From Concept to Flight Delivery in Eighteen Months:
The MECA/Electrometer Case Study

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Abstract—The rapid development of space instrumentation is increasingly important in this faster, better, cheaper era. This paper discusses the development of the MECA/Electrometer. It used a number of innovations including (a) rapid design of three prototypes, (b) fabrication of 20 units, (c) testing by three institutions, and (d) testing over a wide range of temperature, pressures, atmospheres, and vibration conditions in an eighteen month period.

1. INTRODUCTION: Space instruments must perform over a wide set of environmental conditions that usually exceed Earth operating conditions. In addition the development must be accomplished quickly often within 18-months. This paper highlights, in italics, the development principles used in the design, fabrication and test of the MECA/Electrometer which was conceived and delivered in 18 months.

The MECA/Electrometer was designed to facilitate the characterization of electrostatic properties of materials on the surface of Mars in preparation for human exploration. The design requirements are derived from the MECA proposal that stipulates that “mounted to the front of the robot arm scoop is the electrometer, which will be used to monitor triboelectric charging during excavation”. In addition an ion chamber is to be included to measure “atmospheric ionization contributions from soil radiation, solar radiation, and triboelectric ionization of the air”. The strategy is to develop an instrument whose results can be compared to laboratory measurements. If the comparison is favorable then future laboratory measurements can be performed with confidence in characterizing new materials intended for use on Mars. To facilitate the electrometer development, a total of 20 units were fabricated.

2. MECA/ELECTROMETER: The MECA (Mars Environmental Compatibility Assessment) payload is scheduled for launch December 2001. The purpose of the MECA/Electrometer, seen in Fig. 1, is to

Figure 1. MECA/Electrometer and Mars '01 scoop.

determine the electrostatic properties of the Martian atmosphere and regolith. The electrometer is used to measure (a) the triboelectrically-induced charge after the Triboelectric Sensor Array is rubbed through the Martian soil and pulled away from the surface, (b) the electric field...
strength above the Martian soil using the Electric-Field Sensor, and (c) atmosphere ion currents using the Ion Sensor.

3. REQUIREMENTS: The mission environmental conditions are listed in Table 1. The low-temperature conditions exceed Earth-bound conditions especially for commercially available electronic components. The prototype circuits were operational from a cold start at $-105^\circ$C. To minimize temperature drift problems, surface-mount resistors were chosen with a low TCR (thermal coefficient of resistance) of $\pm 10$ ppm/$^\circ$C. Thus, instrument components must be tested early in the development cycle over the appropriate environmental conditions to assure operation and survival during the mission.

The radiation dose was set at 1.5 krads for the mission that has a cruise phase of 8 months and a 90-day operational phase on the surface of Mars. Because the radiation levels are low, COTS (custom-off-the-shelf) parts were chosen that have radiation heritage from other space programs and thus, no explicit radiation tests were performed in this effort. Thus, in low-radiation environments, use parts that are manufactured from processes that are known to be radiation insensitive.

Table 1. Mission Environment

<table>
<thead>
<tr>
<th>Location</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>Planetary Protect. (H₂O₂)</td>
<td>55</td>
<td>°C</td>
</tr>
<tr>
<td>Launch</td>
<td>Acceleration</td>
<td>3000</td>
<td>g @ 3kHz</td>
</tr>
<tr>
<td>Cruise</td>
<td>Radiation Dose</td>
<td>1500</td>
<td>rad(Si)/yr</td>
</tr>
<tr>
<td>Mars</td>
<td>Radiation Dose</td>
<td>10</td>
<td>rad(Si)/yr</td>
</tr>
<tr>
<td>Mars</td>
<td>Temp Operate</td>
<td>-40 to 30</td>
<td>°C</td>
</tr>
<tr>
<td>Mars</td>
<td>Temp Survival</td>
<td>-107 to 65</td>
<td>°C</td>
</tr>
<tr>
<td>Mars</td>
<td>Temp Var.</td>
<td>60</td>
<td>°C/day</td>
</tr>
<tr>
<td>Mars</td>
<td>Pressure</td>
<td>5-10 [1]</td>
<td>Mb</td>
</tr>
<tr>
<td>Mars</td>
<td>Atmosphere</td>
<td>CO₂, 95% [1]</td>
<td>NA</td>
</tr>
<tr>
<td>Mars</td>
<td>Humidity</td>
<td>&lt;0.1 [1]</td>
<td>%</td>
</tr>
</tbody>
</table>

Table 2. Instrument Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tribo Voltage Sensitivity</td>
<td>1.8</td>
<td>kV/V</td>
</tr>
<tr>
<td>Tribo Voltage Range</td>
<td>±7.2</td>
<td>kV</td>
</tr>
<tr>
<td>Tribo Voltage Resolution</td>
<td>3.5</td>
<td>V</td>
</tr>
<tr>
<td>Ion Current Sensitivity</td>
<td>30</td>
<td>pA/V</td>
</tr>
<tr>
<td>Ion Current Range</td>
<td>±120</td>
<td>pA</td>
</tr>
<tr>
<td>Ion Current Resolution</td>
<td>60</td>
<td>fA</td>
</tr>
</tbody>
</table>

The parameters for the triboelectric and electric field sensors and ion sensor are listed in Table 2. In order to meet these requirements, the electrometer must be designed to have very low leakage. The high impedances needed for the electrometer and ion sensor were achieved by using high resistance printed wiring boards, guard rings, one op amp per sensor, and rigorous board cleaning.

4. ELECTROMETER DESIGN: The design approach included developing three different prototypes. The first prototype, shown in Fig. 2, was designed to verify the performance of the electronics [2] over the mission temperature range and likely high voltages. The electrometer requires the maintenance of very high resistance...of the order of $10^{15}$ ohms. Maintaining such impedances is layout and materials dependent and was evaluated by constructing physical prototypes.

Figure 2. Initial 11.7-cm diameter prototype, ELE1, ELE2, ELE3, and ELE4, designed to verify the basic design concept of the electronic circuitry in the Mars chamber shown in Fig. 6.

The second prototype, shown in Fig. 3, was more flight-like in that it demonstrated the approach for arraying the triboelectric sensors. It also allowed for rubbing experiments that established the sensitivity or amplifier gain of the circuitry.

Finally, the flight article, shown in Fig. 4, illustrates the final compaction of the unit that was fitted into a titanium housing and attached to the scoop of the robotic arm. The assignment of the dielectrics for the sensors is given in Table 3 along with their dielectric constant and bulk resistivity. The dielectrics were chosen from the positive and negative portions of the triboelectric series [3].
The prototypes are listed in Table 4 along with the location of the units. The design approach included the fabrication of nine flight-like units. Three units are for the flight team, three units for experimenters outside JPL, two units for JPL experimenters and one model unit. Having multiple experimenters making a variety of measurements aided in identifying problems early.

The project was started in March 1998 and, as seen in Table 4, the first prototypes were started in June 1998. The flight and flight spare units were delivered in mid September and October 1999.

5. FABRICATION: The electric field and triboelectric and ion sensor electrodes, as seen in Fig. 5, were supported above the electronics board by wires connected directly to the input of guarded operational amplifiers. Dielectrics, listed in Table 3, were mounted on top of the triboelectric electrodes. This assembly was mounted in the titanium housing seen in Fig. 4.

Table 4. MECA/Electrometer Development Events.

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Start</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELE1 JPL</td>
<td>14Jun98</td>
<td>Switch leakage too high</td>
</tr>
<tr>
<td>ELE2 JPL</td>
<td>1Nov98</td>
<td>Ion sensor evaluation</td>
</tr>
<tr>
<td>ELE3 JPL</td>
<td>22Nov98</td>
<td>Breakdown ~45 kV</td>
</tr>
<tr>
<td>ELE41 KSC</td>
<td>1Dec98</td>
<td>More breakdown studies</td>
</tr>
<tr>
<td>ELE42 JPL</td>
<td></td>
<td>Ion current studies</td>
</tr>
<tr>
<td>ELE5 JPL</td>
<td>27Dec98</td>
<td>Soil-dust studies</td>
</tr>
<tr>
<td>ELE61 JPL</td>
<td></td>
<td>First insulators installed</td>
</tr>
<tr>
<td>ELE62 KSC</td>
<td>31Jan99</td>
<td>First triboelectric rubbing</td>
</tr>
<tr>
<td>ELE71 JPL</td>
<td>17Apr99</td>
<td>First serial interface</td>
</tr>
<tr>
<td>ELE72 KSC</td>
<td></td>
<td>First titantium housing</td>
</tr>
<tr>
<td>ELE81</td>
<td>2May99</td>
<td>First automatic rubbing</td>
</tr>
<tr>
<td>ELE82 Flight</td>
<td></td>
<td>Flight equipment</td>
</tr>
<tr>
<td>ELE83</td>
<td></td>
<td>Material selection</td>
</tr>
<tr>
<td>ELE84 Model</td>
<td></td>
<td>Martian soil response</td>
</tr>
<tr>
<td>ELE85 Spare#1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELE86 KSC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELE87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELE88 KSC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELE89 Spare#2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The electrometer was fabricated in 35.5-μm double-sided copper-clad 1.52-mm FR-4 printed wiring board. The traces were cut using a milling machine with a minimum pitch of 0.5 mm. This allowed for rapidly prototyping new designs. The components were hand soldered using flux-laden solder paste. The flux was removed at room temperature using an ultrasonic trichloroethylene bath followed by an acetone rinse, alcohol rinse and air dry. This procedure insures fabrication of low-leakage electrodes required for electrometer measurements.
Eight units were fabricated as represented by the four units pictured in Fig. 6. This facilitates the objective of having additional units for use in laboratory tests that can be used to compare with results from Mars.

6. TEST APPARATUS: The characterization of the electrometer involved testing the units over a variety of: (a) temperatures, (b) pressures, (c) atmospheres, (d) humidity, (d) rubbing and (e) vibration conditions. Three apparatuses were used to perform the characterization. The Mars chamber, shown in Fig. 7, can produce environments with temperatures between -100 to 200°C, pressures between 0.01 to 1013 mb, and atmospheres of air and CO₂.

The flight units were subjected to a "planetary protection" sterilizing procedure using H₂O₂ plasma. The procedure was carried out in a chamber heated to 55°C. The sterilization chamber was evacuated five times and an H₂O₂ plasma created for 5 minutes to dissipate the H₂O₂. The H₂O₂ plasma was created outside the region where the electrometer was positioned.

The chamber was used to characterize the basic functionality of the electrometer over the temperature range from -100 to 40°C. Of concern was the DC-DC converter
seen in Fig. 5 and its functionality at low temperature. The electrometer was successfully operated after a cold start at -100°C confirming the operability of the DC-DC converter at low temperature.

The chamber was also used to characterize the triboelectric sensors response to rubbing with wool felt. Two rubbing apparatuses were developed. In the apparatus shown in Fig. 9, the electrometer is stationary and the rubbing media is moved across the sensor head by a motor-driven linear actuator. Head pressure is determined by the weight of the electrometer.

In the rubbing machine shown in Fig. 10, the electrometer moves via a motor-driven linear actuator across the rubbed media attached to a platform. Pressure to the sensor head is applied by a weight and pulley system attached to the sample platform guided by a slider. This apparatus is housed in a temperature-and pressure-controlled chamber.

Results from the rubbing machine shown in Fig. 10 are comparable with results from the machine shown in Fig. 9. The stroke and rubbing speed are higher and better-controlled in the machine shown in Fig. 10 than the one shown in Fig. 9.

The vibration of the electrometer was accomplished using the configuration shown in Fig. 11. Of concern were some 28 0-80 flathead fasteners that secure the sensors to the electrometer housing. To prevent them from loosening, the ends of the fasteners were secured using solithane. Tests
were performed before and after vibration to verify functionality.

7. TEST RESULTS: The response of the electric field (ELF) and triboelectric (TRI) sensors is shown in Fig. 12. In this test, teflon is charged negatively by rubbing with wool felt. The charged teflon is placed before the sensors for about 25 seconds that causes the amplifier to respond with a negative pulse during the exposure period.

Figure 12. Response of ELE81 to black-wool felt charged teflon (charged negatively) between 7 and 32 s after start of test at 21°C and 32% relative humidity.

The electrometer's long-term response, shown in Fig. 13, indicates that the sensors have low-leakage currents. An 0.6 V drift after 10 hours corresponds to an op amp input current of 5 fA given an input capacitance of 10 nF and amplifier gain of 4. The variability between sensors is due in part to differences in op amp input currents. As shown elsewhere [2], the leakage currents decrease dramatically at low temperatures. Thus, the electrometer leakage current is satisfactory for making measurements on Mars that will be less than 100 seconds in duration.

Figure 13 also shows the ion sensor response which has a sensitivity of 30 pA/V. The full-scale ion sensor capability is 120 pA and resolution is 60 fA.

The voltage response of the electric field and triboelectric sensors, shown in Fig. 14, is governed by the dielectric constant of the insulator between the sensing electrode, seen in Fig. 5, and the test plate used in these measurements. The slope of the curves shown in Figure 14 follows the trend for the dielectric constants listed in Table 3. The sensitivity of the triboelectric-sensors is between 0.67 and 2.06 kV/V. The full-scale detection capability and resolution is 7.3 kV ± 3.5 V. The full scale charge detection capability and resolution is 1800 ± 0.9 pC. This corresponds to a detection limit of 5.5 million charges.

The design approach, that is the amplifier sensitivity, was biased in favor of a wide dynamic range rather than high sensitivity. It is important that the measurements on Mars not exceed full scale.

Rubbing measurements, shown in Figs. 15 and 16, illustrate the response that can be expected on Mars. The results, shown in Fig. 15, were taken near ambient conditions. Using the average triboelectric sensor response, the 1 V response corresponds to 1.8 kV generated on TRI3 and TRI4.

The response shown in Fig. 16, was measured at 450 mb, which is approximately half an atmosphere. As seen in the figure, a voltage close to 1 V was generated while the rubbing media is in contact with TRI3 and TRI4 but this
voltage cannot be sustained once the sensors separate from the rubbing media. Thereafter, the response of TR13 and TR14 drops to a value dictated by the Gauss breakdown voltage limit [3]. The charging of TR11, TR12, and TR15 are unaffected at this pressure. This behavior provides a glimpse into the response at lower pressures.

2. Fabrication Principles:
   a. Use a rapid-prototyping board milling machine to aid in the production of many units.
   b. Use rigorous cleaning procedures to maintain high impedances.
   c. Use H2O2 sterilization at 55°C to keep temperatures lower than heat sterilization.

3. Test Principles:
   a. Test components early to ensure operability over the Martian temperature range.
   b. Make many prototypes to (a) facilitate problem-solving by having several units under test at one time and (b) gather statistics to determine operating conditions which are difficult with high impedance circuitry.
   c. Test under conditions that emulate the final use configuration, robotic arm in this case, by developing simple test apparatuses such as the rubbing machines shown in Figs. 9 and 10.

9. CONCLUSION: The development of this novel instrument occurred within an 18 month period because of design simplicity which allowed production of twenty units listed in Table 4 and attention to detail in the fabrication cycle including rigorous cleaning, and parallel testing that identified problems early. Attention was also focused on maintaining high impedance circuitry in the design by using guard rings and one op-amp per sensor and in the fabrication by using chemical cleaning procedures.

10. REFERENCES:
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11. BIOGRAPHIES:
Martin G. Buehler received the BSEE and MSEE from Duke University in 1961 and 1963, respectively and the Ph.D. in EE from Stanford University in 1966 specializing in Solid State Electronics. He worked at Texas Instruments for six years, at National Bureau of Standards (now NIST) for eight years, and since 1981 has been at the Jet Propulsion Laboratory where he is a senior research scientist. At JPL he has developed p-FET radiation monitors for CRRES, Clementine, TELSTAR and STRV, E-nose which flew on STS-95, and an electrometer for the Mars '01 robot arm. Currently he serves on the staff of the New Millennium Program as a technical analyst. Martin is a member of the IEEE and the Electrostatic Discharge Association.

Li-Jen Cheng received the B.S. in Chemical Engineering in 1956 from the Ordnance Engineering College, Taipei, the M.S. in Nuclear Science in 1961 from the National Tsing Hua University, Taiwan, and the Ph.D. in solid state physics from Rensselaer Polytechnic Institute in the 1966. After graduation he worked at the Chalk River Nuclear Laboratories, Chung Cheng Institute of Technology, Institute of Nuclear Energy Research, and the State University of New York. In 1977 he joined the Jet Propulsion Laboratory and spent a number of years with the photovoltaic project. In recent years, he developed the AOTF (acousto-optic tuneable filter) technology and most recently assisted in developing the MECA/Electrometer.

Dennis P. Martin received the received his BSME from California State Polytechnic University in 1976 and pursued graduate work in Material Sciences of Microelectronics at Arizona State, California Institute of Technology, and University of Florida. Dennis joined Jet Propulsion Laboratory and then in 1981 formed the Halcyon Microelectronics, Inc. As president of Halcyon Microelectronics, Dennis heads up the advanced packaging for research and development with emphasis on miniaturization of complex systems for hostile environments; ie: high radiation, high "g" force, and extreme temperature. Halcyon offers a laboratory in which products are developed. More than 300 designs have become working prototypes for customers ranging from Cal Tech and Rockwell Int’l to MIT and Cree Research. In the last five years, Mr. Martin has expanded Halcyon’s role as a service laboratory for package research and development into sensor development. He is a member of ISHM.

Raymond H. Gompf received the BSEE in 1959 from Rose-Hulman Institute of Technology, MS in Engineering in 1961 from Florida Institute of Technology and in 1980 his doctorate from Nova University. He worked at Cape Canaveral from 1959 to 1962 with General Dynamics on the Atlas Missile System. From 1962 to 1970 he was with RCA as an electronics engineer, specializing in telemetry systems. While with RCA, he developed the telemetry planning methods used for lunar and interplanetary telemetry coverage. Since 1970 he has been with Brevard Community College where he initiated and directed the first environmental engineering technology program. For the past 18 years he has been consultant to NASA at Kennedy Space Center doing testing and research into the triboelectric properties of materials. He has been a registered professional engineer in Florida since 1963.

Carlos I. Calle received is the principal investigator for the electrostatics research group at NASA Kennedy Space Center. He is currently working on the problem of electrostatic phenomena on planetary surfaces, particularly on Mars and the Moon. He holds a Ph.D. in theoretical nuclear physics from Ohio University and was Professor and Chair of the Physics Department at Sweet Briar College in Virginia, where he taught for 18 years prior to joining NASA. He has published papers in electrostatics, nuclear reaction theory, nuclear structure, and laboratory methods. His book, Guide to Physics: From Quarks to Superstrings, will be published by the Institute of Physics Publishing in the spring of 2000.

Jon A. Bayliss received the BSEE at Florida Institute of Technology and is currently an Electronics Engineer, at the Kennedy Space Center, Material Science Laboratory (MSL), Electronic Systems Failure Analysis. Jon is responsible for component evaluation and failure analysis on all types of electrical and electronic components and publishes technical reports. His work involves application of standard engineering practices to provide technical support for both flight systems and ground support equipment. Jon has experience in planning and performing flight and GSE hardware failure analyses, component reliability evaluations, and developing automatic test systems for use in electronic/electrical component failure.
analysis and evaluation. In addition, he has helped develop material safety evaluation test techniques to determine the electrostatic properties of plastic films and other materials used in potentially hazardous environments. Jon is a member of the American Society for Testing and Materials (ASTM) and currently participates in the D09 Committee for Electrical and Electronic Insulation Materials.

Jeffrey L. Rauwerdink received the BSEE from the University of Wisconsin-Madison and has pursued graduate work at the University of Cincinnati in solid-state electronics. Since 1989, he has worked at the Kennedy Space Center, Material Science Laboratory, Electronic Systems Failure Analysis, as AeroSpace Technologist, Electrical Engineer. Jeff performs component evaluation and failure analysis on all types of electrical and electronic components and publishes technical reports and is an expert on discrete and integrated semiconductor components. Jeff provides engineering advise and consulting services regarding the capabilities of electrical and electronic systems and components. Jeff has focused on semiconductor reliability and he gained experience in planning and executing component reliability evaluations, performing failure analyses, developing automatic test systems for use in component failure analysis and performing digital circuit simulations. In addition to his failure analysis duties, Jeff is presently adapting an Intergraph CAE workstation to failure analysis so that the workstation can be used to (1) model and test circuit fault scenarios and (2) automatically operate component test systems and compare the test results with the behavior of the component circuit model.