PROGRESS REPORT OF THE EOS IDS VOLCANOLOGY TEAM
August 1995

Page No.

Attachments:

#1 Flynn, L.P., Mouginis-Mark, P.J., Gradie, J.C. and Lucey, P.G. (1993). Radiative temperature measurements at Kupaianaha lava lake, Kilauea Volcano, Hawaii. *J. Geophys. Res.*, 98: 6461 - 6476.

#2 Gerstell, M.F., J. Crisp, and D. Crisp (1995). Radiative forcing of the stratosphere by SO_2 gas, silicate ash, and H_2SO_4 aerosols, shortly after the 1982 eruptions of El Chichon. *J. Climate*, 8: 1060-1070.

#3 Krueger, A. J. et al. (1995). Volcanic sulfur dioxide measurements from the total ozone mapping spectrometer instruments. *J. Geophys. Res.*, 100: 14057 - 14076.

#4 Realmuto V.J., Abrams M.J., Buongiornio M.F., and Pieri D.C. (1994). The use of multispectral thermal infrared image data to estimate the sulfur dioxide flux from volcanoes: a case study from Mount Etna, Sicily, 29 July 1986. *J. Geophys. Res*., 99: 481488.

#5 Zebker, H.A., P.A. Rosen, R.M. Goldstein, A. Gabriel, and C. Werner (1994). On the derivation of coseismic displacement fields using differential radar interferometry: the Landers earthquake. *J. Geophys. Res* , 99: 19617-19634.

REPORT OF THE EOS IDS VOLCANOLOGY TEAM

1. ABSTRACT

This Biannual (1993 - 1995) Progress Report describes both the scientific advances and programmatic issues related to the EOS Volcanology Interdisciplinary Team. We provide an overview of the new science results that we have accomplished in support of our EOS algorithm development. These results are described in the 79 papers we have published over the last 2 years, have currently in press, or have submitted for publication. Our work includes obtaining quantitative data on the spatial distribution of SO_2 at Etna and Kilauea using thermal infrared data, the use of radar interferometry to construct digital topographic maps of volcanoes and the measurement of the area of new lava flows, the thermal mapping of lava flows in Hawaii, and the numerical modeling of atmospheric effects of the El Chichon eruption. Innovative research includes experiments with an FTIR instrument at Mt. Etna, and the development of a new low-cost ground station helps us prepare for real-time eruption detection using TOMS and MODIS. Many of our activities are related to community outreach, both at a professional level and for the general public and we describe these efforts in some detail. Functional aspects of our project management, the impact of the EOS Project rebaselining, and our plans for the future use of EOS are also given.

2. BACKGROUND

Notes for reviewers: 1) The format of this Progress Report was defined by our NASA Program Managers, and takes the form of our responses to a series of questions we were given in letter form earlier this year. 2) For reviewers not familiar with NASA acronyms, we provide a list at the end of this Progress Report.

The EOS IDS Team is one of two Solid Earth Science EOS investigations. We are the only Solid Earth team working on the analysis of volcanic eruptions, and as such have adapted our investigation to represent all of the volcanology community with respect to using remote sensing in volcanology in ways that are appropriate for EOS, and in data collection and distribution by the DAACs. There are 17 team members (see the list on page ii) and a group of 14 other collaborators located in the United States, England and Australia.

Our study will draw heavily on data from EOS instruments that will image the Earth's surface, such as ASTER, MODIS, and MISR, and on EOS instruments that primarily study the atmosphere such as TES, MLS, GLAS, SAGE III, EOSP, and AIRS. We also will be using many other instruments such as TOMS, and other instruments flown by foreign agencies, such as the ENVISAT and RADARSAT II radars.

We are highly active in trying to educate our peers when it comes to the uses of remote sensing in volcanology, and the connection between volcanological research, the effects of volcanoes on the atmosphere, and the analysis of volcanic hazards. Our IDS Team provides assistance to volcano observatories, the FAA, and the FEMA, and leads the Commission of

Remote Sensing in Volcanology under the auspices of IAVCEI. As part of our regular Team Meetings, we invite members of the volcanological community to our meetings both to provide us with an outsider's perspective and to broaden the expertise in our investigation. For the benefit of the international volcanology community, we have also prepared a report on activity at Santa Maria volcano, Guatemala, and how this volcano can be studied using remote sensing data. This report, prepared by Bill Rose and Paul Kimberly at Michigan Tech. University, can be accessed via the WWW at:

http://www.geo.mtu.edu/volcanoes/santamaria/sanmar-remote/

In addition to preparing for the EOS missions, our Team is heavily involved in several field programs related to the analysis of the 15 International Decade Volcanoes, as well as on-going studies of other active volcanoes around the world. We helped organize a Decade Volcano Workshop at Santa Maria (Guatemala) and have a workshop planned for Taal (Philippines) in late 1995. Planning is underway to collaborate with the Japanese in the study of Mt. Unzen (Japan) and Mauna Loa (Hawaii). We have experimented with the use of a Fourier Transform Spectrometer and other thermal IR sensors to monitor sulfur dioxide and HCl at Mt. Etna (Sicily). In 1993, we ran the NASA aircraft deployment to Kamchatka (E. Russia), and we have made several field expeditions to the Atacama Desert of Chile. Mapping, using satellite and aircraft data, is also underway in the Galapagos Islands and the Northern Andes, the Alaska/Aleutian arc, and Central Africa.

This Progress Report is organized along the guidelines provided to us by NASA Headquarters. As such, we must answer specific questions in terms of our progress, development of algorithms related to the EOS instruments, and management issues. We start first with a summary of the goals and objectives of our investigation. We then list our scientific, educational and policy relevant accomplishments. Keeping in mind the changing funding situation and the need for EOS investigations to be relevant to the broader NASA MTPE objectives, we then describe our programmatic contributions and the impacts that funding and policy changes have had on our work. Finally, we describe the management of all our activities.

In a limited page count Progress Report, it is impossible to describe all the science results we have achieved over the last few years. It is also important to remember that total funding for our project has been $650,000 to $670,000 p.a. for the last three years. These funds have been distributed to the 17 Team Members and their collaborators, so that the total level of support to any one Team Member averages ~$38K p.a. Over the last two years, our Team has published 56 papers in the peer-reviewed literature, published three CD-ROM sets (a total of 18 discs), and has a further 23 in press or submitted. To provide a flavor of the diversity and quality of the work that we are conducting under our EOS funding, we are attaching 5 of our recent reprints at the end of this Progress Report.

For further information about our investigation, you can access our WWW pages at:

http://www.geo.mtu.edu/eos/

We also plan to make our documentation for our algorithm development available to the public on the WWW in the Fall of 1995.

What are the goals and objectives of our investigation?

This Interdisciplinary Science Investigation's objectives are four-fold:

1) To understand the physical processes associated with volcanic eruptions, including the eruption and cooling of lava flows, the injection of eruption plumes into the atmosphere, the derivation of digital topography for volcanoes (including the analysis of topographic change);

2) To investigate the manner by which ash, sulfur dioxide, water vapor, carbon dioxide, and other volcanic gases are injected into the troposphere and stratosphere, and the chemical processes associated with this release of volcanic gases into the atmosphere;

3) To place the diverse volcanic eruptions into the context of the regional tectonic setting of the volcano;

4) To educate volcanologists, school children and teachers, the general public, and our university peers about how remote sensing can be used to study volcanoes.

How do they match with the EOS goals/objectives, and areas of scientific priority?

The closest match is with the EOS goal of understanding the role of volcanism in climate change and volcanic inputs into the atmosphere. This is one of the seven high-priority areas of EOS research and we feel that our Team has taken the leading role within the EOS Project with respect to articulating the importance of understanding eruption processes when investigating the influence of volcanism on climate. In addition, our investigation draws upon many of the Solid Earth objectives in hazard mitigation due to volcanic eruptions. Our Team has been instrumental in the development of algorithms for the near real-time analysis of transient phenomena (eruptions, wild fires) and in the derivation of digital topography via radar interferometry that will be of wide use to many Earth Science disciplines.

3. SCIENTIFIC, EDUCATIONAL AND POLICY RELEVANT CONTRIBUTIONS AND ACCOMPLISHMENTS

What are your major research findings to date?

1) We have found that TIMS images can be used to make estimates of the spatial distribution of the SO_2 content of eruption plumes. Studying the amount of SO_2 coming off of a volcano is useful for predicting future eruptions, monitoring magma chamber degassing, and determining the initial input conditions for models of volcano-induced climate change. Up until now, volcanologists have had to rely on COSPEC observations that only provide one-dimensional information, whereas the TIMS data allow the plume morphology to be studied so that short-term (several minutes) variations in gas output can be determined. Our data from Mount Etna, Sicily, indicates that TIMS data can be used to monitor volcanic emissions that are relevant to tropospheric chemistry, where we estimated the SO_2 output to be 6700 tons per day. The attached reprint by Realmuto et al. (1994) describes these results.

   This technique has also been successfully applied to the Pu‘u O‘o vent in Hawaii, and has direct relevance to the use of the ASTER instrument on the AM-1 EOS platform. Before TES is launched in late 2002, this technique for ASTER will be the only way to use an EOS instrument to measure the SO_2 content of low-altitude tropospheric plumes.

2) Studying the topography and deformation of volcanoes has long been recognized as being valuable for assessing volcanic hazards, predicting new eruptions, and evaluating the magnitude of recent eruptions. Through our work with radar interferometry we have made considerable progress in the derivation of high spatial and vertical resolution digital elevation data, and in detecting surface change due to earthquakes and the eruption of new lava flows. For instance, we have developed interferometry techniques using ERS-1 data for the Landers earthquake (California) and SIR-C data for Kilauea volcano (Hawaii). A map of the coseismic displacement field was produced for the Landers quake and a comparison with GPS and electronic distance measurement survey data yield a correlation of 0.96. These results are described in the attached reprint by Zebker et al. (1994). The methods we are currently developing based on this work show that deformation and surface change on volcanoes and other terrain types can be studied via orbital radars.

   We have also used radar phase data to map the daily progress of active lava flows at Kilauea volcano, Hawaii, at a precision beyond that which is possible using conventional field surveys, and at zero risk to the investigating geologists (working at an active volcano always entails risk). We used data collected by the SIR-C, and inferred the mass eruption rate and its distribution over a period in October, 1994. An area of ~350,000 m^2 was seen to change on a daily basis, from which we estimate the effusion rate of the volcano to have been ~2 m^3/s over a period of 4 days. This work, which has just been submitted to *Science*, offers great potential for studying the growth of lava flow fields on many volcanoes since the radar phase data are uniquely well-suited to surface change detection.

   The digital elevation models that we plan to generate via radar interferometry will be used in a variety of studies, including the analysis of the rheology of lava flows as a function of time and distance from the vent, the growth of silicic domes over periods of weeks, the prediction of the flow-paths of pyroclastic flows, and the determination of the change in volume of a volcanic cone associated with a new eruption. Our current research into the atmospheric effects on the radar phase data may also open up new areas of research in the field of “radar meteorology”. This latter experiment exploits differences in radar phase to image moisture variations in the atmosphere and may thus be of use to meteorologists and climatologists.

3) Many of our studies focus on the spatial distribution of thermal energy of an eruption, or the detection of active lava tube systems, both of which depend on the accurate measurement of the temperature and area of different parts of the active lava flow. Through our field and aircraft experiments over Kilauea volcano, we have collected the most complete daytime and nighttime thermal data ever collected over active lava flows and lava lakes. While only a small fraction of the total surface area of a flow may be involved, we have determined that the radiant flux for the whole flow is dominated by small very hot parts of the surface. This information has relevance for the numerical modeling of the emplacement of active lava flows, and the prediction of hazards due to volcanic dome collapse. It also greatly assists our interpretation and recognition of volcanic features in the much lower spatial resolution data from satellite sensors (e.g., AVHRR). Results from our observations at the Kupaianaha lava lake at Kilauea are described in the attached reprint by Flynn et al. (1993). During the EOS missions, we plan to continue this type of local monitoring to cross-check our interpretations of ground temperature as derived from MODIS, ASTER and Landsat ETM+.

4) The role of volcanic gases in the annual modification of the atmosphere remains one of the high priority research areas that our Team is focused on. Results of a radiative-convective model for El Chichon show that although ash and SO_2 have short stratospheric lifetimes, these constituents can produce instantaneous radiative forcings comparable to those of the long-lived H_2SO_4 clouds. This forcing can have dramatic consequences for plume heights and dispersal of aerosols. Using a radiative transfer model and input from a variety of remote sensing instruments (TOMS, SBUV, LIMS, SAMS, SME), we have been able to estimate the amplitude of the stratospheric radiative heating rate perturbations during the first few weeks of the eruption. One week after the April 4th, 1982 eruption, net radiative heating rate perturbations were calculated by us to exceed 20 K per day at altitudes near 26 km. Such calculations are important to EOS investigations since volcanic eruptions can have a major short-term impact on atmospheric temperatures. Results from this work are described in the attached reprint by Gerstell et al. (1995).

5) Long-term data sets will be the norm when EOS has been flying for several years, and in our IDS investigation it will be important to look for inter-annual and inter-decadal variations in the amount and spatial distribution of stratospheric volcanic SO_2 because this record will enable atmospheric scientists to evaluate the naturally varying abundance of sulfate aerosols in the stratosphere. Already, we have built a 16-year record of volcanic SO_2 in the atmosphere using the TOMS instruments. These data are of value not only for assessing where large eruptions have occurred (for example, TOMS data have provided the first indication of certain eruptions such as the December 27, 1992 eruption of Nyamuragira, Zaire), as well as the regional- to hemispheric-

dispersal pattern of the plume. We have developed a simulation model of volcanic clouds for analysis of TOMS to determine the accuracy of the SO_2 retrieval algorithm, which we have shown to be generally within 5%, except when ash and aerosols increase bias to 20 - 30%. The results of our analysis of the 16-year record of volcanic SO_2 as derived by TOMS is provided in the attached reprint by Krueger et al. (1995).

6) Knowledge of the total amount of sulfur released in an eruption and the abundances of different sulfur species erupted are important initial conditions for studies of the resultant sulfuric acid aerosols and their climate effect. H_2S can sometimes be the primary sulfur-bearing species in an eruption, but there is currently no easy way to measure the amount of H_2S in a volcanic plume. In addition, monitoring the abundance of H_2S and SO_2/H_2S ratio can help in predicting eruptions. H_2S absorption line data exist for the mid-infrared, where it is difficult to separate the effects of absorption by other gases, but they do not exist for the near-infrared. As part of our IDS investigation, we have therefore obtained new near-infrared absorption line parameters for H_2S which will allow us to use TES to measure high-temperature H_2S directly over a volcanic vent, if H_2S is abundant.

7) We have developed several new algorithms for analysis of the topography of eruption plumes. Knowing more about the topography of the plume enables us to investigate the distribution of energy in the plume via an analysis of the dimensions of vortices within the observed plume surface. Our modeling of volcanic eruption columns has also resulted in the realization that large eruptions are capable of transporting magmatic and entrained atmospheric water into the stratosphere. Previously assumed to be negligible, this water may have a significant effect on stratospheric chemistry processes. Our algorithms provide a method for assessing the height of an eruption plume, thereby permitting the altitude at which gases and aerosols are injected into the atmosphere to be determined. The same algorithms also have value for evaluating the dynamics of the eruption column, through the comparison of plume height and temperatures. The determination of plume height has significance for the assessment of hazards to air transportation, and will be tested using MODIS and MISR data from EOS.

8) We have developed a retrieval strategy for the analysis of volcanic eruption cloud particles and volcanic cloud dispersal, in preparation for the analysis of MODIS data from the EOS AM-1 platform. This retrieval algorithm was recently applied to AVHRR observations of the 1994 Rabaul eruption plume, and it was discovered that a disproportionate amount of the material in the plume was water ice. This was probably a consequence of the vent being inundated by sea water, but it raises an important question regarding the early detection of such plumes, which represent significant hazards to aircraft, since typical AVHRR band 4 minus band 5 techniques do not work. Our study of the Rabaul eruption was the first to document ice in a volcanic plume, and it has implications for volcano-climate interactions, since ice may decrease the residence time of ash and sulfur in the atmosphere.

9) We have conducted a successful field campaign to Etna, Vulcano and Stromboli (Italy) to use FTIR spectroscopy to measure several volcanic gases. We have shown that SO_2/HCl ratios can be easily measured remotely either actively or passively. We have also found that volcanic SIF_4 could be easily detected. This is an extremely exciting result, since it provides a field method that can be used to monitor changes in gas emissions without placing volcanologists at personal risk during an evolving volcanic crisis. Our field method also provides a means for estimating fumarole temperatures.

   These experiments have importance for EOS in two ways: first, validation of remote sensing measurements, and second - most important - if SO_2 can be routinely monitored by EOS instruments, knowledge of ratios from ground measurements at selected volcanoes can provide vital proxy estimates of fluxes of other gases - an important EOS objective. So far, we have found that HCl is easy to measure with an FTIR, and we are working on identifying other gases. The potential to identify HF appears promising.

10) We have measured the systematic increase in the radiant intensity of Mt. Etna summit craters before the largest flank eruption (in 1991/1992) in the last 100 years, based on the analyses of 24 Landsat TM frames. This work will have direct implications on models of the Etna plumbing system and on the connectivity of eruptive activity exhibited in the summit craters of Etna. More generally, the observation of this kind of correspondence of systematic precursor activity gives promise that systematic high spatial resolution infrared data of volcanic hotspots from the EOS AM-1 platform (ASTER, Landsat TM) could be useful in formulating predictions of eruptions.

How will these research efforts contribute to the development, validation and/or verification of models/algorithms in support of the EOS instrument team(s) of your interest?

1) Our Team has the lead role for the development of an automatic thermal alarm which will be used by the MODIS Team to detect forest fires (we will use the same algorithm to search for new lava flows). We are participating in the SCAR-C forest fire experiment (Luke Flynn was Mission Scientist for part of SCAR-C), and have had a leading role in the analysis of forest fires specifically to support MODIS Team members. This includes generating simulated MODIS data for fires for the MODIS Team, and the testing of a simulated weekly MODIS data set (from AVHRR data) for global fire detection.

2) By building the new Hawaii ground station, we intend to receive POLDER data from the ADEOS spacecraft in 1996. These data will enable us to investigate the distribution of aerosols produced by Kilauea volcano, thereby giving us (and the MISR Team) real experience in the bi-directional reflectance properties of volcanic aerosols over the open ocean.

3) We have improved the HITRAN absorption line database for H_2S and OCS and are continuing to work on improving the database for H_2S and CS_2. This will allow the TES and AIRS teams to more accurately retrieve the abundances of these gases.

4) We plan to provide the MODIS team with simulated MODIS spectra for a variety of volcanic eruption cloud types, using forward radiative transfer modeling. These will serve as test spectra for use in the Level 0 MODIS SO_2 alert algorithm and also may be used to study how volcanic clouds can affect the other MODIS instrument team algorithms, such as the aerosol retrievals.

5) We have rationalized a scheme for observing transient events with ASTER and other EOS instrumentation and published a paper in the Japanese remote sensing literature, at their invitation. This has strong implications for monitoring activities. We have identified four classes of phenomena: building activity, decreasing activity, discrete predictable events following building activity, and unexpected random events. We have identified observational scenarios (including possible synergistic use of multiple EOS AM-1 instruments) for each case.

6) We have a series of TIMS aircraft flights over SO_2 plumes (both manmade and naturally occurring; i.e., volcanic plumes). These flights are coordinated with ground and air measurements by a COSPEC which measures SO_2 in the ultraviolet region of the spectrum. We also plan to use mid-IR detectors to study the column abundance of SO_2. In this way, we have an inter-comparison of data sets that we can use to validate the SO_2 retrieval algorithm that we will be applying to ASTER thermal IR data. Team members from MISR and TES are participating in these experiments. They all want to learn more about how volcanic plumes will affect their instrument algorithms.

What are your specific plans for using existing satellite, aircraft, or in situ observations prior to the first EOS Observatory?

Before the EOS satellites are launched, the team is using analog data sets from existing instruments, including AVHRR, ERS-1, HIRS, SSM/I, UARS MLS, SIR-C/X-SAR, TOMS, TIMS, TOPSAR and Landsat. These plans can be summarized as follows:

1) **ERUPTION PLUMES:** AVHRR data will be used as a MODIS surrogate in the analysis of eruption plumes from Lascar (1993), El Chichon (1982) and Pinatubo (1991) in order to develop algorithms for plume identification and retrieval of ash loadings in young ash-rich plumes. This is especially useful for aircraft hazard mitigation, and for testing models of ash injection, transport, and fallout. ATSR data from ERS-1 and ERS-2 will be used to validate bi-directional measurements of plumes that will be made by MISR, and the photoclinometric determination of plume topography by MODIS. The topographic shape of the top surface of eruption plumes can provide information necessary to understand the physics controlling the injection and dispersal of a volcanic plume in the atmosphere. The SSM/I data are being used as an analog for MIMR and

TMI (TRMM spacecraft) observations of eruptions plumes to estimate ash eruption masses and to forecast ash fallout.

2) **RADAR DATA**: The radar data sets from ERS-1/2, SIR-C/X-SAR, and TOPSAR provide baseline topography for individual volcanoes which can be compared to future EOS digital elevation models derived from MISR and ASTER. Different orbital radar instruments are being used to gain experience in studying temporal changes on volcanoes. ERS-1 and SIR-C/X-SAR data are also being used develop experience in handling large volumes of data and in working with on-going missions. TOPSAR data for the Galapagos and Hawaii are being used to develop radar interferometry algorithms, and to serve as surrogates for digital topographic data prior to the collection of high resolution ASTER DEMs. The SIR-C data also are allowing us to develop algorithms for monitoring active lava flows.

3) **VOLCANIC SO_2:** A variety of instruments will be used to measure volcanic SO_2, since each has different capabilities (spatial and vertical resolution and coverage, temporal resolution and detection limits), but together they will provide a fairly complete picture of the global volcanic SO_2 output. HIRS is an analog for MODIS, and TIMS is an aircraft instrument similar to the mid-infrared portion of ASTER, and both are being used for the development of algorithms to map tropospheric and lower stratospheric SO_2. Different versions of TOMS have been flown on satellites since 1978 and have been routinely used to estimate amounts of SO_2 released by volcanic eruptions. Real-time Earth Probe and ADEOS TOMS data will be available to our Team via S-band receiving stations. Volcanic SO_2 maps will be disseminated to the Volcanology Team through the TOMS SO_2 WWW site. The MLS on UARS is providing experience in the interpretation of daily global maps of SO_2 that started 3 months after the eruption of Pinatubo and serves as a near-identical analog to the MLS instrument planned for the EOS CHEM platform. TIMS aircraft data are being used to test our SO_2 retrieval algorithm over an industrial smoke stack, and we hope to use AES (the airborne version of TES) or IMG (on the ADEOS platform) to provide at least a few high-spectral resolution infrared spectra of volcanic clouds for testing the TES retrieval algorithms for trace gases.

4) **SURFACE THERMAL ACTIVITY:** Multiple Landsat scenes of Mt. Etna are being used in a study of the decade-long thermal output of Mt. Etna so that we can prepare for the analysis of time-series ASTER data. These observations are being supported by field observations in Hawaii that uses portable field spectroradiometers to study the thermal characteristics of lava flows, lava lakes, and lave tubes. Other equipment that we have used to study the thermal properties of flows include SMIFTS (1 - 5 µm) and AIPS (2.4 - 5.2 µm) airborne imaging spectrometers and an AGEMA spectrometer fitted with MODIS-like filters.

5) **FIELD PROGRAMS:** As stated in the introduction, the Volcanology IDS Team is heavily involved in several field programs related to the analysis of the 15 International Decade Volcanoes, as well as on-going studies of other active volcanoes around the

world using aircraft data. At Mt. Ranier, we have initiated a combination of thermal mapping (using TIMS) and topographic mapping (using TOPSAR) to map mineral alteration and resultant hazards if there are avalanches and mud flows. We also have plans to fly the TOPSAR radar interferometer to the Western Pacific so that we can start building a data base of digital topography of volcanoes prior to the first stereo ASTER scenes.

How does your investigation contribute to policy relevant objectives of MTPE/EOS?

Our Team is one of the few IDS investigations working on volcanoes and the impact of volcanoes on the atmosphere. We are the only team that focuses on the volcanoes, volcanic processes, and injection of volcanic materials into the atmosphere. As such, our investigation has a major contribution to the MTPE/EOS objective to understand the impact of volcanoes on the climate. We are also heavily involved in the assessment of how well satellite remote sensing can be used to evaluate volcanic hazards, which is a NASA MTPE objective.

One of the cross-disciplinary studies that we have become involved in is the analysis of fires, since these will directly impact our ability to automatically detect new volcanic thermal anomalies; fires represent “noise” in our data base of volcanic thermal events. Through our work on fires, we are also providing significant input in the area of biogeochemical cycles, since forest fires have a major impact on the amount of carbon monoxide and carbon dioxide in the atmosphere. The amount of each of these gases is, in part, controlled by the flame temperature, so that by developing quantitative methods for the sub-pixel analysis of fires (and lava flows), we can help constrain the amount of these gases released into the atmosphere.

How does your investigation contribute to the educational objectives of MTPE/EOS?

1) We feel that our Team has done an excellent job in establishing outreach to our peers in the volcanology community at large. We have sent out a questionnaire by E.Mail and posted it on the Web to allow people to provide comments on our planned data products. At our last team meeting, we solicited input from special invited guests: Jon Fink (Arizona State University), Terry Gerlach (USGS-Cascades Volcano Observatory), and Chris Nye (USGS-Alaska Volcano Observatory). We have also run a remote sensing in volcanology workshop at the Canberra, Australia, IAVCEI meeting in 1993. For more junior volcanologists, we have just run (in mid-August 1995) a week-long field workshop in Hawaii which will include the analysis of airborne and spaceborne data sets over volcanoes. Steve Self is the leader of the Decades Volcano Workshop at Taal in the Philippines in October 1995, where we will present many of the uses of remote sensing of Taal to the international volcanology community. Finally, when talking to the EDC and other EOSDIS DAACs, we provide them with information about not only our team's data needs, but the needs of the whole volcanological community.

2) Bill Rose is trying to stimulate international electronic communication about the methods that can be used to locate and monitor volcanic clouds and to define the limits of their hazard to aircraft. He has developed his own WWW site in order to provide outreach to volcano observatories, investigators working on Central American volcanoes, and the FAA.

3) As part of our outreach efforts, we have established a new Remote Sensing Commission through IAVCEI. As part of these IAVCEI activities, we helped organize a special session at the July 1995 IUGG. We also have established a newsletter that is sent to ~600 volcanologists worldwide, and established several WWW Home Pages, including one specifically for our EOS investigation. The EOS IDS Volcanology Team World Wide Web page has had 25,000 connections to its Home Page, and 10 times that many connections to its full set of Web pages. Currently this translates to 75 per day to the Home Page, and 1100 per day to all our Web pages. Detailed information about the team's activities is provided, including four educational outreach slide sets on a variety of volcanology/remote sensing topics, and an on-line report: "Development of an Educational and Outreach Panel for the EOS Science Executive Council". Assistance is provided in response to E.Mail inquiries made by school teachers and students who read the Web pages and have further questions. In addition, the P.I., Chuck Wood and Lori Glaze attend meetings of the NASA Science Data Over Internet program and advocate greater interactions between this program and EOS program.

4) The P.I. Chairs the EOS SEC Education and Outreach Panel, and is assisted by Jonathan Gradie (also on our Team). Together with Lori Glaze and Chuck Wood, they attend meetings of the National Space Grant Consortia and make presentations on the educational goals of the EOS project and the EOS IDS Volcanology Team.

5) Lori Glaze has been instrumental in the production of three CD-ROM sets of volcanological data that have been distributed to the community. These sets cover Kilauea, Mauna Loa and the volcanoes in Kamchatka, Russia, and they have been in high demand from geologists both within and outside the United States. Data sets on the CD-ROMs include: AIRSAR, AVHRR, Landsat, TOMS, TIMS, SPOT and SIR-C. This activity has helped our Team educate many people into the uses of remote sensing data for volcanoes.

6) Dave Pieri has participated (with JoBea Way) in JPL KidSat workshop on surface processes, and has been fielding E.Mail responses from participants, promoting the EOS AM-1 platform as a potential future resource for secondary school science students. We expect to be involved in a KidSat workshop that specifically relates to the study of volcanoes from space in the not too distant future.

7) Howard Zebker has assembled the radar and interferometer processing codes for distribution. Howard also hosts community scientists at JPL to learn about interferometry. In this way, more of the EOS science community will become proficient in the analysis of radar interferometry data, which we believe will be one of the main ways that Earth scientists will obtain digital topographic data in the EOS Era.

8) Jonathan Gradie has had a series of satellite-linked discussions with community college professors in Guam and Saipan about the value of remote sensing for Pacific studies. He has given 10 one-hour talks over the past year, and has helped several faculty identify remote sensing data sets that could help them at the local level. His involvement with EOS gives him the in-depth knowledge to talk about global change and place volcanism into this context.

4. PROGRAMMATIC CONTRIBUTIONS/IMPACTS

What are your contributions to the EOS program planning and evaluation?

1) The P.I. serves on ESSAAC (which is the main advisory group to the NASA MTPE Associate Administrator) and on the EOS Science Executive Committee (SEC). This work has also included contributing to the draft plan for the MTPE Plan for the Natural Hazards Program.

2) The PI and several team members are contributing to the chapter on “Volcanoes, Aerosols, and Climate Change” for the EOS Science Implementation Plan.

3) Arlin Krueger, as P.I. for the Total Ozone Mapping Spectrometers, has made the Earth Probe TOMS ready for launch, but is currently waiting for a successful test of the launch vehicle. We also have a test of real-time TOMS data collection by NWS/Anchorage planned after EP launch.

4) We have drafted a Memorandum of Understanding with NOAA/NESDIS for the near real time production of volcanic data from Earth Probe TOMS.

5) We will also make major contributions to future missions since Arlin Krueger will have a TOMS instrument on ADEOS (planned for an August 1996 launch) and on Meteor 3M (August 2000 launch).

6) We have drafted a Memorandum of Understanding with the Goddard DAAC for archival and distribution of TOMS volcanic data products.

7) The PI was the joint leader of the chapter on Volcanoes, Aerosols and Dust (Chapter 10) of the EOS Science Plan.

8) The University of Hawaii has almost completed a Memorandum of Understanding with NASDA, the space agency of Japan, for the reception of JERS-1 and ADEOS data in Hawaii. This capability will enhance the EOS Program’s capabilities to use ADEOS data by providing greater data access. In addition, these data will promote the more rapid development of data systems and direct broadcast capabilities that could serve as enhancements to the ones being planned for EOSDIS.

What are the most important EOS standard data products you plan to use?

1) MODIS Level 1B top-of-atmosphere radiance [MOD02] data for volcanic clouds will be used with retrieval algorithms to derive maps of SO_2, plume height and topography, and particle size distribution, type (ash, H_2SO_4, water, ice), and mass loading. Level 1B data will also be used to test new thermal and SO_2 alert algorithms. Low spatial resolution maps of hot surfaces will also be produced using MODIS Level 1B or we will use the [MOD11] surface temperature products to monitor thermal activity.

2) For studying thermally active areas (lava flows, lava lakes, fumarole fields) and producing maps of surface temperature and temperature change, we will use: ASTER Level 1B2 top-of-atmosphere radiance [AST03], surface emissivity [AST05], decorrelation stretch [AST06], surface temperature [AST08], surface radiance [AST09], and digital elevation [AST14].

3) Supplementary products that we require for the retrievals described above include: MODIS temperature and humidity profiles [MOD30], AIRS temperature and humidity profiles [AIR05, AIR07], land temperature and albedo, and geolocation [MOD11, MOD09, MOD03].

4) MODIS Level 0 data will be used in near-real time to detect hot thermal anomalies and volcanic SO_2. This will alert the team and volcanologists on site to eruptions before they might otherwise be alerted.

5) Other important standard EOS products our team will use to study volcanic clouds include: MLS profiles of SO_2, HCl, H_2O, and temperature; MISR geo-rectified top-of-atmosphere radiance [MIS03], cloud-top elevation [MIS04], aerosol composition [MIS08], and aerosol optical depths [MIS05]; MODIS aerosol optical depth and size distribution [MOD04 and MOD05]; SAGE III aerosol extinction profiles [SAG02]; TES Level 1B radiance, retrievals of HCl, HF, SO_2, H_2S, OCS, CO, H_2O, CO_2, and profiles of temperature and humidity; AIRS Level 1B radiance [AIR02]; MIMR Level 1B radiance [MIM01]; GLAS cloud height [GLA06], aerosol optical depth [GLA09], and aerosol profiles [GLA05]; EOSP aerosol optical depth and particle size, and water/ice phase [EOS04]; and HIRDLS aerosol extinction coefficient [HIR02].

6) Other important standard EOS products we will use to study surface processes are: MISR digital elevation [MIS10], GLAS along-track topography [GLA04], fire temperature [MOD14] for comparison with our thermal alert, TMI brightness temperatures [TMI-1], PR reflected energy [PR2], and VIRS Level 1B data [VIRS-1].

Are there other data products you will need that are not from AM-1 or TRMM, and are they available elsewhere?

We need the data products listed below, which are available through the EOS DAACs, through NOAA, or other data providers:

1) Most importantly, we need frequent access to the raw radar signal samples (ENVISAT ASAR, Canadian RADARSAT 2, ERS-1 and ERS-2, JERS-1 and 2) in order to perform the topographic mapping and surface deformation studies associated with surface activity and volcanic hazards. EOSDIS is expected to archive the radar data from the ASF DAAC, but we will also need data from other ground stations around the world.
2) SO_2 maps from a variety of TOMS instruments aboard Earth Probe, ADEOS, Meteor-3 (archived in GSFC DAAC).
3) Wind profile data (NMC-grid from NOAA or 4D Assimilation Office).
4) Radiosonde profiles of temperature, wind, and pressure.
5) GOES and GMS visible and infrared images (weather satellites).
6) ADEOS Level 1B data from POLDER, IMG, AVNIR, OCTS (receiving station at Univ. Hawaii; or through IDS Volcanology Team members who are ADEOS PI's).
7) Landsat-7 Level 1B radiance data.
8) SPOT 4 stereo MSS and high resolution b/w images.

Do you plan to create any standard products as part of your investigation?

We plan to create 23 different Level 4 special data products. All but MOU81-3281 will be archived in the EDC DAAC. MOU81-3281 (TOMS SO_2 maps) will be archived in the GSFC DAAC.

Table 1 is a listing of the status of each of our products, the data volume to be archived, the time scale under which each product will be produced, and additional comments on how they will be used. Note that all of these products have been discussed with representatives from the Eros Data Center DAAC and with Hughes EOSDIS Core System.

What steps have you taken to identify your EOSDIS needs/contributions?

1) The PI and Joy Crisp required the team to develop Data Product Documents that outline the scientific basis of each algorithm, data input requirements, and data output product description (parameters, file types, data size, spatial/temporal resolution, uncertainties, validation, etc.). We polled the volcanological community (via the Volcano List server and our WWW Home Page) to assess their data needs and incorporated that into our plans. Then the PI and Joy Crisp met with EDC DAAC representatives at EDC to discuss the plans for archiving IDS Volcanology data products and for archiving instrument products the Volcanology team will be using (radar, ASTER, MODIS). The DAAC representatives were provided with draft copies of our Data Products Documents. We have begun a dialogue to define our data product and metadata characteristics, schedule for archiving, user support, and software distribution needs.

2) Arlin Krueger met with GSFC DAAC representatives to discuss plans for archiving the IDS Volcanology data product: TOMS SO_2 maps. He is finalizing a Memorandum of Understanding between the GSFC DAAC and the Goddard Stratospheric Dynamics and Chemistry Branch for archival of the volcanic data products from Earth Probe and ADEOS TOMS missions.

3) Lori Tyahla of the ECS visited the Univ. of Hawaii to help determine the User Scenario Functional Analysis for EOSDIS. Bob Curran, Bruce Moxon, and Femi Babalola (all from Hughes ECS) made separate visits to the Univ. of Hawaii and JPL to discuss the EOSDIS architecture, and our EOSDIS needs and concerns. We have found Tom Dopplick at ECS to be a good source of answers to our questions about EOSDIS.

4) We have tried to identify specifically what channels of MODIS data will be needed, and we are ~90% ready to define the channels we will use. In particular, Luke Flynn has been in regular contact with Al Fleig at Goddard to ensure that our data needs for near real-time analysis will be met. We have estimated the number of requests/year that we anticipate, as well as the number and sizes of each of the output data products that will be archived by EOSDIS.

5) Dave Pieri has begun to investigate data volume and throughput for time-series studies of a variety of volcanic targets, with a view toward monitoring precursor phenomena, as well as eruptions themselves. The Etna time-series Landsat TM study serves as a good prototype. As the U.S. ASTER Team Leader, Anne Kahle is helping assess the impact of Volcanology IDS Team on ASTER throughput and operations. This will require systematic, time-series observations for a basic suite of targets from ASTER and MISR. Volcanology IDS Targets will include (1) algorithm validation targets (test sites), (2) base level monitoring of sites likely to be active, and (3) targets of opportunity (monitoring of targets experiencing correlated geophysical crescendo phase activity). ASTER Instrument Calibration and Validation Test Sites will also be of interest to both confirm ASTER instrument performance at volcanic sites, and provide calibration with respect to MISR and MODIS instruments.

6) Other EOSDIS-related activities include those of Lori Glaze, who has attempted to estimate how much data (and what types) will be needed for data product generation. This includes an estimate of the size and frequency of transfers to the DAAC of the compiled data products. Vince Realmuto attended the ECS seminar at JPL. He has also developed an interactive graphic user interface for the recovery of SO_2 abundances in an eruption plume. This code will be distributed via the DAAC.

7) We have submitted detailed estimates of our Team's data needs (parameter by parameter) for the 1996 — 1999 timeframe to the EOSDIS Project. We also submitted detailed entries (Table 1) to EDC for the products our Team will be creating, to be included in the EOSDIS Science Data Plan.

How has the EOS restructuring and downsizing affected your research plans?

High resolution digital topography remains one of our greatest needs for many of the morphologic studies (and volcanic gas retrievals) that we are planning. The current inability to fund the SRL-3 Shuttle, or any other, interferometric radar mission leaves us, and the rest of the EOS community, with a major gap in our data base. We originally thought that the loss of EOS SAR would be a major impediment to our ability to perform high spatial resolution mapping of volcanoes on a timely basis. However, the more we look into the capabilities of ERS-1/ERS-2 and ENVISAT's ASAR the more confident we are that we will be able to have frequent site revisit capability with sufficient signal to noise to perform many radar interferometric studies.

We are concerned that AIRS dropped spectral coverage at 8.2 — 8.8 µm in 1992. This is particularly important to us for the determination of sulfur dioxide, and we are in contact with the AIRS Team to keep them aware of our requirements.

We are very disappointed that after AM-1, there will be no high spatial resolution thermal infrared instrument — ASTER will only fly on the first generation of the morning platform. ASTER is needed not only for low temperature thermal studies, but also for SO_2 mapping. While it is recognized that there was only one ASTER planned, the restructuring and down-sizing of EOS means that the chances of a multispectral thermal IR instrument flying on Landsat 8 is very slim so we will loose significant capability after the demise of AM-1.

The capabilities of Landsat 7 and 8 are of great interest to us, since they may enable us to perform some of the mapping that we had originally expected from HIRIS. We await the launch of the Lewis spacecraft with the HSI to see if this will produce useful data for us to map thermal anomalies. For now, we are having to plan for MODIS.

Budget restrictions have also prevented us from developing adequate expertise in the analysis of volcanic gases in preparation for TES and MLS data. Peter Francis has been trying to carry out a series of FTIR observations of volcanic gases at Mt. Etna and Hawaii, which will probably be our Team's two main data validation sites during the EOS missions. However, limited funding has prevented us from fully exploring this technique. We would also like to participate in the AES flight experiments as/when they fly over volcanic sites, but we have insufficient funds to commit people to this activity.

What are your short-, mid- and long-term products/deliverables?

All our data products (listed in Table 1) and user-interactive software packages will be ready at or soon after launch. A few of the radar-derived products will be archived at EDC DAAC a year or two before the AM-1 launch. The first set of Data Product Documents will be made available on the World Wide Web during Fall 1995. Between now and launch, several papers will be published which demonstrate the use of our algorithms with input from airborne or satellite instruments similar to those planned for EOS.

Several of our user-interactive software packages are being beta-tested, and one (a package for the analysis of digital topography) is already available via our WWW site. These user-interactive software packages include: 1) Eruption cloud particle retrievals; 2) DEM analyses; 3) Thermal-IR SO_2 retrievals (TIMS as an ASTER analog); 4) The derivation of eruption plume top topography; and 5) The analysis of ground temperature anomalies and change.

In the short term, we want to have an alpha version of the software that creates the output products completed for testing with test data sets created by the EOS instrument teams. Mid-term product would be a revised beta version of the same software that should be more rigorously tested, perhaps outside of the EOS team. Long-term deliverables will be the operating version 1 of the software and the production of actual output within the six months of AM-1 launch.

A specific product that we want to generate and deliver to the EDC DAAC in FY96 is a set of six digital elevation models of volcanoes that we produce via radar interferometry. This will not only challenge us to work all of the issues of phase unwrapping and understand the environmental effects associated with the radar interferometry technique, but also will force us to understand the data ingest requirements at EDC thereby preparing us for routine Level 4 data production.

What role does your team play in defining directions and requirements for the DAACs and Pathfinder program?

We make specific visits to Goddard, EDC and ASF to define their interactions with our Team. This includes working with the DAAC scientists on how our Team's data will be archived at each DAAC. A case in point during FY96 will be our production and delivery to EDC of six digital elevation models of volcanoes that are of high interest to the general volcanology community (for details of this activity, see the section on Budget Description).

The PI will chair the ASF DAAC User Group, and has already had several discussions with the Interim DAAC Chief Scientists about how the Alaska DAAC can better serve a broad range of the Earth Science Community. The identification of new Pathfinder data sets derived from SAR data obtained at the University of Alaska Fairbanks is one of the objectives of this User Group.

Team members have participated in the EOSDIS Product Use Survey and have contributed suggestions to the DAACs and EOSDIS Version 0 IMS after "tire-kicking" the DAAC software. We also intend to do beta-testing of the new version of EOS-View software planned for distribution in late summer, 1995.

The TIMS data set will be a major component of Version 0 at the EDC DAAC. Vince Realmuto has worked closely with EDC to ensure that these data are correctly placed into the DAAC.

Arlin Krueger is establishing an Earth Probe TOMS ground reception facility at Fairbanks so that the ASF DAAC can learn how to process the TOMS data for retrieval of volcanic sulfur dioxide. This capability should be available by the end of 1995.

Through our own ground station in Honolulu, we will be beta-testing many of the aspects of direct broadcast that will be available from MODIS. We plan to use MOS-1, JERS-1 and, hopefully, ADEOS data to test the routine operation of our algorithms prior to the DAACs coming on-line, and to provide them with real information on user demand and the validation of data products in the 1995 - 1996 timeframe. This testing includes data archiving and the rapid dissemination of data (in the form of "event alarms") to the community.

As an aside, under funding that is separate from our EOS investigation, we have been collaborating with Dr. Torben Nielsen (Univ. Hawaii) on the development of low cost satellite ground stations that can receive EOS Direct Broadcast information. We have the first of our antennas built, and are constructing a second. As part of this effort, we have many high-level discussions with NASA's International Relations Office, NASDA and ESA to ensure that the data are transmitted. The final result of this is that we will have an independent data collection and distribution system that could serve as an EOSDIS surrogate should Federal funding for EOSDIS be drastically reduced in FY96. We are also planning to become major participants in the collection and interpretation of ADEOS data to help the Japanese; a function that should help NASA's collaboration with our international partners.

5. MANAGEMENT OF THE INVESTIGATION

How is communication within your team coordinated?

We use a variety of methods, including annual team meetings, postings on a private World Wide Web site, E.Mail, phone, and fax. Some communications also occur when several members meet at an AGU or IAVCEI meeting. In addition to regular mailings from the P.I., Joy Crisp was appointed as the Deputy Team Leader in Fall 1992 so that the Team has two points of contact when issues come up. A series of "Milestones" have been developed for each Team Member so that they know what they are expected to be working on each year, as well as how their work fits into the broader EOS objectives. These milestones are used to assess performance throughout the year, and are one of the primary ways that the Team Leader decides on future years' budgets. Joy and Pete meet or call the Team on a regular basis to talk over objectives and activities related to the Milestones.

Several collaborative efforts within and beyond our team are helping to build a coherent research team. The role of volcanism in climate change is bringing several of us into contact with the atmospheric community. Similarly, we expect that our involvement with several of the Decade Volcano projects will enable collaborative work on topographic mapping and volcanic hazards, as well as bring us into contact with the USGS and foreign volcanologists.

An Educational Specialist and Fiscal Officer at the University of Hawaii keep track of all of the Team's performance and, for the non-field center members, track their sub-contracts for the Team Leader.

How have team members contributed to your successes?

There are really two levels of participation in the Team's efforts by the Team Members. About 80% of the work is done by 10 people, and the remaining 20% is done by the other members. Not surprisingly, this is reflected in the differing levels of support provided to the Team by the P.I.

Joy Crisp is indispensable as the Deputy Team Leader for this investigation. She has taken on many of the detailed technical aspects of the data products that all of the Team produces. She attends the IWG meetings, and travels to the EDC DAAC for the benefit of our investigation. In addition, she has major responsibilities for volcanic gas studies, keeps track on data systems issues, and maintains the Team's Web site.

There is a group of algorithm developers that have taken on the task of ensuring that our Level 4 products will be scientifically accurate, delivered on time, and that we have correctly identified the data volumes involved. These people are Joy Crisp, Luke Flynn, Lori Glaze, Vince Realmuto, Bill Rose, and Howard Zebker. We expect Fred Prata (who has just joined our Team) to join this group. Collectively, these individuals have assembled documents on the physical basis for each of the Level 4 data products described in Table 1.

The rest of the Team contributes through participation in field activities, collaborations on specific research projects that use analog data sets, or in outreach to the general community (which is led by Jonathan Gradie). Peter Francis has been instrumental in running a field program to use an FTIR spectrometer to study volcanic gases. Dave Pieri has had extensive collaborations with the Russians as a result of the 1993 field campaign. Anne Kahle and Arlin Krueger provide crucial insights into the development of the ASTER and TOMS instruments. Interaction with other Federal agencies (e.g., NOAA, FAA, FEMA), and how our EOS work can help in hazard mitigation, is an important role that Lou Walter plays on the Team. Lionel Wilson provides much of the theoretical basis for some of the plume algorithms, and Steve Self and Chuck Wood provide great depth of experience in the geology and eruption characteristics of many volcanoes around the world.

Do you have any flexibility for shifts in your research priorities? Are any needed?

At one level, we feel that our Team has shown remarkable flexibility in its ability to adjust to changes in scope of EOS instrument selection because most of these instruments can be used to study volcanoes and volcanic phenomena. However, in terms of fiscal issues, we have almost no flexibility. Responding to changes in science priorities in volcanology is becoming very difficult now, since we have been almost level-funded for the last three years.

Areas where we need to concentrate more effort are the validation of satellite data sets via field programs and the use of aircraft. This is true for volcanic gas studies (using TIMS and FTIR), topographic mapping, and for the investigation of thermal anomalies.

The only way we can gain flexibility is through budget augmentations argued on a case-by-case basis. A case in point is that in order to carry out the production and transfer to EDC DAAC of six digital topographic maps of volcanoes, we are requesting a budget augmentation in FY96 of $30,000.

Do you foresee changes in your requirement for staff, expertise, or equipment?

Over the last two years we have added three new members to our Team to fill specific gaps in our expertise. Vince Realmuto was added to provide the quantitative analysis of thermal infrared data, particularly in the imaging of SO_2 plumes. Fred Prata was added for his skills in radiative transfer modeling of the atmosphere, as it applies to the detection of volcanic eruption plumes using AVHRR and MODIS data. Fred is also a member of the ERS-1 ATSR Team, and as such can provide the Volcanology team with detailed knowledge of the use of this bi-directional data set for aerosol mapping and the stereo imaging of eruption plumes. Luke Flynn was added because of the growing demands of our work on the analysis of thermal anomalies using MODIS and ASTER. In addition to these new Team Members, we expect to add Lori Glaze to our Team as an official member as soon as she secures a permanent position (she is currently a post-doc at GSFC). Lori is already providing significant input to the Team for the development of algorithms that will determine eruption plume height and topography using photoclinometry.

Additional support people have also been included. Bill Rose has added a Ph.D. physicist/programmer to support his algorithm development. We may need to add more support staff with expertise in HDF and World Wide Web system administration. For many of the radar studies, the University of Hawaii has called upon existing faculty members for support. Gerard Fryer and Stan Zisk have been most helpful in this capacity, and will most likely expand their work on algorithm development for the measurement of topography using radar interferometry.

In terms of hardware, most of the team members will require additional hard disk space as we approach the launch of AM-1. We also envision at least one major upgrade to the workstations used by the group of 6 algorithm developers (Crisp, Flynn, Glaze, Realmuto, Zebker, Rose) in about 1997.

What collaborations have you pursued with other EOS, non-EOS, or non-NASA investigations (including international efforts) and how have they benefited or contributed?

Gregg Bluth is working extensively with Mark Schoeberl's Stratospheric Dynamics IDS Team, using the rate of dispersal of eruption plumes (detected by the TOMS instrument) as a test for the wind trajectory models of Schoeberl.

Even before he joined our Team (in July 1995), we had entered into a major collaboration with Fred Prata at CSIRO in Australia on the analysis of ADEOS data for eruption plumes. Steve Self and Pete Mouginis-Mark are Co-I's on Prata's investigation. This study will include the analysis of data of eruption plumes using the IMG, AVNIR, POLDER, OCTS, and TOMS instruments. This collaboration will be highly beneficial to our IDS Team, since Fred Prata and his team have very strong expertise in radiative transfer modeling, atmospheric chemistry and the modeling of aerosols in the atmosphere.

Collaborators participating in a ground/airborne campaign to test infrared retrieval algorithms for SO_2 emitted from a power plant June 1995 include: Stan Williams (Arizona State Univ.), Philip Kyle (New Mexico Tech.), Jack Margolis (TES Instrument team), and Jim Conel (MISR). They will be contributing by making coincident measurements of the SO_2 using different instruments which can be used to validate Vince Realmuto's retrieval algorithm for ASTER, and everyone will benefit from the comparison of the results using all the different approaches. Similar plans are being made for an August 1995 deployment of the airborne TIMS to Hawaii, with participation by personnel from the USGS Hawaiian Volcano Observatory (using COSPEC) and Terry Gerlach (USGS-Cascades Volcano Observatory).

Pete Mouginis-Mark has established a collaboration with Drs. Torben Nielsen, Gerard Fryer, Stan Zisk and Mike Bevis at the University of Hawaii to build and operate our own X-band satellite receiving station. We built this in 6 months, and are currently working with NASDA (Japan) and ESA (Europe) to get formal memoranda of understanding to acquire data from foreign satellites. An aspect of this has been that our IDS Team has had a major impact on technology development within the ground station community, as well as the development of a low-cost radar processing capability.

Luke Flynn has become heavily involved in collaborative work with Chris Justice on the MODIS Team. They are both very interested in the determination of the temperature of forest fires using MODIS, and the development of real-time detection algorithms for the global analysis of hot spots (either volcanic eruptions or fires). This collaboration has led to Luke joining some of the fire experiments, attending the Chapman Conference on biomass burning, and helping to develop test data sets for the MODIS team using AVHRR data.

A second ADEOS Team is led by Vince Realmuto. The title of this investigation is "The use of ADEOS data to detect and monitor volcanogenic SO_2 in the atmosphere". This project includes five people included in our IDS Team (Realmuto, Crisp, Pieri, Glaze, and

Bluth), and will ensure that the Volcanology IDS Team has good representation on this Japanese mission.

Collaborations between Bill Rose and other investigators include:

Alaska Volcano Observatory, University of Alaska, USGS, State of Alaska, National and Alaskan Weather Service -- we will be providing them with tools for mapping eruption cloud dispersal and particle maps.

Guatemalan Government -- we have provided assistance showing them how remote sensing can be used to monitor and assess volcanic hazards at Santa Maria Volcano.

James Coakley (Oregon State University) provided assistance to us on how we could adapt his cloud particle retrieval algorithms to volcanic clouds.

James Weinman, (NASA Goddard, Microwave Remote Sensing Branch) has assisted us with microwave retrievals.

Peter Francis has collaborated with Charles Chaffin (Dept. Chemistry, Kansas State Univ.), Clive Oppenheimer (Cambridge) and Tommaso Caltabiano (Catania, Italy) on ground-based FTIR measurement of SO_2 and HCl at Mount Etna. Chaffin provided assistance with the data analysis techniques and Caltabiano provided contemporaneous COSPEC measurements. Francis participates in a European Community program to monitor and study Etna's gas plume.

Pete Mouginis-Mark met with a large group of British remote sensing volcanologists in England in July 1995 to outline collaborative efforts that the NASA EOS Team may be able to undertake in conjunction with English efforts to prepare for ERS-2 and ENVISAT.

Steve Self has been the leading U.S. scientist in the implementation of the decade Volcano Workshop to be held at Taal volcano, Philippines in October 1995. As such, he has had to work very closely with R. Punongbayan, who is the Director of the Philippine Institute of Volcanology and Seismology.

Anne Kahle is the U.S. Team Leader for ASTER, and Dave Pieri is also on the ASTER team. This strong link to the ASTER Team is vital for us since we need to work the issues of rapid instrument targeting in order to catch transient events. Both Kahle and Pieri work with the Japanese to ensure that this capability stays as part of the overall ASTER Science Plan.

Arlin Krueger has developed plans to share our TOMS SO_2 maps with the ADEOS POLDER Team. Arlin Krueger, Bill Rose, and Gregg Bluth are working together on a project involving the comprehensive comparison of TOMS and OCTS for volcanic clouds.

Which EOS Instrument Teams have you communicated with, and are you satisfied that your needs and concerns are being addressed?

MODIS -- very satisfied that our requirements for the thermal alarm are being considered. One of our collaborators (Luke Flynn) is working very closely with Chris Justice and Yoram Kaufman on the fire and volcano alarm for MODIS. Flynn attends MODIS team meetings and keeps the rest of the team informed about the MODIS activities, including the potential use of the MODIS Airborne Simulator for thermal mapping of lava flows. Ed Knight (of the MODIS Team) has provided Luke Flynn and Joy Crisp with the preliminary spectral response functions for MODIS. Jennifer Davis (MODIS SDST Algorithm Transfer and Integration Specialist) has kept us aware of MODIS software development plans.

ASTER -- Anne Kahle on our Team is the U.S. Team leader for the ASTER Team. Dave Pieri is a Team Member for both our IDS and the ASTER Teams. Pieri is working on coordinating the list of volcanoes for regular monitoring by ASTER, and we have provided Kahle information about the team's requirements and the volcanological community's requirements. Pieri and Kahle keep the team up-to-date on the details of data requests, instrument capabilities, and data products.

MISR -- Lori Glaze from our Team has contacted Dave Diner concerning the cloud topography data product. We also expect to be interacting more closely with MISR due to our increasing interest in using the ERS-2 ATSR as a MISR analog for study the three-dimensional properties of eruption clouds. In addition, Vince Realmuto has worked with James Conel on the calibration of the sensor. This is in connection with a joint IDS Team/MISR/TES field experiment that we are running over a power plant's smoke stack to validate algorithms for SO_2 retrieval and the analysis of volcanic aerosols.

TES / MLS - Joy Crisp is in regular contact with Reinhard Beer (TES) and Joe Waters and Bill Read (MLS) about the characteristics of their planned EOS data products and pre-EOS data (e.g., airborne version of TES called AES, UARS MLS) that will be available for testing. As Reinhard Beer is on the ADEOS IMG team, he also keeps us informed about IMG. Vince Realmuto is in contact with Jack Margolis of the TES team with questions about their retrieval algorithms.

SAGE -- One of Michigan Tech's graduate students, Dave Delene, worked with the SAGE Team at Langley for a summer in order to better understand the analysis of stratospheric aerosols using SAGE II. Steve Self is also frequently in contact with Pat McCormick (SAGE III P.I.) about the interpretation of the aerosol data for volcanic eruption plumes.

AIRS - Joy Crisp contacts Sung-Yung Lee for questions about the AIRS instrument and data products, and keeps us up-to-date with the AIRS documents posted on the WWW.

GLAS - The PI has discussed with Jay Zwally the possibility of using the laser altimeter on GLAS to measure volcano topography and the height of volcanic eruption plumes.

6. CHANGES IN RESEARCH DIRECTION AND PLANS

What changes have you made in your research direction?

1) Since our original proposal, we have veered away from using HIRIS to do geologic mapping types of studies and instead concentrated on studying topography, thermal activity on the surface, and eruption clouds.

2) We have found that radar interferometry offers great prospects for topographic mapping and topographic change detection on volcanoes. Howard Zebker, along with Stan Zisk and Harold Garbeil from Hawaii, have made great strides in the development of an interferometry code that can be applied to the data collected by the second Space Shuttle radar (SRL-2) flight.

3) Since the discovery by Vince Realmuto that we can map the abundance of SO_2 using TIMS data, more of our Team's efforts have been focused on validating these measurements in preparation for ASTER observations. This validation includes more field experiments in Arizona (power plant with controlled SO_2 output) and Hawaii (volcanic degassing).

Do you envision any changes in direction of your research in the near future?

1) We plan to have more emphasis on testing and validation of volcanic cloud particle retrievals, and on testing and validation of infrared SO_2 retrievals. New interest by Bill Rose has arisen in microwave observations of eruption clouds by SSM/I and MIMR. He has shown that microwave imaging can be used to estimate eruption masses and to forecast fallout during an eruption.

2) With the addition of Fred Prata to our Team (in July 1995), we now have access to the extensive ATSR data sets collected by ERS-1 and ERS-2. These data are, to our knowledge, the best analogs for MISR bi-directional data, and as such, ATSR data will help us prepare for stereo mapping of eruption plumes using MISR. In addition, we wish to run some of our photoclinometric code for determining plume topography and then perform parallax studies with the ATSR data in order to validate our photoclinometry algorithm.

What progress have you made to date on the weaknesses identified in the last review of your investigation, which were:

1) <u>Contact EOSP science team</u>. We have not done this, as EOSP will probably not launch until 2004 at the earliest -- we are kept very busy trying to interact with Instrument

Teams that have instruments flying on AM-1, PM-1 and CHEM. Plus, we are putting a large amount of effort into the foreign satellite data sets -- only so much time!

2) Contact SAGE III science team. Steve Self is in regular contact with Pat McCormick regarding the SAGE experiments.

3) Strengthen ties to other IDS Teams:
Last review we were directed to contact the teams led by Grose (Observational and modeling studies of radiative, chemical, and dynamical interactions in the Earth's atmosphere), Hartmann (Climate processes over the oceans) and Pyle (Chemical, Dynamical and Radiative Interactions Through the Middle Atmosphere and Thermosphere). However, we really do not have much in common with these teams, since we focus on the surface and near-vent areas for the study of eruption plumes. The PI has worked with Hartmann on writing Chapter 10 of the EOS Science Plan, so there has been some discussion of our different disciplines. However, we feel that our time is much better spent by our team collaborating with Mark Schoeberl's IDS team -- for example, on the study of the Rabaul eruption cloud with Bill Rose and Paul Newman (Co-I on Schoeberl's IDS Team).

We have nevertheless had considerable interest from several IDS Teams regarding our development of radar interferometry code for the generation of digital topographic data. Bryan Isacks (Climate, Erosion, and Tectonics in Mountain Systems), Soroosh Sorooshian (The Hydrologic Cycle and Climate Processes in Arid and Semi-Arid Lands) and Thomas Dunne (Long-Term Monitoring of the Amazon Ecosystems Through EOS: From Patterns to Processes) have all asked us if we can generate digital topographic maps of their study areas using radar interferometry. We hope to supply them with some of these maps in the coming year.

Finally, Luke Flynn has started to establish ties with other IDS Teams through his interests in forest fires. The greatest interest comes from the team lead by Piers Sellers (Biosphere-Atmosphere Interactions), where Chris Justice is the team member that we talk most to. Luke served as Mission Scientist for the 9/94 Smoke, Cloud and Radiation experiment, and attended the Chapman Conference on Biomass Burning in 3/95. Luke is developing simulated MODIS data sets that will enable Chris Justice and Yoram Kaufman to determine the temperature and area of fires at 1 km resolution. He is also studying the spatial distribution of fires (number per day, on a global basis). The ultimate objective is to determine the amount of CO_2 and CH_4 that is given off by biomass burning (CO_2/CH_4 ratio is temperature controlled).

4) Improve ties at GSFC and ASF.

We feel that we have made great progress here. Regarding ASF, the PI serves as the Panel Chair for the ASF DAAC User Working Group, and has frequent discussions with the ASF Director (Carl Wales) and the Interim DAAC Chief Scientist (Frank Carsey). The PI also serves on the University of Alaska External Review Board for Volcanology, and so has the opportunity to provide policy-relevant input to the Geophysical Institute and the University Provost about the running of the ASF DAAC.

On a functional level, we have frequently contacted ASF staff for help in the establishment of procedures for our own radar ground station in Hawaii. This includes help with orbit predicts for the collection of interferometric radar data.

At Goddard, Arlin Krueger has established formal ties with the GSFC DAAC, since they will be archiving his TOMS SO_2 products from future missions. Luke Flynn also works closely with the GSFC DAAC (mainly Al Fleig) about the implementation of our code for the processing of Level 0 MODIS data, and the development of beta-test data for MODIS based on spatially-degraded Landsat data.

Which components of your research are proceeding successfully, and which components have encountered unanticipated problems? What are your plans for coping with these problems?

Successes:

1) First and foremost, we feel that we are making great progress with the use of remote sensing in the scientific analysis of volcanoes and volcanic eruptions. We feel that we are creating new baseline science methodologies for the remote sensing analysis of volcanoes and volcanic processes. Our results from Kilauea and Mount Etna are particularly noteworthy. By using these volcanoes as our field laboratories, we have developed new ways to measure the spatial distribution of SO_2, developed radar interferometry techniques to map the topographic change of a volcano due to the eruption of new lava flows thereby enabling the effusion rate to be measured. We have also advanced the community's ability to make quantitative measurements of lava flow temperature and radiative energy. Our science results for eruption plumes shows comparable progress, most notably in our ability to detect ice within the plume, measure the plume topography, and study volcanic gases released from the plume.

2) On the functional side of preparing for the EOS data streams, we are making good progress with the quantitative descriptions of the Level 4 Data Products that we will be generating. We have an exceptionally good working relationship with the EDC DAAC, where they will be archived.

3) We have created a whole new way of receiving satellite data using cheap (~$500K) high data rate ground stations. Together with our successes in attracting interest in purchasing duplicate systems from Japan and Argentina, we are rapidly approaching the point where we can offer EOSDIS an alternative way for operating the ground reception component of many NASA missions. In addition, Howard Zebker, Stan Zisk and Harold Garbeil have made great strides in rewriting the code that is necessary for processing radar data to perform interferometry on low cost (<$50K)

workstations. This development will enable many other groups in the EOS community to perform their own analyses of radar data.

4) We are really pleased with our progress in the quantitative analysis of SO_2 plumes using thermal infrared data. This is has the promise of being very helpful to volcanologists studying gas production rates at volcanoes — it also seems an excellent analog for ASTER data analysis.

5) Through his work on the thermal characteristics of lava flows and forest fires, Luke Flynn has made excellent progress on developing a quantitative understanding of thermal anomalies and how they may be studied in near real-time. Such work could have important payoffs for the future NASA Natural Hazards Program.

6) Our outreach effort to the international volcanology community is working well. We get hundreds of people accessing our WWW sites each day, and are often invited to give seminars and workshops both in the U.S. and abroad on a wide range of remote sensing in volcanology topics.

Problems:

1) We have been planning for a test of the real-time comparison of TOMS and AVHRR data for volcanoes in Alaska, using the Earth Probe TOMS. Arlin Krueger and Gregg Bluth have put in a considerable effort to establish the ground capabilities there, and have been working with Carl Wales and Ken Dean at Fairbanks to conduct this test. However, the inability to launch EP TOMS on the Pegasus has meant that this experiment is on hold. At the level of getting the new Pegasus launch vehicle flying, we have to rely on NASA Headquarters assistance!

2) The TIMS experiment over an industrial smoke stack in Arizona in June 1995 was only a partial success due to tape recorder problems on the aircraft. We are planning another field and airborne experiment over this site, as well as the Kilauea experiment, in Fall 1995.

7. CONCLUSIONS

We feel that our Team is as productive and energetic as can be expected for the total level of funding. We have taken on the task of representing an entire discipline (volcanology) within the EOS Project, and as such not only have to argue for resources within the Project, but also have to be the interface between NASA, other agencies (such as the U.S. Geological Survey) and the international volcanology community. Public education takes up a considerable amount of our time, as well as drawing together the different skills that are required for the study of volcanic gases, eruption plumes, lava flows, and volcanic hazards.

We are clearly resource limited in terms of the level of effort that our funding permits in terms of data set validation, our interactions with the DAACs and other EOS teams (both instrument teams and IDS teams), and in the inter-disciplinary science that we are conducting. The fact that over the last two years we have published 56 papers and have 23 more submitted or in press in the open literature (see Section 8 below), most of which are in volcanology/geology journals, shows that we are making a major impact on the community.

Team morale in general remains high, and several investigators are really making invaluable contributions to the success of the investigation. We feel that we have addressed and solved the short-comings identified in our 1993 Site Review, and have laid the foundation for some pioneering research endeavors for NASA in the fields of data processing and collection. We hope that the reviewers will agree that our efforts and productivity make us valuable members of the EOS Project.

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9. SUMMARY OF MOST IMPORTANT FINDINGS

Over the last 2 years, our investigation has pioneered the development of several new remote sensing techniques for the analysis of volcanoes and volcanic eruptions. In addition to preparing our Team for the analysis of EOS data (including the definition of our data products and interactions with the DAACs and the science community at large), we feel that it is our progress in science that is most important. Over the last 2 years, we have published 56 papers, and have another 23 in press or in review. Highlights include:

1) The use of TIMS thermal infrared data to make quantitative total column abundance measurements of tropospheric sulfur dioxide from volcanoes. These imaging data represent a significant improvement over field and airborne COSPEC data, and provide an excellent opportunity to study temporal variability in the gas emissions from volcanoes. We estimate that the emission rate of SO_2 from Mt. Etna was 6700 tons per day during our observations. This technique has importance for the monitoring of volcanoes for impending eruptions, and provides detailed information on the volcanic contribution to sulfate aerosols in the troposphere. Our technique has already been field tested at Mt. Etna and Kilauea (Hawaii), and has direct relevance to algorithms that will be used to reduce ASTER data.

2) We have developed much of the code necessary to produce digital elevation models of volcanoes, measure the surface displacement of earthquake fault zones using radar interferometry, and compare surface displacement with GPS survey data. We have published our results on the 1992 Landers earthquake, and we have just submitted for publication our work on the measurement of the daily effusion rate from Kilauea using radar correlation maps. Much of our work is exploring the use of different orbital radars to topographically map the globe, and the environmental effects associated with the surface and atmosphere. This way, we hope to enable the volcanology community to gain the full potential of radar interferometry studies of volcanoes.

3) Detailed thermal studies (both imaging and point measurements) of active volcanism in Hawaii and at Mt. Etna have been conducted to interpret the cooling history of flows and to study the long-term thermal budgets of volcanoes prior to eruption. These data have been collected during the day and at night, over active flows and lava lakes, to provide input data to numerical models of lava flow emplacement and cooling. As part of our thermal work, we are developing a real-time alarm system using MODIS data that will enable the volcanology community to detect new eruptions and assess the global occurrence of eruptions.

4) Studies of the El Chichon (1982), Redoubt (1989), Pinatubo (1991), and Rabaul (1994) plumes using weather satellite data have enabled us to study plume dynamics via temperature and altitude observations, as well as the topography of plumes. Use of TOMS data has enabled us to assemble a 16-year record of sulfur dioxide produced during larger eruptions. We are developing methods for the real-time use of TOMS and weather satellite data for eruption detection in order to assist other Federal agencies in the task of hazard mitigation. We have also conducted radiative transfer modeling of the effects of such eruptions on the atmosphere. This work on plumes and volcanic gases will directly help in

the analysis of AIRS, MODIS, MLS, SAGE, EOSP, MISR, TES and TOMS data during the EOS missions.

5) During our field experiments on Mt. Etna, we have demonstrated that the SO_2/HCl ratios can be easily measured remotely either actively or passively using FTIR measurements. This work has importance for the monitoring of the changes in gas released prior to an eruption, and also to the way in which EOS instruments such as TES can be validated.

10. ACRONYMS

ADEOS	ADvanced Earth Observation Satellite
AES	Airborne Emission Spectrometer
AGU	American Geophysical Union
AIPS	Airborne Instrument Program Spectrometer
AIRS	Atmospheric Infrared Sounder
AIRSAR	AIRborne SAR
ASF	Alaska SAR Facility
ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer
ATSR	Along track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVNIR	Advanced Visible Near Infrared Radiometer
COSPEC	Correlation Spectrometer
DAAC	Distributed Active Archive Center
DEM	Digital Elevation Model
ECS	Eos Core System
EDC	Eros Data Center
ENVISAT	ENVIronmental SATellite
EOS	Earth Observing System
EOSDIS	EOS Data Information System
EOSP	Earth Observing Scanning Polarimeter
EP	Earth Probe
ERS	Earth Resource Satellite
ESSAAC	Earth System Science Applications Advisory Committee
ETM+	Enhanced Thematic Mapper (flown on Landsat)
FAA	Federal Aviation Authority
FEMA	Federal Emergency Management Authority
FTIR	Fourier Transform Infra-Red
GSFC	Goddard Space Flight Center
HIRIS	HIgh Resolution Imaging Spectrometer
HIRS	High Resolution Infrared Radiation Sounder
HITRAN	HIgh Transmission atmospheric model
HRV	High Resolution Vidicon
HSI	Hyper-Spectral Imager
IAVCEI	International Assoc. Volcanology & Geochemistry Earth’s Interior
IDS	Inter-Disciplinary Science
ILAS	Improved Limb Atmospheric Spectrometer
IMG	Interferometric Monitor for Greenhouse Gases
IUGG	International Union of Geology and Geodesy
IWG	Investigator Working Group
JERS	Japan Earth Resource Satellite
JPL	Jet Propulsion Laboratory
LIMS	Limb Infrared Monitoring of the Stratosphere
MIMR	Multifrquency Imaging Microwave Radiometer
MISR	Multi-angle Imaging SpectroRadiometer

MLS	Microwave Limb Sounder
MODIS	Moderate-Resolution Imaging Spectroradiometer
MTPE	Mission to Planet Earth
NASA	National Aeronautics and Space Administration
NASDA	NAtional Space Development Agency
NOAA	National Oceans and Atmosphere Administration
NWS	National Weather Service
OCTS	Ocean Color and Temperature Scanner
POLDER	POLarization and Directionality of the Earth's Reflectances
PR	Precipitation Radar
RADARSAT	Radar Satellite
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar
SBUV	Solar Backscatter UltraViolet radiometer
SEC	Science Executive Council
SIR-C	Shuttle Imaging Radar-experiment C
SME	Solar Mesosphere Explorer
SMIFTS	Spatially Modulated Imaging Fourier Transform Spectrometer
SSM/I	Special Sensor Microwave/Imager
TES	Tropospheric Emission Spectrometer
TIMS	Thermal Infrared Multispectral Scanner
TM	Thematic Mapper (flown on Landsat)
TMI	TRMM Microwave Imager
TOMS	Total Ozone Mapping Spectrometer
TOPSAR	TOPographic Synthetic Aperture Radar
TRMM	Tropical Rainfall Measuring Mission
UARS	Upper Atmosphere Research Satellite
USGS	United States Geological Survey
VIRS	Visible Infra-Red Spectrometer
WWW	World Wide Web
X-SAR	X-band Synthetic Aperture Radar