on the potential impact of MFAS on marine mammals. Additionally, these results form a basis for further improvements on the approach used. For example, one improvement would be to replace the first step of analysts defining bouts with an automated method which would reduce personnel effort needed to monitor and quantify MFAS. Also, after packet detection, additional parameters could be measured, such as frequency content, number of sweeps and tones used, as these may be important variables for understanding impact on marine mammals. Furthermore, the frequency range of these studies needs to be expanded beyond 5 kHz to include MFAS from higher frequency sources, such as AN/SSQ-62 DICASS sonobuoys.

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