Operation of Third Generation JPL Electronic Nose on the International Space Station

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ABSTRACT

The Third Generation ENose is an air quality monitor designed to operate in the environment of the US Lab on the International Space Station (ISS). It detects a selected group of analytes at target concentrations in the ppm regime at an environmental temperature range of 18 - 30 °C, relative humidity from 25 - 75% and pressure from 530 to 760 torr. This device was installed and activated on ISS on Dec. 9, 2008 and has been operating continuously since activation. Data are downlinked and analyzed weekly. Results of analysis of ENose monitoring data show the short term presence of low concentration of alcohols, octafluoropropane and formaldehyde as well as frequent short term unknown events.

INTRODUCTION

An electronic nose has been developed at the Jet Propulsion Laboratory (JPL) to monitor spacecraft cabin air for anomalous events such as leaks and spills of solvents, coolants or other fluids with near-real-time analysis [1-5]. It is an array-based sensing system which is designed to run continuously and to monitor for the presence of selected chemical species in the air at parts-per-million (ppm) to parts-per-billion (ppb) concentrations. The JPL ENose uses an array of 32 semi-selective chemical sensors; sensing materials are primarily polymer-carbon composite films, but also include inorganic and carbon nanotube sensors.

There have been three phases of development of the JPL Electronic Nose. In the first phase, a device capable of detecting, analyzing and quantifying ten

analytes at the 1-hour Spacecraft Maximum Allowable Concentration (SMAC) was developed. This device was tested successfully in 1998 on Space Shuttle flight STS-95 [4]. In the second phase, the ENose was miniaturized and the capabilities were significantly expanded to include 21 analytes and detection at varying humidity and temperature. The Second Generation ENose was tested extensively on the ground and was demonstrated to be able to detect, identify and quantify the 21 analytes at or below their 24-hour Spacecraft Maximum Allowable Concentrations (SMACs° [6]. This Third Generation ENose, shown in Figure 1, was built as a Technology Demonstration instrument and is now in a six-month demonstration period aboard the International Space Station (ISS).

The Third Generation ENose is designed to detect, identify and quantify eleven chemical species, including seven organic compounds as well as formaldehyde, ammonia, mercury and sulfur dioxide. The chemical species and the concentrations targeted for this Technology Demonstration are shown in Table 1. Tier 1 is chemical species for which there is a requirement to detect, identify and quantify with a 90% success rate. Tier 2 is chemical species for which there is a requirement for detection, identification and quantification with an 80% success rate. Detection of the Tier 3 species, formaldehyde, was a goal in this program.

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Figure 1: The Third Generation ENose. The Sensor Unit developed in the Second Generation, is enclosed in the Interface Unit, which is connected to EXPRESS Rack 2 on ISS.

The ENose was tested in the laboratory before it was launched on STS-126 in November, 2008. Success rates for detection, identification and quantification, and requirements on the ENose, have previously been discussed in detail [7]. Results of ground testing showed an overall success rate for detection, identification and quantification of all analytes of 87% under nominal temperature and humidity conditions and 83% over all conditions.

The JPL ENose has been designed to operate in the environment of the US Lab on ISS. It detects targeted analytes at concentrations in the ppm regime at an environmental temperature range of 18 - 30 °C, relative humidity from 25 - 75% and pressure from 530 to 760 torr. It is designed to run continuously by pulling ambient air over the sensing array. Data analysis is done on-board, in quasi-real time, and results are stored for later review. This paper will discuss the data acquired by the ENose during its period of operation on the EXPRESS Rack on ISS, and results of on-board data analysis.

Table 1: Analyte List and Target Detection Concentration; mg/m³ is a pressure independent unit; ppm is for 1 atm.

	ANALYTE	QUANT. TARGET (mg/m ³)	QUANT. TARGET (ppm)
TIER 1	Ammonia	3.5	5.0
	Mercury	0.080	0.010
	Sulfur Dioxide	3.0	1.0
TIER 2	Acetone	500	200
	Dichloromethane	35	10
	Ethanol	940	500
	Freon 218	150	20
	Methanol	13	10
	2-Propanol	240	100
	Toluene	60	16
	Formaldehyde	0.12	0.10
TIER 3	Formaldehyde	0.12	0.10

THE JPL ENOSE ON ISS

The JPL ENose was launched on STS-126 on November 14, 2008. It was unstowed, installed on EXPRESS (EXpedite the PROcessing of Experiments to Space Station) Rack 2 in the US Lab and activated at 08:46 GMT, December 9, 2008. A photo of the ENose installed on EXPRESS Rack 2 is shown in Figure 2. Installation on an EXPRESS Rack allows an experiment to be tested in a realistic space environment. Instrument health and status data are transmitted from the EXPRESS Rack to ground one time per second; it was possible for ENose to be designed to fold raw sensor data into the health and status data, and so we are able to capture real time ENose sensor as well as instrument health data on the ground.

Within minutes of activation, data from ENose were received at JPL. Data are streamed through a Graphical User Interface (GUI) designed for the process. Data which are streamed include both Health and Status data for EXPRESS Rack monitoring and sensor data and device health information. The data stream and can be read when there is Ku Band signal from space to ground. Figure 3 shows a snapshot of the GUI as it is running on a JPL local computer.

Data acquired through the ENose GUI are saved on a local computer hard drive. Full files are downloaded from ENose to a JPL local computer during weekly command windows, via the Huntsville Operations Support Center (HOSC) at Marshall Space Flight Center; data files downlinked include log files, data files and on-board data analysis. These files are saved on a local computer at JPL for review and analysis.

Shortly after activation, the unit was checked for nominal operation (LEDs lighted correctly, screen on). In addition, a similar status check is performed by a crew member weekly. In addition to the weekly status check, there is a bimonthly confirmation event performed by a crewmember. This confirmational event is performed to ensure that ENose is operating nominally and that sensors respond as expected. A crew member holds a disinfectant wipe in front of the ENose inlet for one minute and notes the time. ENose team members at JPL check the analysis of ENose data to confirm that the event has been detected by ENose.

In addition to downlinking commands, commands may be sent to change activity or to control parameters on the ENose. For example, the temperature in the ENose sensing chamber was slightly higher than expected, by about 2°C. After finding this higher temperature, we tested new thermal control parameters in the laboratory then uploaded a new thermal control file to ENose during a weekly command window. This new file now keeps the ENose sensing chamber at a temperature consistent with optimum operation.

DATA ANALYSIS APPROACH

Data from the ENose are recorded for each individual sensor as resistance versus time. Because the ENose is designed to function as an event monitor, the data are analyzed as change in resistance vs. time. Individual sensor resistances are recorded simultaneously, with a point being taken every twenty seconds. While it would be possible to take data more or less frequently than three times a minute, this data rate has been established as an optimum rate to show fairly rapid changes in the environment without overwhelming computer memory with data. Our data analysis approach defines an "event" as a change in the composition of the environment which lasts longer than ten minutes, or thirty points at the standard data rate, in part because events of duration shorter than ten minutes cannot practically be addressed or mitigated using either breathing apparatus or clean-up techniques. The data analysis algorithm needs about ten points (~ three minutes) to establish that resistance has changed significantly and reports a species and concentration, or classifies a change as unknown, once every five minutes.

The data analysis algorithm is a Levenberg-Marquardt non-linear least squares fitting approach to deconvolution of change in resistance across the sensing array into identification and quantification of the analyte causing response in the sensors. The analysis approach has been discussed in detail previously [8, 9]. Data used to develop the algorithm, and provide the coefficients applied to the data were developed in the laboratory through training sets under a variety of conditions [7]. The data analysis program was developed and validated in MatLab, then translated to C for use in the ENose on-orbit. Analysis runs on orbit and results are recorded in a file separate from the sensor resistance file.

On downlinking data, files are processed by converting them to text files of sensor resistance and of operating parameters such as temperature, humidity, pressure, voltage and current. Sensor resistance files are analyzed using the MatLab analysis program, and the results compared with the on-orbit analysis.

Data are also plotted as change in resistance vs. time (as shown in Figure 4), for ease of visualization of ENose monitoring, although this step is not necessary, as analysis requires only the raw resistances.

INITIAL DATA FROM ISS

Humidity Cycles Initial data sets acquired by the ENose on ISS showed a periodic rise and fall of about 3 percent relative humidity with a period of 144 minutes. Figure 4a shows an example of a 24-hour data file, where the upper trace is percent relative humidity, as measured by a humidity sensor installed in the same chamber as the ENose sensors (y-axis on right), and the lower traces are normalized change in resistance of

eight polymer-carbon black sensors (y-axis on left; dR/R_0 where R_0 is set arbitrarily to the first point in the file.) This figure shows that sensor resistance change follows humidity change with little or no time offset. If the species detected had been one of the targeted species, there might be somewhat more of a time offset, but earlier work has shown that deconvoluted sensor response looks similar to that shown in Figure 4.

Figure 4b shows the results of the automated analysis of sensor data. The analysis program detected a rise and fall of about 1000 ppm water on a 144 minute period, with little or no time delay. This plot shows percent relative humidity on the left y-axis and ppm change in water content on the right y-axis. The two axes are set to span the same range; i.e. a change of 4.5 percent relative humidity is equivalent to a change of 1700 ppm water.

Earlier laboratory work on the ability of ENose to detect changes in the environment showed that changes of 5 – 10 percent relative humidity over short periods would interfere with the ability of the ENose analysis program to deconvolute the data and recognize target species; however, the humidity changes detected on ISS occur over 20 – 30 minutes and do not interfere with the data analysis process.

The periodic rise and fall of humidity was present for the first several days of operation on ISS, then stopped, and humidity and temperature were steady. It is possible that the periodic humidity change is caused by the operation of the Carbon Dioxide Removal Assembly (CDRA), which was under test at the time ENose was activated. The CDRA has a 144 minute half cycle and can expel humidity during the desiccant bed regeneration [10].

Confirmational Event The first confirmational event for ENose was done about two weeks after activation. A crew member held a disinfectant wipe in front of the ENose air inlet for one minute, to provide a stimulus to the sensors of a known species at a recorded time. The first confirmational event was easily seen in the sensor resistance data and was detected by the automated analysis program. The analysis program reported the stimulus as "unknown." The signature of the disinfectant wipe used in the confirmational event is not included in the ENose data library, as this event gives us the opportunity to confirm that ENose is able to report unknowns. Subsequent to this first confirmational event, a crew member has performed one once every two weeks. They have not been mis-identified as a targeted species.

EVENTS REPORTED

In normal operation, very few changes in environment which might be considered to be events are reported. The source of these reports is generally crew observation. There are grab samples taken in the US Lab of ISS about once a month. Analysis of those samples lags considerably in time from when they are taken because they must be transported to the ground and analyzed at Johnson Space Center.

Previous work in testing air quality instruments on ISS has included the Volatile Organics Analyzer (VOA) from NASA and the Analysing Interferometer for Ambient Air (ANITA) from the European Space Agency [11]. VOA measurements are taken up to a few times a day, and so provide a snapshot of the presence (or absence) of some forty chemical species, but does not give insight into air constituent changes lasting less than several hours. ANITA measurements are taken more frequently, and the instrument is designed to run continuously. However, measurements are reported about forty minutes apart, and so would not give insight into changes lasting less than one or two hours.

Results from ANITA experiments showed that there was much greater fluctuation in the composition of air in the US Lab than had previously been thought [11]. In particular, the ANITA experiment showed a persistent presence of low-concentration Freon 218 (octafluoropropane) with occasional spikes in concentration. [11]

With this knowledge, we expected that we might see changes in Freon 218 concentration in the environment, along with other small organic molecules previously measured in the ISS atmosphere, such as alcohols and formaldehyde.

Table 2 is a complete list of all events detected in the period December 9, 2008 through April 7, 2009. As can be seen in the table, the majority of events last less than one hour, and several are less than 30 minutes. There are several reports of “unknown” species causing a stimulus to the ENose sensors. The identity of these unknowns has not yet been unraveled. The ENose team is working to determine whether there is a pattern in the time and length of appearance and the identity of the unknown species. We have not been able to establish a pattern in time of the appearance of the targeted species on the table. It would be interesting to compare ENose results with results of parallel measurements of other instruments, such as ANITA or VOA.

Table 2: All events detected in US Lab on ISS and identified by ENose ; Dec 9, 2008 through April 7,

	Date	Conc (ppm)	Start Time (GMT)	Finish Time (GMT)	Duration (hr:min)
Ethanol					
	28-Dec-09	800	10:02	10:51	0:49
Methanol					
	3-Jan-09	10	11:17	12:01	0:44
	17-Jan-09	3	18:47	19:05	0:18
	29-Jan-09	40	21:19	22:49	1:30
	6-Feb-09	8	4:28	5:02	0:34
	8-Feb-09	3	13:50	14:22	0:32
	14-Mar-09	3	1:44	2:16	0:32
	16-Mar-09	3	2:55	3:27	0:32
	31-Mar-09	8	16:28	17:07	0:39
	2-Apr-09	17	9:26	9:48	0:22
	3-Apr-09	19	16:40	17:17	0:37
	4-Apr-09	6	11:30	12:01	0:31
Formaldehyde					
	17-Jan-09	0,20	14:34	15:24	0:50
	12-Feb-09	0,20	23:11	23:48	0:37
	13-Feb-09	0,20	2:37	3:12	0:35
	14-Feb-09	0,20	11:32	11:55	0:23
	14-Feb-09	0,20	16:23	16:49	0:26
	16-Feb-09	0,20	6:45	7:28	0:43
	17-Feb-09	0,20	11:46	12:20	0:34
	19-Feb-09	0,19	6:57	7:28	0:31
	25-Feb-09	0,18	13:48	14:28	0:40
	26-Feb-09	0,16	6:44	7:37	0:53
	27-Feb-09	0,19	13:00	13:56	0:56
	3-Mar-09	0,20	22:59	23:41	0:42
	4-Mar-09	0,20	6:39	7:08	0:29
	7-Mar-09	0,20	10:50	12:17	1:27
	9-Mar-09	0,18	3:44	4:32	0:48
	27-Mar-09	0,19	9:17	10:35	1:18
	27-Mar-09	0,19	21:34	22:16	0:42
	28-Mar-09	0,20	14:36	14:57	0:21
	6-Apr-09	0,22	2:25	2:45	0:20
Freon 218					
	25-Jan-09	90	20:17	20:34	0:17
	3-Feb-09	80	11:30	12:16	0:46
	4-Feb-09	90	20:54	23:03	2:09
	5-Feb-09	90	20:57	22:57	2:00
	12-Feb-09	15	19:10	19:27	0:17
	13-Feb-09	15	15:29	16:13	0:44
	18-Feb-09	6	0:17	1:35	1:18
	8-Mar-09	90	7:31	7:59	0:28
	8-Mar-09	15	11:31	12:10	0:39
Unknown (not conf event)					
	28-Dec-09		16:54	17:12	0:18
	9-Jan-09		13:28	14:34	1:06
	13-Jan-09		11:02	11:30	0:28
	13-Jan-09		20:37	21:52	1:15
	15-Jan-09		23:01	23:24	0:23
	27-Jan-09		12:23	12:53	0:30
	27-Jan-09		21:27	23:18	1:51
	29-Jan-09		11:02	12:09	1:07
	30-Jan-09		1:33	3:32	1:59
	30-Jan-09		4:37	4:57	0:20
	30-Jan-09		23:33	1:35 (31 Jan)	1:02
	1-Feb-09		2:25	4:52	2:27
	2-Feb-09		13:46	14:54	1:08
	3-Feb-09		14:04	15:27	1:23
	4-Feb-09		5:12	5:43	0:31
	4-Feb-09		6:07	6:43	0:36
	7-Feb-09		12:58	13:30	0:32
	8-Feb-09		1:53	3:33	1:40
	9-Feb-09		11:02	11:46	0:44
	9-Feb-09		22:40	23:59	1:19
	21-Feb-09		12:10	12:41	0:31
	26-Feb-09		11:01	11:34	0:33
	4-Mar-09		10:45	11:01	0:16
	13-Mar-09		0:02	1:55	1:53
	14-Mar-09		3:31	4:21	0:50
	26-Mar-09		0:42	1:05	0:23
	26-Mar-09		7:08	7:29	0:21
	26-Mar-09		10:20	10:40	0:20
	29-Mar-09		6:54	7:13	0:19
	7-Apr-09		21:13	21:30	0:17

As we do not have insight into minute-to-minute activities in the US Lab, we are not in a position to comment on the source of the events recorded..

Figure 2: The ENose deployed on ISS; it is located on EXPRESS Rack 2, on the “ceiling” above a hatch (circled in red). The picture on the right shows the green power light is on. The screen is dimmed, and so does not show the time, humidity and pressure in this picture. The screen can be “woken up” by pressing one of the front panel keys.

Figure 3: ENose GUI, showing instrument operating parameters such as voltage, current and power; environmental information such as temperature and pressure; interior temperature; sensor raw resistances; heater states.

Figure 4: ENose sensor data taken on ISS (A) Eight sensors plotted with change in resistance against the initial point in the trace. The trace on the top is relative humidity as measured by a humidity sensor in the sensing chamber of ENose (right axis). (B) Relative humidity in the sensing chamber varied by about 3% RH with a period of 144 minutes. The analysis program detected a change of about 1000 ppm for each variation. The two axes, Relative Humidity and ppm Water Reported, are scaled to be the same amount of water; i.e. 4.5% RH is 1700 ppm water. Water detection is used as an example because it is the species seen most frequently and repeatedly on ISS.

CONCLUSION

As of this writing, ENose has operated continuously for some 3200 hours on ISS. ENose has detected and reported several events lasting from 15 to 120 minutes. The majority of events are less than 60 minutes in length. None of these events might be considered to be a major event, as in all cases the concentration was at or below the 24 hour SMAC. There have been no reports by the crew of major events of species which are on the ENose target list.

ENose has detected several low concentration; short-lived events of methanol, ethanol, Freon 218 and formaldehyde. ENose analysis has also reported ammonia at 1 ppm, but it is not reported in Table 2 because it is below the ENose target range. In addition, there have been several events classified as "unknown." To date, it has not been possible to characterize any of the events as happening at the same time of day. While some of the unknown events appear to be caused by the same species; as evidenced by a similarity of sensor response signature from one event to another, it has not been possible to detect a pattern in their occurrence.

Interestingly, in addition to octafluoropropane; ANITA reported frequent presence of sulfur hexafluoride, which is not an ENose target species. This compound may be responsible for some of the reported unknown events, as it would be expected that ENose sensors designed to detect octafluoropropane would respond to SF₆. Finally, ANITA reported detection of three other species from the ENose target list, ammonia, methanol and ethanol [11], all of which are reported by ENose. The concentrations reported by ANITA are averaged over time, and are well below those seen as events by ENose. These average concentrations are consistent with occasional spikes into the ENose detection range.

Further work in analyzing data from the ENose on ISS will consider the results reported by ANITA to determine whether any of those species are responsible for the unknown events reported by ENose. In addition, work in classifying the unknown events by functional group and by applying models of sensor-analyte response [12, 13] is underway.

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