Integration of Chem/Bio Sensor Systems into Life Detection Missions

Authors:
Allie C. Fox (NASA Glenn Research Center/HX5 LLC; allison.c.fox@nasa.gov)
Jeff Balcerski (Kent State University)
Chris Bradburne (JHU Applied Physics Laboratory)
Christoper Carr (Georgia Institute of Technology)
Peter J. Hesketh (Georgia Institute of Technology)
Gary Hunter (NASA Glenn Research Center)
Noam Izenberg (JHU Applied Physics Laboratory)
Tibor Kremic (NASA Glenn Research Center)
C. C. Liu (Case Western University)
Richard Quinn (NASA Ames Research Center)
Aaron Regberg (NASA Johnson Space Center)
Antonio Ricco (NASA Ames Research Center)
Cosigners:
Natasha Johnson (NASA Goddard Space Flight Center)
Bronwyn L. Teece (NASA Jet Propulsion Laboratory)
Bethany Theiling (NASA Goddard Space Flight Center)

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1. Introduction and Background

The definitive detection of life beyond Earth will likely require multiple measurements that provide individual lines of evidence for extant or extinct life. Astrobiology-focused planetary missions will need to select technologies that are capable of both direct detection of *in situ* biosignatures (i.e., biogenic organic compounds or minerals, elemental or isotopic patterns, microfossils, etc.) and provide a complete assessment of an environment's habitability and biosignature preservation potential (*1)*. Selecting a suite of instruments capable of achieving the breadth of measurements needed while balancing power, mass, and size concerns can be a significant challenge for life detection missions. The integration of chemical/biological sensors into instrument suites can help meet these challenges by providing low mass and power options to complement and/or direct more power and time intensive analyses such as mass spectrometry or spectroscopy, which have higher power demands and require more time-intensive analyses.

For this discussion, sensors that measure the chemical or biological properties of the environment will be described as chem/bio sensors and encompass a range of transduction mechanisms and sensing approaches ranging from electrochemical, optical, mechanical, and electrical (*2-6*). At a basic level, chem/bio sensors consist of a receptor and physicochemical transducer. The electrical signal produced by the chemical reaction that occurs between the receptor and the analyte of interest is converted into a qualitative or quantitative signal. Because the receptor element can be tailored to a variety of organic and inorganic species, chem/bio sensors have been developed for a wide variety of analytes and are routinely used in environmental, biomedical, and food safety applications. Further, the integration of these sensor transducers into compact Smart Sensor Systems as described in (*7*), that include integrated intelligence and can be fully self-contained, increase the quality of the data provided and improve the ability to integrate into applications.

While significant progress has been made in chem/bio sensor development that make them ideal for planetary exploration including miniaturization, sample preconditioning, and increasing capabilities (*2-6*), they have not been routinely integrated into life detection and astrobiology applications. **Here, we suggest that the versatility of chem/bio sensor systems combined with their high sensitivity and low size, weight, and power consumption (SWaP) make them an attractive option for instrument suites on astrobiology and life detection focused missions.**

2. Integration of Chem/Bio Sensor Systems into Life Detection Missions

2.1 Direct Measurements of Molecular Biosignatures

There is significant overlap between analytes of interest for astrobiology and medical diagnostics. As a result, a variety of chem/bio sensors have been developed that target potential molecular biosignatures of interest for planetary exploration, such as amino acids, nucleic acids, DNA/RNA, and carboxylic acids**.** For example, tryptophan, an essential amino acid and important diagnostic molecule for mental health disorders, was detected at nanomolar concentrations in human serum by a biosensor that used a glassy carbon electrode coated with chitosan, a biopolymer that can be adapted to bind specific molecular targets *(8)*. The limit of detection can be further improved by advances in nanogap and nanopore sensing, which detect molecules by measuring the change in ionic current when they pass through a narrow pore or between a pair of nanogaps. For this type of sensor, single molecule detection of key biomolecules such as amino acids or DNA could be achievable (*9,10*). Another area of research growth is the application of nanomaterials to biosensing, either through use of the nanowires, nanotube, nanoparticles, as transduction elements for sensing using plasmonic properties of the particles or quantum dots for optical detection (*11*). They have been explored for detection of infectious diseases with selective binding to a target molecule and for cancer diagnostics. Application of chem/bio sensors in astrobiology-focused missions could be a powerful tool to detect potential molecular biosignatures, or organic carbon phases that may indicate a habitable environment. Given the low mass/low power requirements for individual sensors, it is feasible to use an array of sensors for a variety of organic compound classes to increase the chance of a successful detection.

2.2 Context Measurements for Habitability and Biosignature Preservation Potential

A critical aspect to evaluating the authenticity of a potential biomarker is determining if the environment is conducive to its production and preservation *(1*). Chemical evidence of habitability (i.e., available energy to support metabolic activity, bioessential elements, organic carbon etc.) and preservation processes (i.e., absence of oxidation and/or radiolysis products) are detectable by chem/bio sensors. For example, the Wet Chemistry Laboratories (WCL) on the Phoenix Lander used an array of ion-selective electrodes to detect ions leached from Martian soils. A key finding from the WCL experiments was the detection of perchlorate, a strong chemical oxidant, which indicated that Martian soils are highly reactive and may not readily preserve molecular biosignatures *(12*). This finding was critical to understanding the results of the Viking biological experiments and interpreting the presence of chlorinated hydrocarbons detected by the SAM instrument onboard the Curiosity rover (*13, 14*). Similarly, the detection and quantification of hydrogen variations over spatial and temporal scales on Titan could provide a better understanding potential prebiotic processes such as serpentinization and possible biological consumption. To address these science questions, a solid-state hydrogen microsensor is included in the instrument suite planned for Dragonfly (*15*). These examples highlight how chem/bio sensors can enable the search for biosignatures by providing important contextual information about the environment.

Electrochemical sensors are particularly well suited for characterizing aqueous environments, where sensor electrodes can be placed in solution without any sample preparation. A recent application of electrochemical methods has examined the potential for detection of nanomolar quantities of trace metals and micromolar quantities of certain nutrients (i.e., NH_3, NH_4^+, PO_4^{3-}, etc.) in terrestrial oceans *(16)*, and could therefore provide critical information about water/rock interactions and potential energy sources on Ocean Worlds. Currently, instrument concepts such as the Microfluidic Icy-World Chemistry Analyzer are being developed to leverage the power of electrochemical sensors in Ocean World exploration *(17).* Inclusion of chem/bio sensors on life detection missions could provide a low mass, low-cost option to better understand the environment where potential biosignatures are found, increasing confidence in their authenticity.

2.3 Detection of Terrestrial Contamination

Life detection missions are responsible for establishing a high degree of confidence that the potential biosignature signal is not terrestrial contamination. Established guidelines for outgoing spacecraft use the NASA Standard Assay to culture spore-forming bacteria as a proxy for total biological contamination, but recent technological advancements in the field of planetary protection may offer a more comprehensive look at contamination *(18)*. Chem/bio sensors, and in particular biosensors which use biological components to interact with analytes, are a potential avenue to improve current planetary protection procedures as they can be used to rapidly quantify microbial activity. In this application, spacecraft surfaces could be sampled via swab or wipe and then the sample would be submerged in solution to interface with the appropriate biosensor to monitor for microbial activity. Similar applications are already routine in the food safety industry, which rely on a range of sensors to monitor contamination in the food chain. For example, a variety of electrochemical biosensors have been developed to detect *Salmonella* in food samples (milk, chicken, water, human serum) with concentrations as low as 5 CFU (colony-forming unit) mL^{-1} *(19)*. Use of biosensors during spacecraft assembly and storage prior to launch could provide additional confirmation that biological contamination control requirements have been met. Unlike traditional culturing methods that are time and labor intensive, biosensors can provide rapid detection of microbial activity (minutes to hours vs. 48 hours for the NASA standard assay). While these technologies would need to be adapted to fit specific planetary protection needs (i.e., non-aqueous sampling, broader detection [see section 3.1]), the diversity of applications for monitoring microbial activity in the biomedical and food safety fields indicate this could be a promising technology for limiting biological contamination on life detection missions.

2.4 Enhancement of Science Outcomes through Targeted Sample Selection

Sample selection for life detection missions is not straightforward, as possible biosignatures and habitable zones may not be visually apparent. As a result, it can be difficult to strategically employ more power and time intensive measurements, such as mass spectrometry or spectroscopy. **Supplementing instrument payloads with a suite of targeted chem/bio sensors can maximize the science return of life detection missions by triaging samples that are more likely to host biosignatures.** Indicators such as disequilibrium concentrations of ions (i.e., nitrate/nitrite, sulfate/sulfite), presence of potential biomolecules (amino acids, nucleic acids, etc.), and/or the absence of oxidation/radiolysis products could prompt the use of more complex instrumentation. For planetary targets with shorter transit times, like Mars and Venus, a robust assessment of habitability requires measurements over a wide range of spatial and temporal scales. Such distributed measurements permit the characterization of locally-variable environmental conditions as well as quantification of chemical species with sufficiently low kinetic rates of reaction to prevent global equilibration. Thus, distributed regional or local data can be leveraged to provide important context to the globally-averaged data that are provided by a primary, comprehensive instrument suite (*20*).Conversely, for planetary targets with long communication times where science operations that rely on scientist input to select sample targets will not be feasible, data collected by chem/bio sensors could be used to guide autonomous science decisions (*21*).

3. Challenges and Future Work

3.1 Sensor Specificity/Sensitivity vs. Agnostic Targets

Most technological advances in chem/bio sensors for other applications are driven by increasing sensitivity and specificity. The latter, while beneficial for medical diagnostics and food safety, can be potentially problematic for astrobiology-focused missions that will not know *a priori* what analyte to target. This could be limiting for chem/bio sensors targeting molecular biosignatures, as the fundamental building blocks of extraterrestrial life may differ from Earth life. Similarly, applications of chem/bio sensors in the context of planetary protection are limited by the specificity of the sensors, as the source of contamination is unknown. While sensors that are too general may lead to false positives, employing sensors targeting molecular features, such as carbonyl or amine groups, or those that monitor changes in electrochemical activity over time may be a viable strategy. For example, semiconductor-based biosensors detect the dielectric change between capacitive electrodes that occurs due to the ionic cloud of cell membrane, providing a method to monitor real time changes in cell populations which could be useful in life detection and planetary protection applications *(22)*.

Alternatively, employing sensor arrays targeting multiple, distinct potential biomolecules is feasible given their low mass and power requirements. Combining sensor arrays with microfluidic systems can provide useful features including collection, sample reagent mixing, and reaction zones during sensing, in addition to control of flow, and filtration based upon molecular size distributions. A range of molecular targets can be delivered to an array of sensing elements, i.e., providing separation based upon properties such as size or charge into the measurement channels. Future work should focus on developing sensors that can offer versatility in detecting target analytes with an appropriate response time and determining the most efficient way to incorporate sensors and sensor systems into life detection science operations.

3.2 Integrating Chem/Bio Sensor Systems in Instrument Workflows

Coordinating optimization of different chem/bio sensors requires careful thought on integrated, upstream sample preparation systems. While some aqueous environment may not require extensive, if any, sample preparation, integration of chem/bio sensors in multi-faceted analyses needs to be considered. The physicochemical material requirements may be very different between methods, e.g., a receptor biological detector, a mass spectrometer which may require sample volatilization and derivatization, and a nanopore sequencer which may require a processed polymer library. Solutions range from splitting the samples into portions with distinct workflow fates to a combined physiochemical sample preparation that separates out the analytes in a combined workflow. Solutions are being developed, engineered, and tested *(23, 24*), and these need to be considered for SWaP, detector compatibility, and mission design considerations.

3.3 Stability and Ruggedization of Chem/Bio Sensor Systems

Adapting current sensor technologies for the harsh environment of space is required for their integration into spaceflight missions. Material selection for chem/bio sensors will depend on environmental factors such as high temperatures and pressures, exposure to ionizing radiation, and interactions with harsh chemical oxidants. For example, a range of chemical sensors, including the VfO_x sensor scheduled for DAVINCI, have been developed to measure the partial pressure of species near the surface of Venus. These sensors are composed of predominately ceramics and precious metals that can withstand the high temperatures of Venus *(25, 26).* For Ocean Worlds, exposure to ionizing radiation and chemical oxidants will be the major environmental challenges, particularly for biosensors. The biological compounds that interact with analytes in biosensors are labile, even in ideal radiation and chemical environments. More stable sensors suitable for potential biomolecule detection, such as nanogap sensors, should be the focus of future life detection research as they use stable materials like silicon nitride and gold nanoelectrodes. Continued development and testing of chem/bio sensors for harsh conditions will be needed to ensure their success in various planetary environments. Further, integration of individual transducers into a sensor system, including potential preconditioning of the sample while keeping low SWaP, will allow future mision implementation of these systems.

4. Summary

In the last ten years there have been significant advances in improving the stability, sensitivity, and specificity of chem/bio sensors for diverse set of applications. Integration of these sensors to astrobiology-focused missions can have significant benefits to life detection efforts, especially when used in tandem with other instruments. **Chem/bio sensors can be used to (1) directly detect organic compounds of interest, i.e., potential biomolecules, (2) provide measurements to put potential biosignatures in context and better assess their authenticity, (3) quantify potential terrestrial contamination quickly during spaceflight assembly, and (4) improve sample selection for more power and time intensive measurements and enable autonomous science decisions.** As noted above, significant progress has been made, but more development is needed to adapt chem/bio sensors to specific extreme environments, coordinate sample preparation approaches in larger instrument suites, and strategize on the best approaches to sensors suited for agnostic biosignatures.

5. References

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