Solid earth science in EOS—Report of the Solid Earth Panel

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Introduction

The Solid Earth Panel of the Earth Observing System (EOS) Investigators Working Group prepared this document in response to the consideration of scientific priorities for EOS that took place during the late Summer and Fall of 1991, at the Seattle meeting of the IWG and the Easton meeting of the Payload Panel. The discussions at those meetings centered on the research priorities set forth in the IPCC assessment of climate change (Houghton et al., 1990). This report thus focuses on the importance of solid earth science to those issues of climate change and does not consider a number of other important areas where satellite remote sensing plays critical roles in understanding the solid earth component of the earth system. These areas, well summarized in the Coolfont Report (NASA, 1991), include studies of the earth’s geopotential fields, tectonic plate motions, surface deformation related to earthquakes and other internal processes, and lithospheric structure and evolution. Within these constraints, the report thus focuses on the dynamic interactions of the solid earth and climate as manifested primarily in the terrestrial land surface system and by the effects of volcanoes on climate.

The report first argues for a high priority for the terrestrial land surface system overall, describes the critical roles of solid earth science in the study of this system, and then discusses solid earth sciences instrument priorities.

Land surface system as a high priority for EOS science

As the abode of our species, the terrestrial land surface system must clearly be the most critical part of the earth system to observe and understand. Human beings live on the land surface, have affected it the most, and therefore give it the most concern. However, the extreme degree of heterogeneity and complexity of the land surface make it the most challenging and least understood component of the earth system. It demands patient and careful observation at scales ranging from very local ones relevant to human activities to continental scales important to the global climate system. The local scales are critical, not just to better parameterize sub-grid processes in computer models, but to understand how the system actually works at the human scale. Similarly, the time scale of primary interest must be the human one of minutes to decades, but it must also extend back long enough to reveal the full range of behavior of the system.

However, unlike the oceans and the atmosphere, study of the very complex land surface system has become fragmented into diverse disciplines in both academic and applied arenas, including biology, hydrology, soil science, environmental science, geology, geography, and climatology. This fragmentation is well summarized by the recent National Academy of Sciences report of the Committee on Opportunities in the Hydrologic Sciences (1991). It is also exemplified by the inclusion of the land surface system in four of the disciplinary panels of the EOS Investigator Working Group (Land Biosphere, Biogeochemical Cycles, Physical Climate and Hydrology, and Solid Earth). Nevertheless, EOS is likely to have a revolutionary impact on the study of the land surface system, not only because of the unprecedented range of spatial scales and monitoring possibilities provided by satellite observation, but because it will force the integration of disciplines that is required to understand the human habitat.

The Solid Earth Panel thus supports the view that the land surface system, broadly conceived to include the interactions of the terrestrial biosphere, hydrosphere, lithosphere, and atmosphere, should be among the highest priorities in EOS science.
Solid earth science in the land surface system

Modern processes

Besides providing the long-term perspective on earth structure and evolution, solid earth science plays a major role in the study of the interactions of the lithosphere, atmosphere, hydrosphere and biosphere that constitute the land surface system. The components include soil, rock, groundwater, topography, and crustal structure involved in the processes of volcanism, crustal deformation, and the weathering, transport and deposition of crustal materials. Interactions of the solid earth with the atmosphere, hydrosphere and biosphere occur over an enormous range of time scales. Closely coupled interactions between the solid earth and climate are generally assumed to have time scales substantially longer than those of concern to human activities. An example is the interaction among crustal tectonics producing mountain belts, the orographic effect of mountains on atmospheric circulation, and the climate control of weathering and erosion (a major component of the global carbon cycle). Although this type of interaction overall has a long time scale related to the uplift of mountains, its operation includes important short term components. In general, interactions of the atmosphere and solid earth feature the occurrences of large "events"—volcanic eruptions, earthquakes, large storm-triggered erosional (fluvial or aeolian) episodes, glacial surges—which have significant impacts on climate or the land surface system over a wide range of spatial scales.

Large volcanic eruptions affect the chemistry and radiative properties of the atmosphere globally and deposit ash over large areas of the land surface with sudden but drastic effects on the hydrosphere and biosphere, and little known but probably important effects on oceans. Eruptions of volcanoes such as Mount Pinatubo in June, 1991, can inject millions of tons of ash, gases and aerosols into the upper troposphere and lower stratosphere over a time scale of a week to several months. Assessing the impact of these eruptions on the earth system requires both the estimation of the rate at which solid and gaseous material are erupted (i.e., the volume, temperature, velocity-field and height distribution of these materials) and the measurement of the nature and recovery time of the transient disturbances to the atmosphere, land surface and/or sea surface. Particularly in the case of volcanicogenic material injected into the stratosphere, it is the rate of conversion of sulfur dioxide to sulfate aerosols and the residence time of the aerosols in the stratosphere which are responsible for the duration of the regional or hemispheric cooling due to volcanic eruptions. The direct and indirect effects of eruptions on a wide range of biomes, particularly alpine or boreal biomes which are already under stress, can last for months to decades.

While explosive eruptions are more spectacular than volcanic activity that produces lava flows and volcanic domes, the contribution of gases released into the atmosphere from surface activity may also have significant impact on the Earth system. Because of the greater solubility of sulfur in basaltic magmas compared to more silicic magmas, eruptions of volcanoes such as those found in Iceland can inject more than an order of magnitude more sulfur into the atmosphere than an eruption of an equivalent volume of silicic magma. The 1783 eruption of Laki in Iceland is a case in point, where the eruption of large volumes of basalt over a period of seven months resulted in a volcanic fog ("vog") that affected the weather in northern Europe for a couple of years.

A major element of terrestrial hydrology and geochemistry is the weathering, erosion, transport and deposition of rock material. In mountainous areas where erosion rates are among the highest on earth, the dominant mechanism of hill slope erosion is by landslides. Earthquake shaking or volcanism in concert with climatically controlled instability can lead to large and often very destructive landslides that affect the regional hydrological regime and may permanently alter the landscape. Earthquakes also change the elevations of coastal regions by up to 10–20 m over many hundreds of kilometers and thereby affect the interactions of ocean, land and climate in those areas. The main contribution to the transport of sediment by streams occurs during the extremely large runoff events associated with very large storm systems. In arid regions, erosion is dominated by the action of wind as well as by the rare rain storm. Most of the injection of material into the atmosphere occurs during major dust storms. A changing climate can alter the locations and strengths of the major sources of wind-eroded particles in the atmosphere, which in turn can have important effects on regional and global scales climate.

The climatically controlled redistribution of crustal material is thus not a smooth, slowly acting process but is characterized by major, short-lived episodes where most of the work is done. Study of these processes is an important part of a unified science of the land surface. Study of these processes is also critical to considerations of the impact of climate change on human societies and the development of adaptation and mitigation policies. Examples of areas of particular concern include—the supply and quality of ground water; topsoil erosion; siltification of reservoirs and estuaries; vulnerability to earthquake, volcanic, and
landslide hazards; and tsunami, earthquake or storm
related changes in coastlines in relation to changing
sea level.

Studies of fast acting, interactive solid earth phe-
nomena are thus an important contribution to EOS
objectives whether those objectives are the develop-
ment of an all-embracing Earth system science or the
prediction of future climate change and its impact on
human societies. These studies will be largely enabled
by EOS capabilities to detect and monitor transient
phenomena such as volcanic activity and major episodes
of erosional and depositional land surface modification
by wind and water, and to relate these to atmospheric
and oceanic phenomena also sensed concurrently by
EOS.

History of the land surface system

Past climate change that is most relevant to the
study of modern and future climates is the transition
from full glacial to our present inter-glacial global
climate system during the past 20,000 years. This last
cycle of the dramatic Quaternary climate oscillations
has left striking imprints on vast areas of the terrestrial
landscape and has had profound impacts on the hydro-
sphere and biosphere. All considerations of the mod-
ern state and change of the land surface system must
have this historical perspective. It is the primary source
of our information on “natural” climate variability,
especially in regard to the possibility of rapid transi-
tions or “surprises” in the evolution of the highly non-
linear earth system.

Solid earth science has had the major role in reveal-
ing climate history through analyses of various proxies
for climate parameters preserved in datable sedimentary
sections (including ice caps). However, well cali-
brated terrestrial records are only sparsely distributed
over most of the earth. A complementary record, com-
prehensive in spatial coverage but an integrated, “over-
written” view in time, is the terrestrial landscape itself.
Over vast regions of the land the effects of the last
glacial maximum and subsequent deglaciation are dra-
matically represented in the form of glacial moraines,
cirques, and periglacial features indicative of past dis-
tributions of snow and ice; stabilized sand dunes, win-
d-carved landscape features and other indicators of
past wind velocities; relict lake shores, alluvial fans,
fluvial systems buried beneath sand, river valley mor-
phologies not in equilibrium with the modern hydrolog-
ical regime, and other terrain features indicative of
past precipitation/evaporation regimes. EOS class in-
strumentation will contribute significantly to the deter-
minations of ages and chronologies of these types of
features and thereby aid in the interpretation of the
history of the land surface system.

However, in the interpretation of both the strati-
ographic records and the landscape imprints of climate
change, the outstanding potential of EOS is the capa-
bility to characterize the complex spatial and temporal
variability of modern climate and hydrology in terres-
trial regions. One of the primary uncertainties in the
interpretation of the evidence of past climates is the
problem of sampling a complex, spatially variable ter-
restrial climate and relating the results to global cli-
mate. This problem is particularly severe in mountain-
ous regions where much of the record of past climate
change is preserved. The most promising solution to
this problem is part of major objectives of EOS in the
development of 4-D assimilation systems and mesoscale
climate models. The better characterization of modern
climate will permit better interpretation of the evi-
dence of past climate on both regional and global
scales. Combining studies of modern and past climates
provides a valuable historical perspective to the devel-
opment of adaptation and mitigation policies in respect
to the impacts of future climate change. The study of
past variability shows what types of change have oc-
curred and how these changes are manifested in the
terrestrial system.

Satellite geodesy: changing sea level, ice volumes,
earthquakes, and earth rotation

Sea level rise from a combination of increased wa-
ter temperature and melting of ice is one of the press-
ing concerns discussed in the IPCC document. This is a
multi-faceted problem requiring significant input from
oceanography, climatology, hydrology, and solid earth
science. We assume that the problems of monitoring
ice volume changes and sea level changes would be the
provenance of the Physical Climate and Hydrology
Panel and the Oceans Panel, respectively. The solid
earth component of this problem is essential. Knowl-
edge of the motions of the solid earth along ocean
coastlines and near the margins of ice sheets are re-
quired to determine changes in ice and water volumes.
These measurements require space geodetic tech-
niques to establish an absolute reference frame for tide
gauge and altimetric measurements and to monitor the
deformations of the solid earth near the margins of the
oceans and ice sheets.

Satellite techniques to determine the position of
surface points to sub-centimeter accuracy has impor-
tant applications to the measurements of the motions
of transient deformations of near plate boundaries,
near the source regions of most of earth’s largest
destructive earthquakes. Earthquake-related deformations can produce uplifts of the order of several to tens of meters which can significantly alter the local and regional hydrological or coastal environment.

Space geodetic techniques have revolutionized the measurements of variations of earth rotation (length of day and pole position). In addition to external gravitational effects, these variations reflect transfers of angular momentum between the atmosphere, the oceans, the solid earth and the liquid core. Increased resolution of the measurements and better global determinations of motions of the atmosphere and oceans are necessary to separate the various components controlling the variations within the spectrum of temporal variability from hours to decades. Of particular relevance to climate change is to understand better how mountain torques and surface friction couple angular momentum transfers between the oceans, atmosphere and solid earth. A further important component of earth rotation variation to seek is that due to the transfer of mass from ice to oceans.

Contributions of EOS and non-EOS sensors

High Resolution Imagers

Study of the land surface system requires high resolution (30 m or better) imagers as the single highest priority. For the solid earth components of the land surface system, the requirements go beyond a need only to “calibrate” and interpret observations to be made primarily with medium resolution sensors. High resolution imagers are required to correctly identify and quantify the fast acting geological processes discussed in the preceding section as well as related components of hydrology such as river state and the distributions of standing water, snow and ice. High resolution is required to identify and select areas where change is to be monitored, to establish baseline observations, and to calibrate the medium resolution imagers to serve as effective monitors and detectors of change. Upon detection of an interesting event, the high resolution imagers would be focused on the area of interest and the critical measurements made. The ability to see through cloud cover is essential and requires radar imaging to be continued through the EOS era.

Presently “available” high resolution data include primarily Landsat Thematic Mapper and SPOT, but these exist now as expensive commercial products and can only be acquired for limited areas for limited time periods with presently available research budgets. The access to multi-temporal coverage over large regions, restricted only by the ability of the researcher to deal with the data volumes, is a capability that so far has not existed and would probably not exist with commercial satellite imagery. ERS-1 and ERS-2 SARs, JERS-1 AVNIR and SAR, RADARSAT, and SIR-C will provide extremely valuable pre-EOS data to help define the monitoring strategies, but these sensors will operate for limited periods only and some will have only limited regional coverage.

The long-term monitoring capability and accessibility of EOS data combined with the advanced, high resolution capabilities of ASTER, the EOS SAR, and HIRIS would revolutionize the study of the land surface system. Given the decisions (1) to place EOS SAR outside the EOS funding considerations for the October Payload Panel Meeting and (2) to place HIRIS on a later platform, we have ASTER as the remaining high resolution imager for early flight. We strongly support this instrument for solid earth studies. The combination of visible, near-infrared and thermal infrared, the high spatial resolution, and the stereo capability make ASTER an extremely powerful tool for both volcanological and geomorphic/tectonic studies of the land surface.

The unique and potentially revolutionary spectroscopic capabilities of HIRIS to discriminate mineralogies of the surface would have a broad impact on solid earth studies of the land surface, not only with respect to geologic mapping but particularly in regard to the detection of change related to the effects of wind, water, ice, volcanoes, earthquakes and other transient impacts on the exposed soil and rock component of the land system.

The panel recognizes the unique multi-wavelength and polarization capabilities of the EOS SAR to penetrate clouds and image important features of the landscape. If the EOS SAR were descoped, the multi-frequency, multi-look angle capabilities may be more important to solid earth sensing than the multi-polarization capability. Multi-look angle capabilities are seen as the highest priority of the EOS SAR for rapid site-revisit capability.

The combination of physical properties sensed by SAR and chemical properties sensed by HIRIS has the potential to date the ages of geomorphic surfaces and thus provide a vast new data set to determine rates of erosion and deposition. The potential for this type of work has been demonstrated and continues to be developed through extensive site work with sensors such as LANDSAT, SIR-A and SIR-B, and airborne instruments such as AIRSAR, TIMS and AVIRIS for areas mainly in the western USA.

Volcanoes pose specific requirements to detect and measure the temperatures and morphologies of lavas and plumes. Critical to the analysis of both explosive
and lava-producing eruptions is the temporal perspective of the activity provided by the EOS sensors. Gas release during an eruption may vary on time scales of a few hours and can be related to the segment of the subsurface magma reservoir that is being tapped at different stages of the eruption. In the case of lava flow fields, magma production rates, the cooling history of lava flows, and the spatial distribution of activity, provide crucial information on the internal structure of the volcano (magma chamber size, location of fissures) and the rheological properties of the melt. In the case of lava flow studies, the high spatial resolution EOS sensors is an essential attribute due to the relatively small size (a few tens to hundreds of meters) of the phenomena. In addition, the determination of pixel-integrated temperatures (e.g., lava flows that have sub-pixel sized areas at more than one temperature) require both high spatial resolution and high spectral resolution. ASTER (particularly the thermal infrared capability) and HIRIS are vital for these temperature determinations.

Medium resolution monitoring imagers

MODIS N is required to detect change by monitoring frequently on regional to global scales such phenomena as thermal anomalies associated with volcanic eruptions, large dust storms or other rapidly occurring land surface processes. MODIS-N can thus be used to locate specific areas of significant change that can then be examined with high resolution instruments to determine the nature and magnitude of change. MISR's capabilities to determine the amounts of particulates in the atmosphere are required for studies of volcanic eruptions and processes of wind erosion and transport.

Topography

Topography is perhaps the single most important land surface characteristic that determines the climatic, hydrologic and geomorphic regimes. The limited number of digital elevation models that have recently become available are already stimulating new areas of interdisciplinary study of the terrestrial land surface combining geomorphology, tectonics and climatology. The urgent need to obtain new digital topographic data is described in several reports and will not be repeated here. The Solid Earth Panel strongly supports requests to the Department of Defense to release its enormous DTED data base of topography, and also strongly supports the NASA initiative to fly a special topographic satellite mission as an Earth Probe. Analysis of SPOT stereo and new stereo data to be derived from Japanese satellites (e.g., JERS-1 and ADEOS) will also contribute to developing a global topographic data base.

The capabilities of ASTER, EOS SAR, GLRS-A, HIRIS and MISR to obtain elevation data make these instruments particularly attractive to the solid earth community. ASTER's high spatial resolution (15 m pixel) and its fore-and-aft pointing capability are particularly useful, while the EOS SAR used either in interferometric or stereographic modes provides data in areas of continuous cloud coverage. Digital elevation models ("DEM's") can be derived from stereo data collected by ASTER, HIRIS or MISR, and from interferometric measurements made by the SAR. MISR will be able to obtain elevation data on a 240 m grid, which, although lower in resolution than ASTER or the EOS SAR, would be obtained continuously and would be useful for obtaining a uniform global data base.

The measurement of change in topography or water level is a critical requirement for EOS monitoring. GLRS-A's highly accurate elevation profiles will provide unique monitoring of the shape or height of a number of important features, including river and lake levels, land slides, sand dunes, and coastal features, and will provide unique capabilities to identify and measure elevations of relict coastline and lake shore markers indicative of past change. Because it is a profiling instrument, GLRS-A would be of greater use to the land community if the EOS orbit were not exact-repeat, thereby enabling a larger fraction of the land surface to be studied. The larger number of orbit overlaps in non-repeat orbits will also enable a more accurate measure of ice topography for ice sheet volume determinations.

The capability to measure topographic change using double-difference radar interferometry is a particularly exciting capability of the EOS SAR. Examples of such measurements include the deflation/inflation rates of volcanic craters and rift zones and the determination of the spatial distribution of new lava flows or collapse craters created during a volcanic eruption.

The topography of evolving volcanic plumes represents a special problem and requirement. The capabilities of ASTER and MISR to provide stereo views of short-lived phenomena that change on time scales of a few hours—the transient eruption plume heights and morphologies—are essential for adequate modeling of eruption dynamics. GLRS-A will also provide valuable plume height measurements when the nadir-looking profile crosses the plume.

Remote site monitoring

The Wide Band Data Collection System (WBDCS) presents the opportunity to transmit data from remote
sites, such as from seismograph stations, water level gauges on coastlines, lakes or rivers, ground meteorological stations, and other types of ground sensors, to the EOS data processing system. This would be of great value in the detection and study of events such as volcanoes, earthquakes, floods and other geomorphological events and changes. In remote areas, the early detection of seismic events related to volcanic eruptions via WBDCS will enable observations of these sites by other EOS instruments to be initiated early in the evolution of the activity. Since the WBDCS system was designed for the transmission of high sampling rates of seismic data, abundant capability is available for the substantially lower data rates generally required for hydrological and meteorological monitoring.

**Satellite geodesy**

The measurements of sea level and ice volumes require accurate control of satellite orbits, geodetic level measurements of the vertical movements of the land around the oceans and ice sheets, and the establishment of a uniform global reference frame for vertical movements. These objectives are well discussed in the Coolfont Report (NASA, 1990) and Bilham (1991). Bilham argues that characterization of annual mean sea level with an uncertainty of a few millimeters should be possible by the end of the century with a combination of available space- and ground-based geodetic techniques and a new more uniformly dispersed network of tide gauges. Instruments of the EOS class including ALT, GGI, and GLRS-A and Earth Probes such as ARISTOTLES would be critical for this work. The tide gauges need to be tied to a global reference frame based on measurements of absolute gravity, very long baseline interferometry (VLBI), Satellite Laser Ranging (SLR), Global Positioning System (GPS) and GLRS-R. ALT class measurements of dynamic ocean topography would be necessary to extrapolate the tide gauge data to large areas of the oceans. The related problem of determining ice sheet volume changes requires GLRS-A class measurements of ice topography with accurately modelled orbital parameters and GLRS-R class measurements of vertical deformations of the solid earth near the ice sheets. The proposed FLINN network would be an integral part of this system of measurements.

The application of satellite geodesy to tectonic problems was pioneered by the NASA Geodynamics program. Modern work with the Global Positioning System (GPS) in many tectonically active regions includes networks of benchmarks separations of the order of tens to hundreds of kilometers and observations repeated every 1–2 years. The spatial and temporal densification of such measurements in earthquake-prone regions is required to detect deformations possibly precursory to destructive earthquakes, to understand better the physical mechanisms of earthquake generation, and to determine the motions of the ground that affect coastline and hydrological environments. The GLRS-R instrument provides this densification in both time and space by the use of permanently sited passive retro-reflectors on the ground and by having the active range measuring system in the satellite. This strategy is quite different than that used in GPS surveys and thus adds an important complementary capability for the measurement of earth deformation.

**Related atmospheric and oceanic sensors**

The injection of volcanic gases and aerosols into the upper troposphere and lower stratosphere may have a significant input on atmospheric chemistry. Several EOS instruments are valuable for the analysis of volcanic emissions. MISR and EOSP will be particularly important for the observation of aerosols. SAGE, TES, and MLS will be required to determine the concentration of SO2 and the rate of dispersal around the globe. Modeling the dynamics of the eruption plume and the rate of release of SO2, HCl, CO, H2O and other gases relate to the magnitude of the eruption, the magma chemistry and the tectonic setting of the volcano. The use of MLS and TES to monitor the abundance of gas species (particularly SO2, HCl, CO, and H2O) that are exsolved during an eruption enables not only the residence time of magma within the magma chamber to be assessed, but also permits the role of the tectonic setting of the volcano to be considered.

LAWS, STIKSCAT and ALT are important to determinations of momentum transfers involved in earth rotation variations, while LAWS, AIRS and MIMR would be important to determinations of regional climates over land areas required by land surface studies.

**Priorities**

It is important to stress that the priorities discussed in this section reflect scientific considerations convolved with the financial and instrument readiness questions that were subjects of discussion during the 1991 meetings, and with the evolution of scientific priorities for EOS from the original “earth system science” to the more recent emphasis on “global change” and “climate change”.

The Solid Earth Panel proposed in Seattle that a first platform composed of ASTER, MODIS N, MISR, and GLRS-A, flying with a 10:30 AM crossing time, could be launched as early as 1997. This would provide
an early science return from a package with direct application to policy decisions and to the development and validation of process models and detection of change in the critical land surface system and ice caps. In the detection of change, ASTER would provide a major technical advance and valuable continuity in the high resolution global monitoring record that started with MSS. The high resolution sensors would also provide essential information for calibration of nearly all of the down-looking EOS sensors. Substantial reduction of the cost of the package would be obtained because ASTER is provided by an international partner, Japan. However, significant delay in scheduling of this instrument on later EOS platforms may not to be possible. Our priority ordering of the four instruments for the early package would be as follows: (1) ASTER; (2) MODIS-N; (3) MISR; and (4) GLRS-A.

Additional high priorities proposed to fly as soon as possible include the (1) EOS SAR, (2) HIRIS and (3) GLRS-R, in that order of priority. These instruments are considered critical for solid earth sciences. We strongly support efforts to obtain extra-NASA support for future development of GLRS-R.

Atmospheric instruments of great value to solid earth sciences include for the analysis of volcanic eruption plumes (in order of priority), (1) MLS, (2) Sage III, and (3) TES; for the determination of regional climatologies AIRS, MIMR and LAWS; and for the study of the earth’s rotational momentum budget, LAWS, STIKSCAT and ALT.

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References


