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Acoustical Issues and Proposed Improvements for NASA Spacesuits

Durand R. Begault[1] and James L. Hieronymus[2]

[1] Advanced Controls and Displays Group, Human Systems Integration Division (TH),
NASA Ames Research Center, Moffett Field, CA 94035 USA
Durand.R.Begault@nasa.gov

[2]Collaborative and Assistive Systems Group, Intelligent Systems Division (TC),
NASA Ames Research Center, Moffett Field, CA 94035 USA
jimh@email.arc.nasa.gov

ABSTRACT

This presentation reviews current acoustical issues relevant to the design of future NASA Spacesuits, based on measurements conducted in the current Mark III advanced prototype surface suit, and proposes solutions for improving voice communications. Methods for mitigating problems including noise from the air supply, structure-borne noise from the suit, and detrimental acoustical reflections are reviewed.

1. INTRODUCTION

New surface space suits are being designed at NASA for the return to the Moon and for Mars exploration. Space Suits have common characteristics that make adequate signal-noise ratios for speech and sound quality difficult to achieve. These include large Plexiglas helmets that cause multiple sound reflections of speech; fan and pump noise due to required air circulation; and arm and leg bearing noise and mechanical noise transmitted within the suit. In addition, the suits are closed pressure environments, so walking causes air movement noises heard as "swishing" sounds.

Previous designs used a "Snoopy" cap, which held the earphones in place, provided some padding and hair control and had a pair of boom microphones at the corners of the mouth. These systems have the advantage that the suit borne noise is not well transmitted though the body, and thus a minimum of mechanical noise corrupts the microphone signal. However, airborne noise is still a problem and, on occasion, a microphone has contacted an object inside the helmet and moved away from the mouth.

In this paper we discuss acoustic measurements of the present prototype planetary suit called the Mk. III.

Measurements of suit impulse-frequency response, noise levels during static and motion conditions were made. Multiple channel measurements of several spoken phrases typical of those given to a natural speech voice recognition system were spoken by the suit subject and were also preliminarily analyzed.

The first section discusses the experimental set up for the measurements. The second section discusses the result of the impulse response measurements. The third section discusses the noise levels generated in the suit and their likely sources. Finally, the characteristics of the speech recorded from the subject using a "Snoopy" cap with an advanced active noise canceling microphone and a series of fixed microphones around the helmet ring are examined. The possibility of using beam-forming microphone arrays to provide virtual microphones positioned in front of the subject's mouth as the head is moved is also considered.

2. SUIT CHARACTERISTICS

The Mk. III prototype surface suit has been underdevelopment for over a decade. It consists of a hard torso which includes the helmet, and soft material arms and legs. Entering or donning the suit is accomplished though a back hatch, which also holds the life support system. The boots and gloves are specially designed for and dexterity of movement in a vacuum environment. Figure 1 shows a photo of the suit at its present state of development.

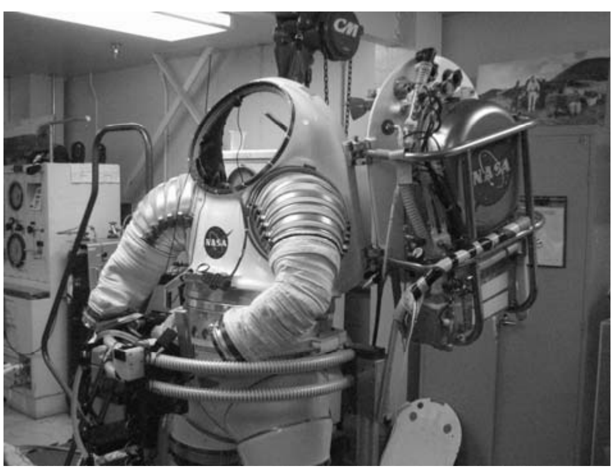

Figure 1: Mk. III Prototype Surface Space Suit

Figure 2: Helmet bubble attached to the Mk. III suit. The subject is donning the 'Snoopy cap', to which th Andrea ANC-700 noise canceling microphone is attached. The measurement microphone is visible at the upper left side of the head.

A liquid air, life support backpack provides air and cooling for the suited subject for approximately one hour. Water is circulated from a heat exchanger on the backpack to a liquid cooling garment (long underwear with small water tubes woven into the fabric) to keep the person at a constant, comfortable temperature. The evaporation of the liquid air provides cooling for the liquid, and approximately 80% of the liquid air is used for cooling. The backpack can be recharged with liquid air with a person inside so that the total mission time can be up to 3 hours. On Earth, however, the suit and backpack weigh around 200 lbs, so subject fatigue limits the in suit time in practice.

Acoustically, the hard torso space suit and helmet bubble form a cavity in which reflections from the bubble and the back of the suit hatch give the experience of talking inside of a can. The resonances inside the suit system are very pronounced and the reverberation effects can be shown to degrade speech intelligibility.

3. EXPERIMENTAL SETUP

Two types of microphone systems were evaluated in the suit. The first type was a head mounted active noise canceling microphone (Andrea ANC-700) attached to a

Snoopy cap. This microphone was evaluated as a baseline condition. The second type was an electret microphone (YOGA EM 060 omni-directional with 3 v power). Three to four (when the Snoopy cap is not used) of these electret microphones were positioned around the helmet-mounting ring of the suit on foam rubber mounts. These microphones were evaluated individually and against the baseline microphone for sound quality, noise immunity and signal-noise ratio. They were also to gather relevant data towards design of beam steering microphone arrays and noise-canceling DSP algorithms.

Because of the close fit of the subject's head in the helmet area, the electret microphones could not be placed at the top or bottom position (12 or 6 o'clock). Since there is an air inlet on the top of the hatch blowing air down the helmet faceplate to scrub out carbon dioxide, it is best to have the microphones in the lower hemisphere of the mounting ring. For the first set of measurements we used the 7, 9 and 10 o'clock positions. Figure 3 shows the microphones *in situ*. Note that the positions of these microphones are outside the direct path of the mouth.

Two reference microphone systems (Bruel and Kjaer 4155 ½" microphone, and 4101 in-ear binaural microphone) were added to the suit systems to provide calibrated measurements of the acoustic characteristics. The subject wore the binaural microphones, and the subcomponents (preamp and DAT recorder) were mounted on the rear hatch of the suit. The ½" reference microphone was connected via an umbilical to a sound level meter (Bruel and Kjaer 2230); the AC output sent a line-level signal that was stored directly to a computer via fire wire connection (Edirol FA-66; Hairersoft Amadeus II).

Sine sweeps were generated by the laptop computer system (Fuzzmeasure) and played into the suit loudspeakers in order to measure the impulse response of the suit system and its frequency response. Synchronous averaging of multiple sine sweeps was used in order to improve the signal-noise ratio.

For speech analysis, the subject read a set of spoken dialogue system commands in each condition.

Measurements were made in five conditions, with the suit pressurized:

1) subject inside suit on the "donning stand", a device that holds the suit in place,

2) subject standing (volume of the suit changes relative to when the subject is inside the suit on the donning stand).

3) subject walking (footfall impacts and hip bearing noise),

4) subject walking and moving arms (shoulder bearing noise plus walking noise)

5) subject seated in a rover seat (volume change and head lower in helmet area).

The setup of the audio recording and intercom system is shown in Figure 4. Two stereo microphone preamplifiers (Shure F24) are mounted on the backpack for the electret microphones. The approximate cable lengths between the electret microphones and the preamps are one meter. Then the four signals are sent at line level down a 25 foot umbilical to an A/D converter and fire wire computer interface (MOTU Traveler) and stored directly to a laptop disk with a multi-channel digital recorder (Sony Vegas).

4. MEASUREMENTS OF SUIT LOUDSPEAKER AND BACKGROUND NOISE

Figures 5 and 6 indicate characterizations of the acoustic environment from the reference microphone systems. Figure 5 indicates the background noise levels in octave bands for the binaural microphones and the ½" microphone, in octave bands, A-weighted, and linear levels. The A-weighted level of the background noise is about 70 dB(A), a level at which a talker would normally use a raised voice in order to be heard.

Figure 6 shows plots of the internal helmet loudspeaker frequency response used for communicating with the subject. Two 3.5" diameter thin-profile (1.125") loudspeakers are mounted in the rear hatch door behind the head. (A 2" loudspeaker was replaced due to insufficient response below 400 Hz). The first measurement (plot A) was made 2" from the loudspeaker with the hatch door open, representing the baseline frequency response of a single loudspeaker. The second measurement (plot B) was made with both loudspeakers with the hatch door closed, in an empty suit. Finally, a measurement was made with a subject in the suit and with pressurized air (4.3 PSI) (plot C). The suit enclosure and helmet contribute several frequency notches in the speech range, from 500 Hz - 3 kHz, and are more severe with the subject present.

Figure 3. Suit with helmet bubble removed, showing head-mounted noise-canceling microphone on Snoopy cap, and the electret microphones as placed along the helmet ring (arrows). The ½” measurement microphone is on the right side and penetrates into the helmet bubble approximately 4”. Binaural microphones are on the ears below Snoopy cap and are therefore not visible.

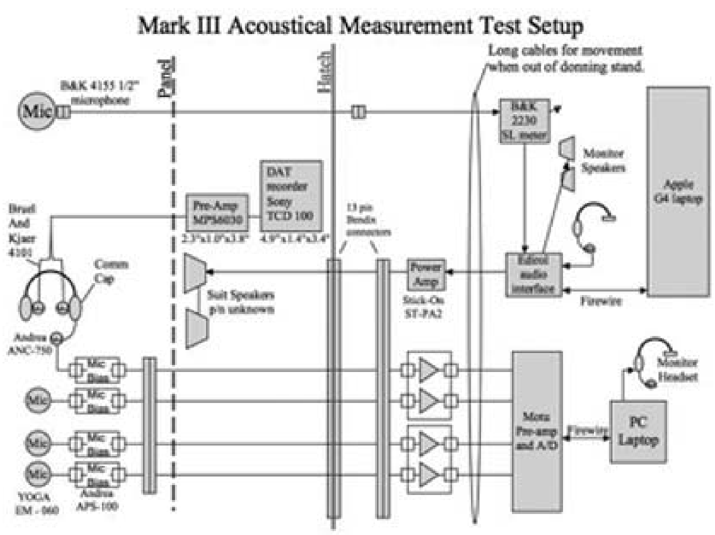

Figure 4. Diagram of test set-up (*courtesy Craig Bernard, NASA JSC).*

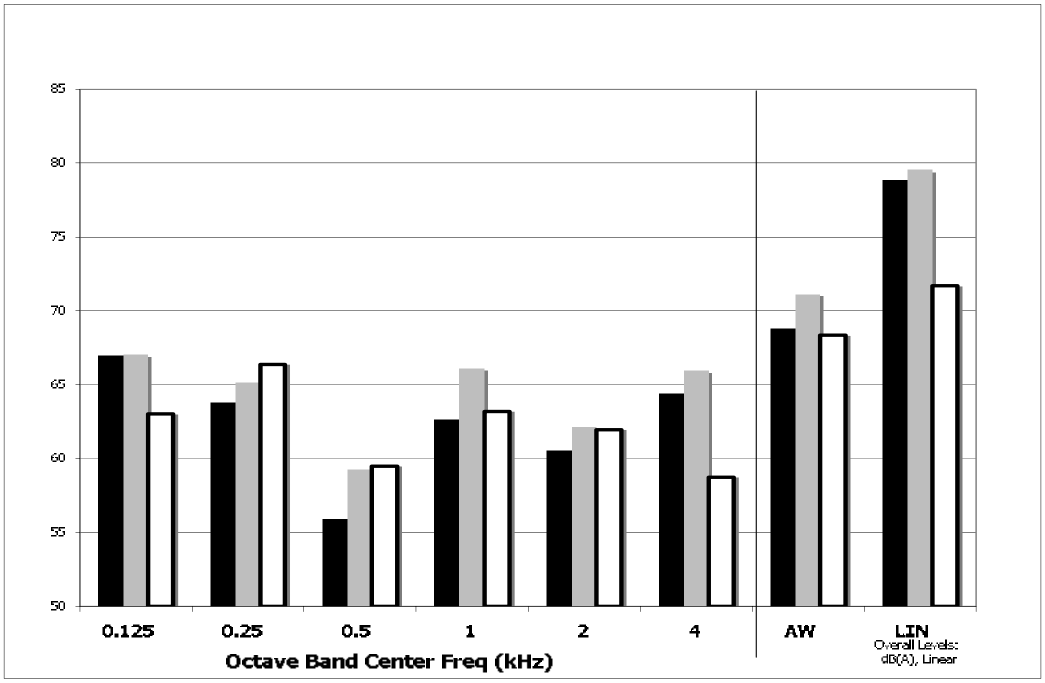

Figure 5. Background noise level. Filled and shaded bars: binaural measurement; unfilled bars: ½" microphone measurement. Average A-weighted level = 70 decibels.

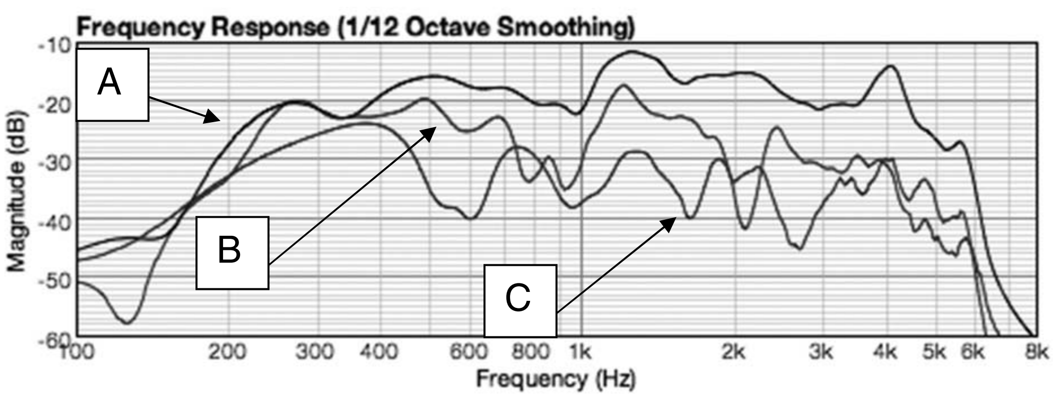

Figure 6. Effect of enclosure on loudspeaker frequency response. See text for explanation.

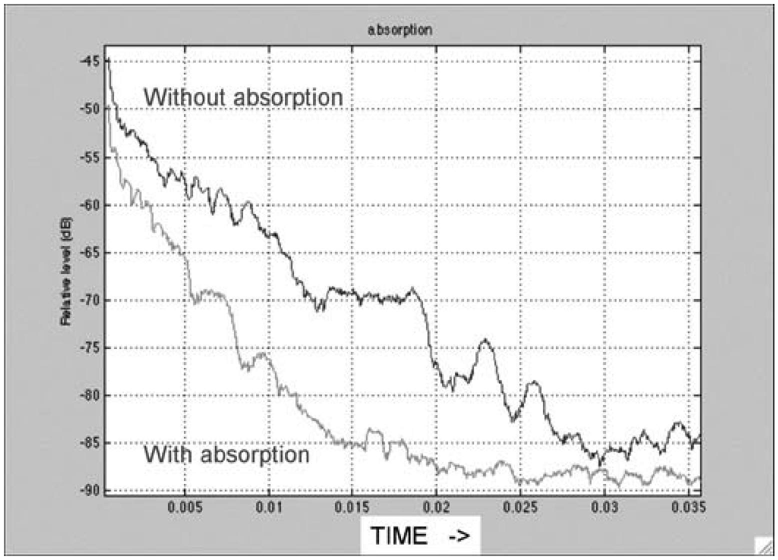

Figure 7. Effect of absorptive material: time domain decay of impulse response derived from sine sweep.

With the reflections from the helmet bubble present, there are significant response notches between 600 Hz- 3 kHz. Adding acoustical absorption to the back of the hatch (dense 2” foam) minimized these reflections somewhat. Figure 7 shows two integrated decays of the impulse response measured using the suit loudspeakers and ½” microphone, with the suit closed. The lower line shows with absorption, the upper line, without. Clearly, the presence of absorption helps to mitigate some of the early reflections that result from the hard surfaces of the suit interior as well as from the concave surface of the helmet bubble.

5. RESULTS OF COMMUNICATION MICROPHONE MEASUREMENTS

For the first set of measurements, the subject was fitted with the Snoopy cap and the other microphones placed as shown in Figure 3. In other tests, additional microphone positions and types were evaluated (not reported here). The following illustrates some comparative analyses of the different communication microphone signals in terms of noise immunity and signal-noise ratio.

Critical listening and spectral analyses indicated that each of the electret microphone signals had a significantly different timbre as a function of the microphone position. The signal sounded more ‘muffled’ as the microphone position went from 7 to 10 o’clock, and all were somewhat inferior in quality to the noise-canceling Snoopy microphone. This is due to several factors, including proximity of the microphone to the mouth, proximity of the microphone to the air flow, and the influence of reflective surfaces.

Besides noise from the airflow described in Figure 5, there is noise caused by foot impact and mechanical noise from the suit joints. Figure 8 illustrates the influence of foot impact noise on the signal from different microphones. Three time-domain waveforms corresponding (top to bottom) to the Snoopy cap microphone and the 7:00 and 9:00 electret microphones is shown. The subject is walking, while on the right portion the person is walking and talking. The circled areas indicate pauses between speech, for comparison of the peak signal levels from each of the microphones.

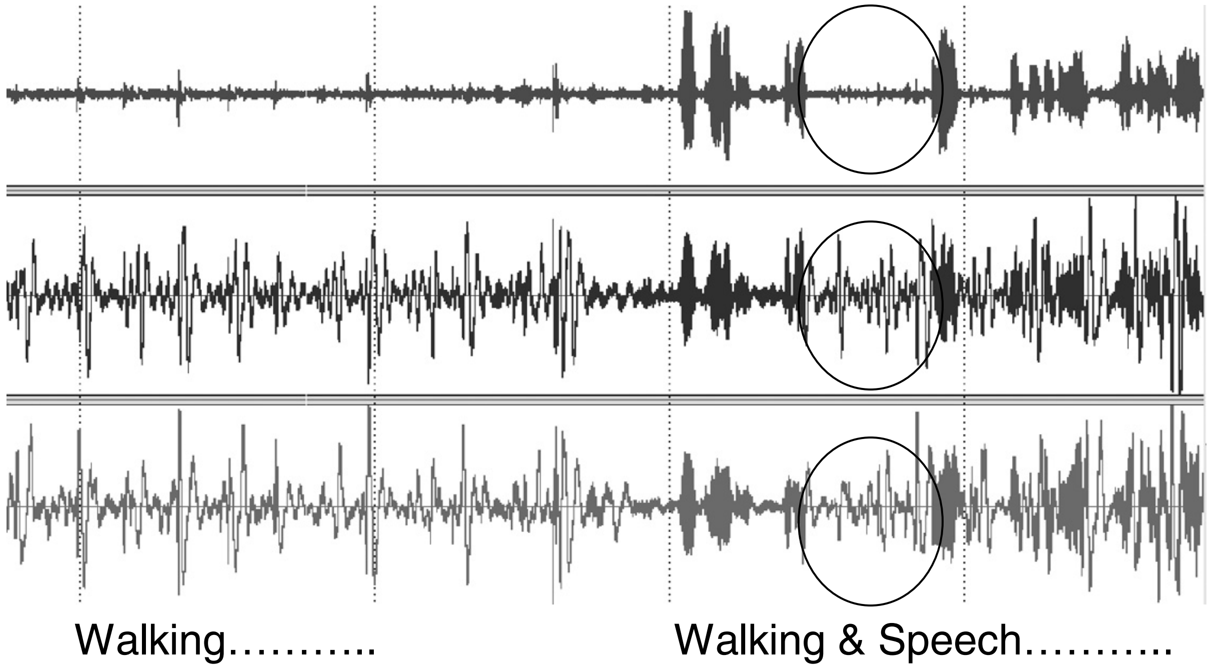

Figure 8. Time-domain waveform of subject walking and talking, showing influence of mechanical noise. Top: Snoopy cap microphone. Middle and bottom: electret microphones at 7:00 and 9:00. Circles show pauses between spoken phrases.

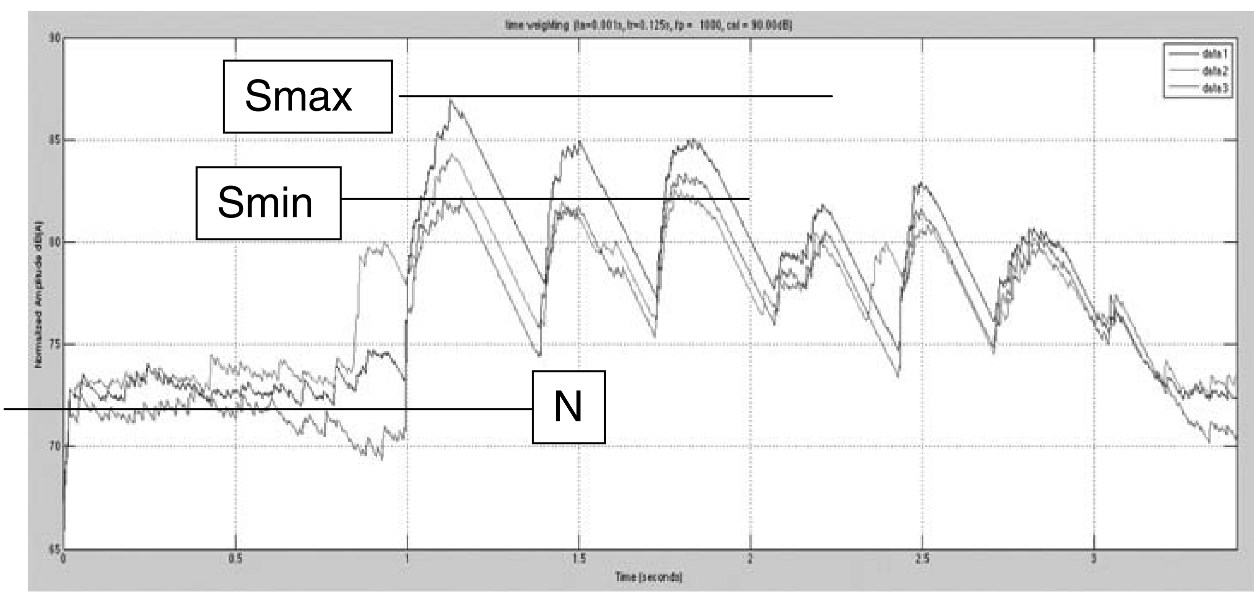

Figure 9. Signal-noise ratio for different microphones tested (A-weighted, fast time integration display) for speech. Smax- maximum signal levels; Smin- minimum signal levels; N – noise floor.

Figure 8 indicates that the foam-mounted microphones are influenced by footstep noise via structural vibration while the head-mounted Snoopy cap acts as a shock absorber. Some of the reduced noise level may also be due to the noise canceling aspects of the Snoopy microphone. Figure 9 shows signal-noise ratios for the same microphones (different recording time), using fast (.125 ms) time integration and A-weighting. The signal-noise ratio difference is about 5 dB between the "best" microphone (Snoopy cap) and the "worst" microphone (electret at 9:00).

Measurements of worst-case signal to noise ratios in the standing, walking and walking and waving arms conditions for different microphones and positions were computed. The results are shown in Table I. For the helmet mounted electret microphone at the 9 o'clock position the SNR was 16 dB for standing, -0.4 dB for walking and 0.7 dB for walking and moving arms. This means that the noise of footfalls is as loud as the speech for the electret microphones. For the Snoopy cap microphone, the signal-noise ratios were 19 dB peak for standing and 10.2 dB peak for walking.

Microphone	**Standing**	**Walking**	**Walking and Arms**
Snoopy noise canceling	19.5 dB rms 22.0 dB peak	11.9 dB rms 10.5 dB peak	11.8 dB rms 10.2 dB peak
Electret 7:00	11.91 dB rms 15.71 dB peak	0.3 dB rms 0.0 dB peak	0.2 dB rms 3.0 dB peak
Electret 9:00	15.5 dB rms 17.4 dB peak	-0.4 dB rms 0.0 dB peak	0.7 dB rms -1.9 db peak

Table I. Worst case signal-noise ratios for different conditions and microphone positions

The foot fall amplitude from all the microphones except the Snoopy cap is stronger than the speech signal. The foot falls are impulses which occur approximately every half second. If the foot noise occurs in the middle of an utterance, we would expect that the speech intelligibility would be lower for a brief period of time and the speech recognition performance would be lower. It is clear that most of this noise is suit borne, since the Snoopy cap microphone which is not attached to the suit picks up much less of this noise. Efforts are being made to reduce this noise by soft mounting the microphones and these will be reported in later experiments.

Clearly the Snoopy cap with ANC microphone reduces the static suit noise and provides isolation from walking noise, while the helmet ring mounted microphones with foam mounts do not. Improving the isolation of the helmet ring mounted microphones will be a future work, by examining compliant mounts of various types.

6. CONCLUSION

This presentation reviewed acoustical issues relevant to insuring adequate signal-noise ratio in speech communications in space suits. The design of future NASA spacesuits, based on measurements conducted in the Mark III advanced prototype surface suit, indicate that mitigation of missed words in speech recognition systems and overall speech intelligibility and sound quality will require careful design.

One likely way to provide performance comparable with the head mounted microphone is to use a beam forming microphone array, which places a virtual microphone at the mouth of the talker [1]. This virtual microphone tracks mouth motion by following the strongest signal. The technique uses phase and waveform correlation to find the optimal way to sum the signal from several microphones to produce the clearest sound. The beam steering technique involves advanced DSP to form the beam and then steer it to the strongest acoustic signal source. We plan to build a prototype of an advanced beam steering microphone array and test it in the Mk. III environment in future studies.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

[1] G. W. Elko, *Superdirectional Microphone Arrays*, **Acoustic Signal Processing for Telecommuncation**, Kluwer Academic Publishers, Chapter 10, pp. 181-237. (March 2000).