EOR: A University Small Satellite for Low Cost Remote Sensing of Ozone

Ellen L. Riddle

Abstract—The Educational Ozone Researcher (EOR) is a small scientific spacecraft designed by students of the Colorado Space Grant College (CSGC) at the University of Colorado at Boulder. EOR was a finalist in the Universities Space Research Association (USRA) Student Explorer Demonstration Initiative (STEDI) program and received Phase I funding in the amount of $160K during late 1994 and early 1995. This paper provides a description of the scientific rationale and the design of the EOR mission.

I. INTRODUCTION

THE STEDI program is funded by NASA with the goal of demonstrating that significant science and/or technology experiments can be performed with small satellites and constrained budgets. STEDI requires a mission budget limit of $4.3M exclusive of the launch vehicle and communication services; involvement of students in the design effort; design, manufacture, test, and launch of the spacecraft within two years; and launch on a Pegasus XL.

The EOR mission, designed to meet the STEDI requirements, has the following major characteristics:

- One year duration
- Global mapping of Earth's ozone every 10 days
- Spacecraft remotely commanded by students at the University of Colorado
- Circular, sun synchronous, 661 km orbit
- No propulsion system
- No deployable parts
- Major involvement of students in all project phases and systems

EOR was proposed to provide valuable global measurements of ozone and atmospheric constituents affecting ozone and to advance ozone measurement technology. The constituents affecting the processes and mechanisms contributing to ozone creation and depletion include nitrogen dioxide (NO2), chlorine dioxide (OCIO), sulfur dioxide (SO2), and bromine monoxide (BrO). The EOR mission is one of the first experiments to exploit advanced and low-cost CCD detector technology in the measurement of ozone (O3) concentrations, and is one of the first missions to measure the critical atmospheric constituent chlorine dioxide.

These atmospheric constituents are measured by the EOR instrument - a single spectrograph utilizing three charge-coupled device (CCD) detectors and costing less than $20,000. The experiment observes the ozone spectrum at wavelengths longer than previously and currently measured, from 290 nm to 675 nm, and therefore extends the measurement of ozone to much lower altitudes. The instrument senses atmospheric elements using backscatter ultraviolet (BUV) and differential absorption spectroscopy detection techniques. EOR measurements complement other data sets from previous, present, and planned space missions.

II. SCIENCE

A. History and Basis of Ozone Research

The earth's atmosphere is responsible for preventing most of the sun's biologically harmful radiation from reaching the Earth's surface. Solar radiation at wavelengths between 320 nm and 800 nm is only partially absorbed in the stratosphere and penetrates to the earth's surface. However, radiation at shorter wavelengths, between 220 nm and 320 nm, is predominately absorbed high in the atmosphere by stratospheric ozone. This absorption represents the prime energy source for the energetics and dynamics of the stratosphere [7]. When struck by the sun's rays, oxygen molecules photodissociate into extremely reactive oxygen atoms (O). The oxygen atoms are then free to bond with other oxygen molecules, producing the ozone molecule. Simultaneously, ozone is also being destroyed as a result of other aeronomic reactions, creating a precarious balance. Specific constituents, such as
oxides of chlorine, are believed to catalytically destroy ozone through the following chemical process.

\[
\begin{align*}
2(\text{Cl} + \text{O}_3 &\rightarrow \text{ClO} + \text{O}_2) \\
\text{ClO} + \text{ClO} + \text{N}_2 + \text{O}_3 &\rightarrow \text{Cl}_2\text{O}_2 + \text{N}_2 + \text{O}_2 \\
\text{Cl}_2\text{O}_2 + \text{sunlight} &\rightarrow \text{ClO}_2 + \text{Cl} \\
\text{ClO}_2 + \text{N}_2 + \text{O}_3 &\rightarrow \text{Cl} + \text{O}_3 + \text{N}_2 + \text{O}_2
\end{align*}
\]

\(\text{NET: } 2\text{O}_3 \rightarrow 3\text{O}_2\)

Oxides of nitrogen also play an important role in atmospheric photochemistry not only by affecting the equilibrium of ozone (Eq. 2), but by playing a critical role in the formation of nitric acid clouds in the stratosphere.

\[
\begin{align*}
\text{NO} + \text{O}_3 &\rightarrow \text{NO}_2 + \text{O}_2 \\
\text{NO}_2 + \text{O} &\rightarrow \text{NO} + \text{O}_2 \\
\text{NET: } \text{O} + \text{O}_3 &\rightarrow 2\text{O}_2
\end{align*}
\]

Nitric acid clouds form in the polar regions where they act in concert with chlorine monoxide (ClO) and bromine monoxide to rapidly destroy ozone (Eq. 3).

\[
\begin{align*}
\text{Cl} + \text{O}_3 &\rightarrow \text{ClO} + \text{O}_2 \\
\text{Br} + \text{O}_3 &\rightarrow \text{BrO} + \text{O}_2 \\
\text{ClO} + \text{BrO} &\rightarrow \text{Br} + \text{ClO}_2 \\
\text{ClO}_2 + \text{N}_2 + \text{O}_3 &\rightarrow \text{Cl} + \text{O}_3 + \text{N}_2 + \text{O}_2 \\
\text{NET: } 2\text{O}_3 &\rightarrow 3\text{O}_2
\end{align*}
\]

The ozone loss rate due to this reaction between ClO and BrO can be derived by the measurement of another atmospheric constituent, OCIO. OCIO, related to ClO and BrO by Eq. 4, plays a significant role as an indicator of perturbed halogen chemistry in the polar stratosphere.

\[
\text{ClO} + \text{BrO} \rightarrow \text{OCIO} + \text{Br}
\]

OCIO is believed to be the major free radical responsible for the Antarctic ozone loss and is the dominant loss mechanism in the polar lower stratosphere. As an indirect measurement of the ClO concentration and a direct measurement of chlorine activation, OCIO is a key constituent in understanding the dynamics of ozone depletion. Antarctic OCIO has been found to be highest in September, a period that has been noted for extensive ozone losses in Antarctica. Observations of elevated OCIO during late June to August imply that some ozone is also being destroyed in Antarctica during midwinter.

Sulfur dioxide and sulfate aerosols also play a role in the destruction of ozone. Volcanic eruptions can inject sulfur directly into the stratospheric where it provides a surface for ozone destroying reactions to occur. Measurement of SO\(_2\) provides an indication of the level of these aerosols in the atmosphere.

In accordance with the importance of these constituents in the entire ozone balance, the proposed EOR experiment measures NO\(_3\), SO\(_2\), BrO, and OCIO along with global measurements of ozone. In addition to making standard measurements of ozone in the Hartly band (260-300 nm), the EOR experiment provides observations of ozone far into the lower atmosphere (below 5 km). The newer technology of the EOR instrument make these observations possible by providing good resolution at the longer UV and visible wavelengths of the Huggins (300-420 nm) and Chappuis (450-750 nm) ozone bands. It is important to measure the amplitude and location of these lower stratospheric ozone changes because the largest ozone losses occur in the lower stratosphere. However, this region has proven to be the most difficult to measure from space.

Table 1 shows a direct comparison of current, past and planned ozone monitoring missions and demonstrates how EOR will complement and extend knowledge of ozone and key constituents in our atmosphere. Past and current missions have failed to

<table>
<thead>
<tr>
<th>Mission</th>
<th>Gases Measured</th>
<th>Wavelength Coverage</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBUV</td>
<td>O(_3), SO(_2)</td>
<td>255-340 nm</td>
<td>1 nm spectral</td>
</tr>
<tr>
<td>SME</td>
<td>O(_3), NO(_2)</td>
<td>246-770 nm</td>
<td>64 nm spectral</td>
</tr>
<tr>
<td>SAGE</td>
<td>O(_3), NO(_2), H(_2)O</td>
<td>290-1550 nm</td>
<td>1-2 km vertical</td>
</tr>
<tr>
<td>TOMS</td>
<td>O(_3), SO(_2)</td>
<td>312-380 nm</td>
<td>1 nm spectral</td>
</tr>
<tr>
<td>GOME</td>
<td>O(_3), NO(_2), O(_2), BrO, OCIO</td>
<td>240-790 nm</td>
<td>0.2-0.4 nm spectral</td>
</tr>
<tr>
<td>EOR</td>
<td>O(_3), NO(_2), SO(_2), BrO, OCIO</td>
<td>290-675 nm</td>
<td>0.35-1.45 nm spectral</td>
</tr>
</tbody>
</table>
return accurate results in the lower stratosphere. The Stratospheric Aerosol and Gas Experiment (SAGE) is limited by high clouds along the solar occultation path and the Solar Backscatter Ultraviolet (SBUV) experiment measures only the difference between total ozone and integral amounts above the ozone maximum [6]. EOR will therefore extend the current data sets from present missions to include information on lower stratospheric and tropospheric (below the stratosphere) ozone. Information on tropospheric ozone is important because, although stratospheric ozone filters out dangerous ultraviolet radiation, tropospheric ozone contributes to smog and the greenhouse effect. In addition, tropospheric ozone can have biologically harmful effects on the living tissues of plants and animals.

B. Need for Current Investigation

During the past decade, the lowest levels of ozone in recent history have been measured. This fact, combined with the possibility that ozone concentrations will reach critical levels within the next decade, makes it essential that this protective shield be measured and measured accurately. Satellite measurements have revealed that the concentrations of stratospheric ozone have dropped to record low levels during the 1991 and 1992 winter-spring periods over the middle latitudes and polar regions of the planet [1]. In fact, global averages of total ozone concentration are two to three percent lower than the lowest values observed in earlier years. More alarmingly, the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus-7 satellite indicated an acceleration in the decline of ozone due to aerosols in the stratosphere from the eruption of Mount Pinatubo in June 1991 [5].

An increase of ozone-hostile constituents in the stratosphere has played a significant role in this increasing rate of ozone destruction. Chlorine levels have risen in the stratosphere due to the continued use of chlorofluorocarbons (CFCs) in aerosol sprays, refrigerants, vehicle air conditioning, and cleaning agents. CFCs are inert in the troposphere but photodissociate at higher altitudes and thus are the major source of stratospheric reactive chlorine. In response to concerns over potential effects of ozone depletion a variety of national and international regulations have been introduced to reduce the emissions of CFCs into the atmosphere. However, global stratospheric CFCs are still increasing and are expected to reach a maximum within the next decade and decline thereafter [4]. During the next decade, the ozone layer will therefore be at its most vulnerable stage. Consequently, it is critical that we continue to obtain global measurements of total atmospheric ozone, understand the processes and mechanisms that contribute to ozone variations, and verify that current measurements are correct. Verification of ozone concentrations through comparative measurements is vital.

EOR is designed to complement and extend the measurements of the TOMS series of flights. The TOMS instruments have provided global measurements of the ozone column, but are conservatively designed using 1970's technologies. The EOR experiment will provide a better correlation between space-based and ground-based measurements. Comparison of satellite results with data from ground-based instruments is complicated by the fact that ground-based instruments look through the lower atmosphere (troposphere) to collect data. Because tropospheric ozone is increasing in the northern hemisphere, it is likely that discrepancies of ozone measurements between satellite and ground-based instruments will result.

C. Science Instrumentation

Table II lists the specific science objectives of the EOR mission along with the requirements these

| TABLE II |
| SCIENCE INSTRUMENT REQUIREMENTS |

<table>
<thead>
<tr>
<th>Measurement objectives</th>
<th>Required spectral coverage</th>
<th>Required spectral resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total column, vertical profile, and global measurements of the Huggins Ozone Band</td>
<td>Total column, global measurements of the Chappuis Ozone Band</td>
<td>Vertical profile, global measurements of the Hartley Ozone Band</td>
</tr>
<tr>
<td>310-350 nm</td>
<td>1.0 nm</td>
<td>400-700 nm</td>
</tr>
</tbody>
</table>
objectives put on the science instrument. These requirements along with the two year development time and budget limitations of the STEOI program drove the instrument design. To meet the spectral bandwidth and resolution requirements in an instrument compatible with a small satellite, the EOR science experiment consists of a single spectrograph utilizing advanced charge-coupling device (CCD) technology. The spectrograph is a single pass grating spectrometer comprised of three channels to measure the spectral intensities from 290 nm to 675 nm. Each of the spectrograph's three channels uses a holographic replicated dispersion grating and CCD linear array detector.

As shown in Fig. 1, incident light is reflected into the instrument from a rotating mirror. This light is then focused by telescopic mirrors onto the entrance slit. After entering through the slit, a collimator directs the light through a beam splitter which reflects light from 290-320 nm, constituting Channel 1, and transmits the longer wavelengths. A second beam splitter then separates the light between channel 2 (315-425 nm) and Channel 3 (420-675nm). A diffraction grating in each channel performs a Fourier transform on the light to distribute the light by wavelength across the channel's linear CCD array. This CCD array can then measure the intensity of light at each wavelength, from which an absorption cross section can be obtained. This cross section, along with a current solar flux profile, provides a measurement of each atmospheric constituent's concentration.

EOR achieves the resolution necessary to meet its science objectives mainly by exploiting CCD technology. Typical quantum efficiencies (QE) for a back-side thinned CCD exceed 50% from 375 nm to 450 nm and are higher than 70% from 450 to 700 nm. This makes CCDs better detectors than typically used diodes (QE=50%) in the visible and near infrared wavelengths. The CCD used in Channel 1 is coated with Metachrome II to improve the ultraviolet (<375 nm) QE of the detector. Currently a prototype of the EOR spectrograph is being built for a student-developed rocket project at the Colorado Space Grant College. This prototype is furthering CCD technology by using CCDs specially processed at the Jet Propulsion Laboratory (JPL). JPL has allowed CSGC to flight demonstrate a delta-doped CCD. These CCDs show an enhanced responsivity in the ultraviolet above the responsivity gained by using a Metachrome II coated CCD. To minimize thermal noise, the CCDs are cooled to 20 degrees Celsius with a passive radiator plate and thermal stability is maintained with a thermoelectric cooler (TEC) attached to the backside of each detector. Each CCD is an array; of 2048x1 pixels with a pixel size of 15 microns. The small pixel size has two benefits: it allows for extremely high spectral resolution and it minimizes signal noise.

To meet program requirements, instrument components were selected for their availability and cost. By using commercial off-the-shelf (COTS) parts, the cost and development time of the instrument are substantially reduce. However, key items, such as the CCDs, were contracted to perform to mission specifications.

As a proof of design, the instrument's theoretical performance was predicted using radiative transfer modeling. Modeling consisted of a two-stream, multi-layer inhomogeneous atmosphere from which upwelling flux and absorption strengths were determined. Key constituents to be studied were inserted into the model and instrument signal was determined. Instrument characteristics such as optical efficiency, throughput, detection efficiency and related noise were considered.

As the heart of the spacecraft, the EOR spectrograph places numerous requirements on the rest of the spacecraft. Similar to other small satellite designs with the better, faster, cheaper ideology, the EOR philosophy balances the instrument performance with spacecraft characteristics for...
overall optimization. Table III lists the requirements the instrument places on the rest of the spacecraft.

### TABLE III

**SCIENCE REQUIREMENTS ON THE SPACECRAFT DESIGN**

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Requirements on Subsystem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude Determination &amp; Control</td>
<td>Line of sight stability = 100% field of view; spacecraft jitter &lt;10 Hz</td>
</tr>
<tr>
<td>Structure</td>
<td>Mass 10 Kg, Volume 30&quot;x12&quot;x6&quot;</td>
</tr>
<tr>
<td>Command &amp; Data Handling</td>
<td>24 Kbits/image, real-time control of instrument</td>
</tr>
<tr>
<td>Thermal</td>
<td>Steady state ≤ 20°C, ΔT ≤ 15°C</td>
</tr>
<tr>
<td>Orbit</td>
<td>Maximize orbit altitude; maximize time that sun angle is &lt; 80 degrees</td>
</tr>
</tbody>
</table>

### III. SPACECRAFT DESIGN

The design of the spacecraft meets the requirements imposed by the STEDI program as well as the requirements imposed by the science objectives and instrument.

#### A. Orbit

The EOR mission is baselined as a one year mission but sized for a two year lifetime. The nominal orbit parameters enable a two year mission to be completed without active propulsion and provide spatially continuous atmospheric measurements while maximizing the coverage of the sunlit earth. An orbit altitude of 661 km provides a balance between minimizing atmospheric drag and maximizing the weight-to-orbit capabilities of the launch vehicle. As dictated by the science instrument, it is desirable to have a constant sun-geometry which requires a sun-synchronous orbit. A polar orbit was required by USRA, which, for the purposes of global mapping, was also desirable for this mission. A repeatable ground track and circular orbit provide spatially continuous global coverage. An hour angle of 8 A.M./8 P.M. was chosen after considering the sun angle to the spacecraft and image slit. This hour angle is a compromise to optimize instrument performance and solar panel efficiency.

#### B. Structure

EOR’s main support structure is a hexagonal, longeron/plate design, and was designed with a length of 34 inches and a width of 34.5 inches to meet the Pegasus XL launch vehicle shroud restrictions. The addition of the science instrument, mounted to the bottom of the support structure, increased the total length of the spacecraft to 40 inches. The hexagonal design, shown in Fig. 2, optimizes solar array area and spacecraft volume. The modular three-plate design simplifies integration, as students can easily separate the spacecraft and work on the subsystems on each plate independently. A finite element analysis was performed to determine the spacecraft’s characteristics with regard to maximum acceleration and shock limits and to verify that the structure meets Pegasus XL safety requirements.

![EOR structure without solar panels](image)

**Fig. 2.** EOR structure without solar panels. A modular three plate design allows students to work on the subsystems on each plate independently. During flight, solar panels cover each side of the structure. A shunt regulator, attached to one of the deep space pointing solar panels, dissipates excess battery power. Four GPS antennas are located on the upper side of the top plate.

#### C. Power

A direct energy transfer system provides EOR with an efficient means of supplying required power throughout the spacecraft’s lifetime. Body-mounted silicon solar arrays provide the spacecraft power and charge batteries when the spacecraft is in sunlight,
and nickel-cadmium batteries supply eclipse power. The panel layout on the hexagonal structure delivers sufficient power during worst-case solar angle in the case of improper satellite orientation or random tumble.

D. Thermal

EOR uses a passive thermal control system. A thermal analysis of the spacecraft using TAK II software kit verified that such a system would meet the requirements of the mission while remaining inexpensive and efficient. A shunt regulator for the batteries enables excess electrical power to be dumped from the satellite. The surfaces of the science instrument are covered with an MLI blanket to keep its temperature consistent.

E. Attitude Determination & Control

Both attitude determination and attitude control are necessary to meet the science objectives of EOR. Two independent methods are used for attitude determination: a magnetic attitude determination system (MADS) and a global positioning system (GPS). The MADS is comprised of two two-axis magnetometers and provides sufficient knowledge of attitude to meet the mission’s minimum success criteria. In order to meet the more stringent attitude knowledge goals of the mission, GPS is required. A Trimble TANS Vector GPS receiver with four antennas provides this attitude knowledge. Since this receiver performs all low level GPS processing autonomously, the command and data handling (C&DH) processing load of the GPS is minimal. In the even of MADS and GPS failure, a redundant method for ground-based attitude determination is afforded by a sun sensor used by the science instrument.

For 3-axis stabilized attitude control, torque rods and a momentum wheel are used. The torque rods are sufficient to meet the requirements imposed by science, power, and thermal subsystems, but in order to produce more consistent global maps of ozone, a momentum wheel is used. Spin stabilization was not used due to the requirements of the science instrument. A gravity gradient spacecraft was not used due to constraints on the satellite length and mass imposed by the launch vehicle. Use of a gravity gradient deployable boom was rejected due to the increased reliability and simplicity afforded by a non-deployable design.

F. Command & Data Handling

A powerful flight computer is necessary to support the relatively heavy processing load presented by the COTS command and control software. To meet the project goals of using inexpensive COTS hardware, a VME architecture was chosen for the EOR command and data handling system due to its desirable structural strength and wide availability. COTS hardware allows a system design costing much less than standard flight computers. As shown in Fig. 3, a Motorola 68030 processor operating at 25 MHz provides 5 MIPS of processing ability. Four MB of parity DRAM is used and provides protection against single event upsets due to radiation. Two 16 MB Flash PROM mass storage boards are used for non-volatile storage of science, engineering, configuration data, and the CPU code image. Since one day’s data amounts to approximately 8 MB and since downlink of data is scheduled once per day, each card can store about two day’s worth of data, providing a margin in case downlink on a specific day is not possible. A separate student-designed VME board provides interfaces to other spacecraft subsystems. To guard against ionizing radiation, 100 mils of aluminum shielding is used to surround the C&DH elements. A watchdog timer protects against an errant CPU condition which could prevent ground system control of the satellite.

![Core C&DH Resources](image)

Fig. 3. Command and Data Handling Subsystem. RS-422 serial communication links between the C&DH subsystem and most other subsystems provide an easy method of individually testing each subsystem, independent of the flight computer.
In addition, a command decoder is used which can decode the incoming commands and control power to various subsystems as well as reset the flight computer.

A real-time operating system (RTOS) provides real-time response to events, multitasking capability, and methods for interprocess communications. Redundant images of the spacecraft computer code are stored in Flash PROM so that a hard error in one version of the code will not cripple the spacecraft. The command decoder is capable of selecting which version of boot code the computer will use upon reset, thereby providing a means for ground system control in the event of memory errors.

G. Communications

The transponder system for EOR provides a 450 kbps downlink data path and a 56.25 kbps uplink data path. A bit error rate of 10E-6 combined with a packet resend protocol provides a reliable communication link. By using a COTS system, the communication subsystem cost is decreased. A satellite dish and ground station located at the University of Colorado provides local, full-time availability of the communications link.

IV. MISSION OPERATIONS

EOR not only provides essential science data, but also provides an opportunity to advance knowledge in distributed mission operations, automation, and autonomy. The mission is controlled by a distributed team located at the University of Colorado. The end-to-end mission operations system is built to allow the migration of automation from a flight systems testbed to the ground control center to the spacecraft on-board control as the mission progresses. Subsystem simulations allow for progressive implementation of the spacecraft hardware during development as well as testing of software before its migration to the flight computer during flight. The Spacecraft Command Language (SCL) enables identical software scripts to be run on both ground and flight systems, and provides rule and constraint mechanisms which increase spacecraft automation and autonomy. In addition to these scientific and technological benefits, EOR provides hands-on education for undergraduate and graduate students at CSGC. Students not only design the mission operations software, but they also act as mission controllers during the mission.

V. MANAGEMENT

One of the major challenges in designing a satellite at a University, using primarily student labor, is meeting the budget and schedule constraints of the project while still achieving the goal of educating students. In order to allow the student team to learn from their mistakes and improve the satellite design over time, the spiral development model is followed. In this model, shown in Fig. 4, multiple iterations through four development phases are made. These four phases are: planning, risk analysis, engineering, and evaluation and maintenance. In each iteration through the spiral, the design is reviewed and corrections are made. By completing iterations early in the design process, problems are uncovered early on when they can be fixed with a minimal impact on both cost and schedule. We have found this spiral model to be an effective tool for involving and educating students on all CSGC projects.

![Fig. 4. EOR Spiral Development Model.](image)

The process starts near the middle of the spiral in the planning stage. It then iterates through the other three phases. As each cycle through the process is completed, improvements and corrections to problems uncovered during the previous iteration are made. An increasing level of cost and commitment to the design results as each cycle is completed.

VI. CONCLUSION

Technologies that support EOR science and mission operations continue to be developed at CSGC. A Space Shuttle Hitchhiker payload, called DATA-CHASER (Distributed and Automation Technology Advancement - Colorado Hitchhiker...
And Student Experiment of solar Radiation), is scheduled for launch in 1997. This payload contains three science instrument which will measure wavelengths from 1 nm to 40 nm and from 115 nm to 190 nm. An enhanced version of the mission operations design proposed for EOR will be used on this mission and will provide valuable data on system performance.

A sounding rocket payload, called HOMER (High altitude Ozone Measuring and Educational Rocket), is scheduled for launch from Wallops Flight Facility in August, 1996. This payload carries four science instruments which will measure wavelengths at 270 nm, 1250 nm, 450 nm and from 190 nm to 245 nm. EOR CCD technology will be used on this rocket.

Further investigation of ozone and the atmospheric constituents affecting ozone remains an important mechanism for our understanding of the sun and its effects on Earth's inhabitants. EOR is an example of how this investigation may be done in a low-cost manner by using university personnel and resources. We remain hopeful that this mission and the students of the Colorado Space Grant College will be able to build and operate this significant scientific mission in the near future.

ACKNOWLEDGEMENTS

The success of the EOR proposal would not have been possible without the dedicated efforts of many students, faculty, and advisors. Donations of equipment, time, and expertise were made by many people at the university and from industry. I would like to thank the many students who comprised the EOR proposal team and Phase I design team; faculty advisors and staff form the University of Colorado; the science advisors from the National Oceanographic and Atmospheric Administration, the High Altitude Observatory, the Cooperative Institute for the Research in Environmental Science, and the Center for Astrophysics and Space Astronomy; and the industry advisors from Ball Aerospace, JPL, Goddard Space Flight Center and Wallops Flight Facility, Martian Marietta, TRW, DAB Engineering, COSA, Lockheed, and MoJo Designs, Inc. Special thanks to Linden McClure for his help in writing this paper.