

Geodesy in the 21st Century

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From flat Earth, to round Earth, to a rough and oblate Earth, people's understanding of the shape of our planet and its landscapes has changed dramatically over the course of history. These advances in geodesy—the study of Earth's size, shape, orientation, and gravitational field, and the variations of these quantities over time—developed because of humans' curiosity about the Earth and because of geodesy's application to navigation, surveying, and mapping, all of which were very practical areas that benefited society.

Today, geodesy is no different. The field is now concerned with changes in the shape of Earth's surface, because small detectable changes are associated with issues of great societal impact such as ice melting, sea level rise, land subsidence, and aquifer depletion. For example, the rate of polar ice melt may be estimated from combined satellite gravity and ground Global Positioning System (GPS) measurements. Global estimates of sea level changes are measured by altimetry satellites within entire ocean basins. Human-induced depletion of aquifers is reflected in subsidence measured by synthetic aperture radar (SAR) satellites.

Twenty-first-century geodetic studies are dominated by geodetic measurements from space. Space geodesy uses a set of techniques relying on precise distance or phase measurements transmitted or reflected from extraterrestrial objects, such as quasars, the Moon, or artificial satellites. Early space geodetic measurements, beginning in the 1980s, had accuracy levels between 5 and 10 centimeters. These measurements were conducted across the entire globe and yielded the first direct observations of tectonic plate motion. Further improvements to space geodetic technologies have increased the accuracy to subcentimeter levels.

Today, space geodetic observations can detect small movements of the Earth's solid and fluid surfaces as well as changes in the atmosphere and ionosphere. Hence, geodesy has many applications in a variety of fields extending well beyond its traditional role in solid Earth sciences (Figures 1 and 2).

Geodesy and the Space Era

Geodesy, like many scientific fields, is technology driven. Over the centuries, it has developed as an engineering discipline because of its practical applications. By the early 1900s, scientists and cartographers began to use triangulation and leveling measurements to record surface deformation associated with earthquakes and volcanoes. For example, one of the most important

geophysical discoveries, the basic understanding of earthquake mechanics known as the "elastic rebound theory" [Reid, 1910], was established by analyzing geodetic measurements before and after the 1906 San Francisco earthquakes.

In 1957, the Soviet Union launched the artificial satellite Sputnik, ushering the world into the space era. During the first 5 decades of the space era, space geodetic technologies developed rapidly. The idea behind space geodetic measurements is simple: Distance or phase measurements conducted between Earth's surface and objects in

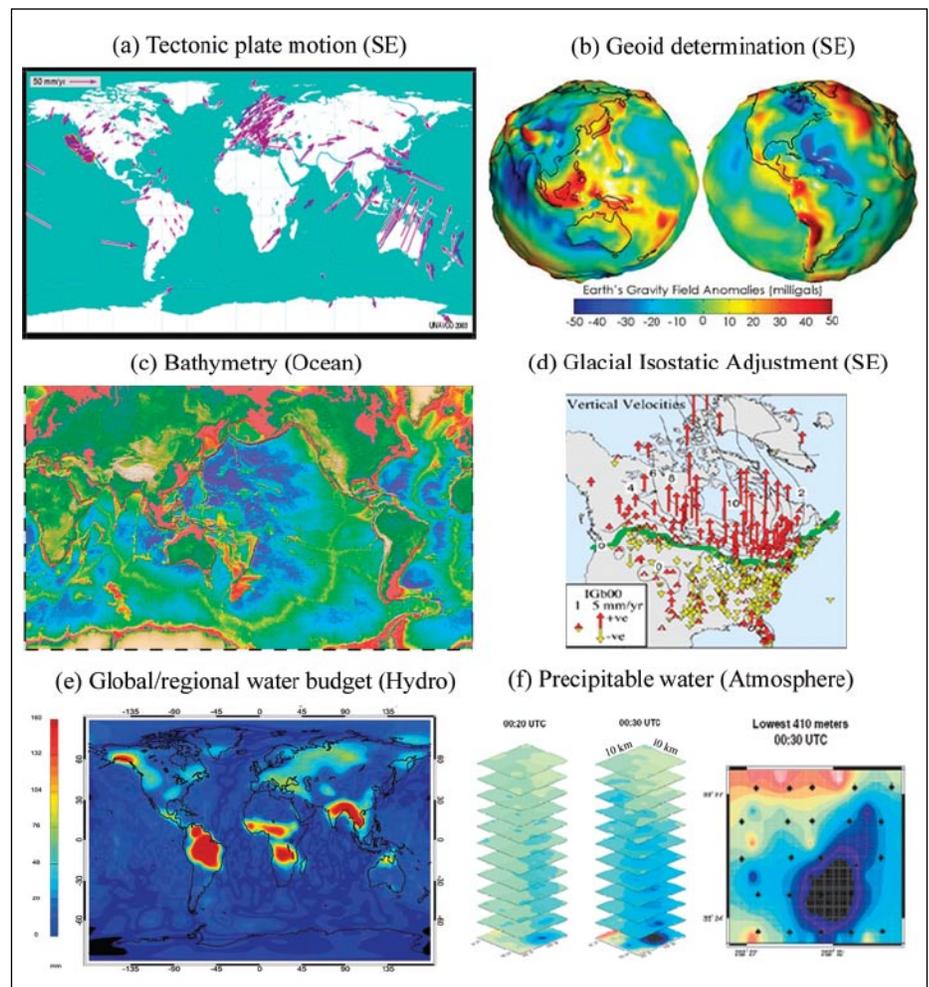


Fig. 1. Space geodetic applications in various Earth science disciplines at global and continental scales. SE stands for solid Earth, and Hydro represents hydrology. Sources for this figure are provided in the electronic supplement to this Eos issue (http://www.agu.org/eos_elec/). Additional information can be found at <http://www.unavco.org/geodesy21century>.

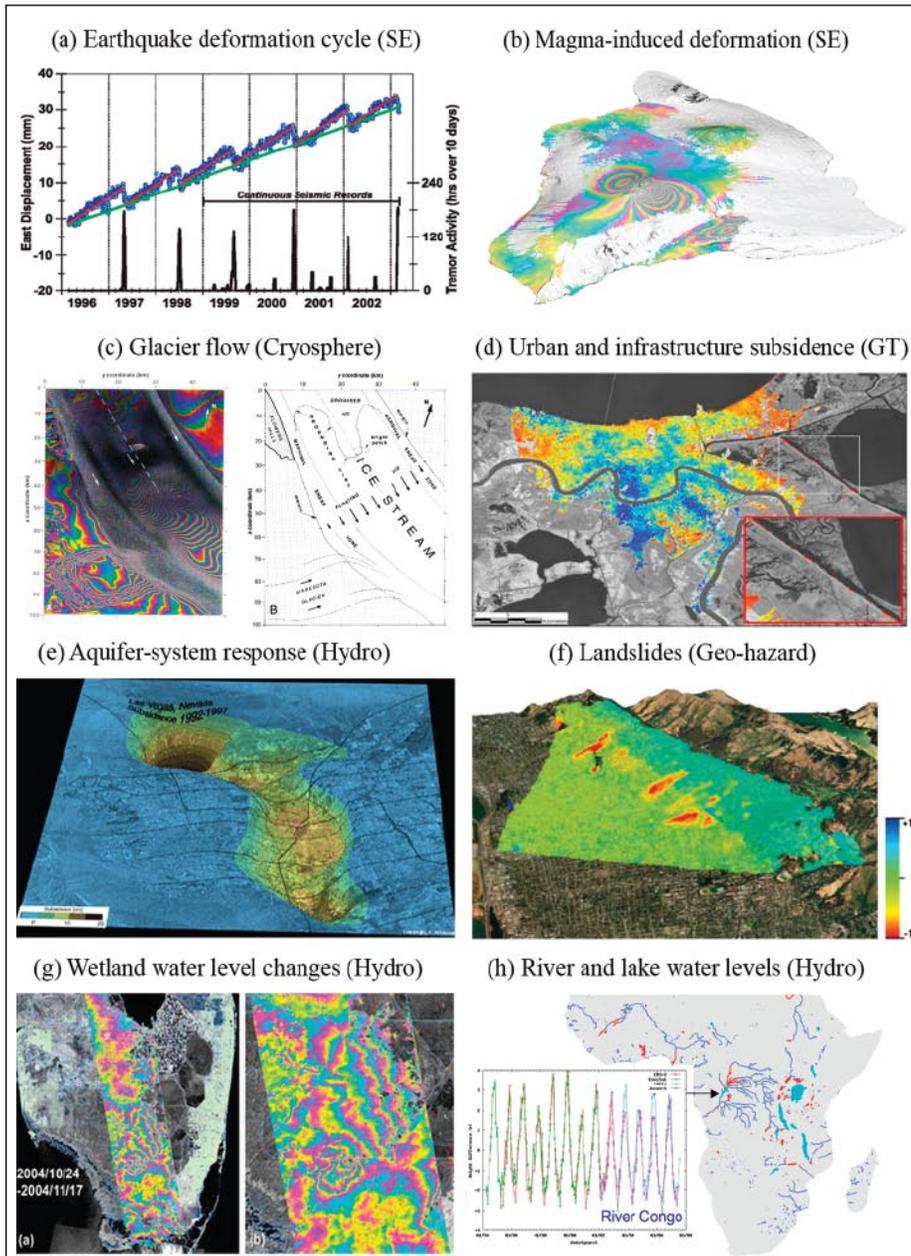


Fig. 2. Space geodetic applications in various Earth science disciplines at local scales. SE stands for solid Earth, GT stands for geotechnical, and Hydro stands for hydrology. Sources for this figure are provided in the electronic supplement to this Eos issue (http://www.agu.org/eos_elec/). Additional information can be found at <http://www.unavco.org/geodesy21century>.

space (satellites, the Moon, or quasars) are very precise, easily repeated, and obtainable for almost any surface location. Consequently, positioning, surface elevation, and gravity field and their changes with time can be determined precisely with global coverage.

The first generation of space geodetic observations relied on existing astronomical equipment such as the radio telescope, and on analysis of early satellite orbits. These observations yielded the first space-based measurements of tectonic plate motion and Earth's gravity field. Dedicated satellites for geodetic measurements were soon

developed. In parallel, clever utilization of observables from nongeodetic missions such as GPS or SAR satellites resulted in very precise positioning or change measurements—scientists could now detect earthquake and magma-induced crustal deformation, subsidence, glacial movements, and wetland surface water level changes.

During the short history of the space geodetic era, innovative development of space technologies has yielded numerous geodetic methods (see Table S1 in the electronic supplement to this Eos issue (http://www.agu.org/eos_elec/)). A quick look into the main space geodetic technologies

shows how far and how rapidly space geodesy has advanced since its beginnings about 50 years ago.

Types of Modern Geodetic Missions

Space-based geodetic observations can be categorized into four basic techniques: positioning, altimetry, interferometric synthetic aperture radar (InSAR), and gravity studies.

Precise positioning is the fundamental geodetic observation required for surveying and mapping. Instead of the traditional triangulation and leveling networks that require line of sight (LOS) between measurement points, space geodetic methods use LOS between the measurement points and celestial objects or satellites. For example, to measure changes in distance across the San Andreas Fault, scientists used radio telescopes at Vandenberg (California) and Yuma (Arizona) to detect the phase delay in the arrival of quasar signals between the two sites. Similar distance changes have also been determined by satellite laser ranging (SLR) and more recently and more precisely by GPS. As a result of these techniques, relative positioning can be achieved over very large distances in which the precision is almost independent of the distance between the two measurement points.

Building on this idea, scientists have developed advanced positioning techniques through Global Navigation Satellite Systems (GNSS). GNSS encompasses the various satellite navigation systems, such as the United States' GPS, Russia's Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS), and Europe's Galileo. Although these satellite systems were designed mainly for navigation, they were found to be very useful for precise positioning, with accuracy levels of less than a centimeter. GNSS also provides very high temporal resolution measurements (second by second, or even faster), yielding key observations of time-dependent processes in the lithosphere, atmosphere, and ionosphere.

By contrast, rather than measuring three-dimensional (3-D) changes by positioning techniques, altimetry involves only changes in surface elevation. Space-based radar and laser altimetry techniques accurately measure the satellite's height above the Earth's surface, which is then converted to the surface's height above a reference ellipsoid. Altimetry measurements are conducted by releasing pulses toward the Earth's surface every several milliseconds, resulting in circular ground measurements (footprints) along the satellite track. Because of the large footprint (diameter > 75 meters), altimetry measurements are useful for measuring flat surfaces. Radar altimetry was actually designed for measuring the height of ocean water surfaces but also was found to be useful in measuring changes in ice cap elevation and water levels in rivers and lakes.

Similar types of data, not measured from satellites, involve airborne light detection and ranging (lidar) and terrestrial laser scanning (TLS), both of which measure 3-D positions of a large number of points located on surfaces facing the instrument. Airborne lidar is widely used to measure elevation, whereas TLS measures small-scale structures and detailed surface features.

A powerful method to detect surface change is InSAR. This method compares pixel-by-pixel SAR phase observations of the same area acquired from roughly the same location in space to produce digital elevation models (DEMs) or surface displacement maps with high spatial resolution (typically from 5 to 100 meters). Such maps, termed interferograms, are obtained from repeat orbit observations and can reach centimeter-level precision.

In addition, satellite orbits are very sensitive to lateral variations in the Earth's gravity field. Precise measurements of satellite orbits by ranging (distance) and other technologies yield accurate determination of the geoid shape and its variations over time. The geoid is defined as the equipotential surface of Earth's gravity field that best fits global mean sea level. It describes the mass distribution within the Earth, from which one can infer Earth's dynamic structure. The new generation of gravity satellites are also very sensitive to short-term changes in the geoid reflecting near-surface mass redistribution such as ice melt or large-scale seasonal changes in water budget. Geoid measurements are also crucial for calibrating GPS-determined height with a standard mean sea level datum.

Space geodesy provides observations at various spatial and temporal scales with a corresponding variety of applications. High spatial resolution measurements and global coverage provide the means to investigate localized, continental, and global-scale processes. The precise and repetitive nature of satellite orbits enables reliable, repeated data acquisition, with temporal resolution of seconds (GNSS techniques) to tens of days (altimetry, InSAR, and gravity techniques). Some measurements began in the 1980s, providing scientists with data sets of repeated observations that span decades.

Global-Scale Applications

The different geodetic measuring techniques, along with varying spatial and temporal accuracies, allow for geodetic insight on a global scale.

In addition to broadly monitoring plate motion (Figure 1a), independent geodetic measurements have revealed congruence of short-term plate motions with those on geological timescales and provide better constraints for quantitative plate motion models. The same positioning techniques have been used to monitor Earth's rotation, including variation in rotation rates affecting the length of each day and pole motion

(Chandler wobble). These properties are essential for precise determination of satellite orbits used in a variety of applications, such as weather forecasting and GPS navigation.

The global coverage of altimetry satellites allows decadal observations of sea level change over entire ocean basins, complementing tide gauge records, many of which span the past 100 years, acquired only along coastlines. In addition, GPS measurements help improve the relative sea level change record by monitoring the subsidence or uplift of gauge stations, which can decouple the relative movement of land from sea.

Accurate determination of the Earth's shape by measuring the geoid (Figure 1b) is another important contribution using precise tracking of altimetry and gravity mission satellites. Altimetry measurements over oceans combined with gravity models can yield detailed information on the bathymetry of the ocean floor. For example, they can help detect the location of unknown seamounts (Figure 1c), which show up as localized gravity anomalies reflecting lateral mass differences between seamounts and ocean water.

Applications on a Continental Scale

Relative motion of tectonic plates produces deformation along plate boundaries through associated volcanoes and earthquakes. Geodetic studies can determine the details of earthquake- and magma-induced deformation on a local scale. Integrating these details for a larger geographic area reveals the full picture of plate boundary deformation.

For example, the geodetic component of EarthScope—the Plate Boundary Observatory, funded by the U.S. National Science Foundation—has expanded on existing local GPS networks to provide continental-scale coverage of the western United States. The broad and dense geographic coverage of EarthScope, with its high-quality, continuous data, is ideal for measuring volcanic and plate tectonic motions, strain accumulation on faults, earthquake surface displacement, and postseismic deformation on timescales of seconds to decades.

Geodetically observed vertical movements by GPS in Europe and North America reflect glacial isostatic adjustment (GIA, previously known as postglacial rebound; see Figure 1d) due to the melt of ice caps following the last glacial period (~110,000 to 10,000 years ago) and corresponding mass adjustment in the newly unloaded mantle. These observations provide excellent constraints on mantle viscosity. GIA also has a global-scale contribution as it changes the Earth's dynamic oblateness (J_2), which reflects changes in the latitudinal distribution of mass within the Earth.

Shorter-timescale seasonal and multi-year redistribution of water and ice mass are expressed by small but detectable changes in the geoid shape. The high precision of

the Gravity Recovery and Climate Experiment (GRACE) satellite enables estimation of large-scale regional water budget changes (Figure 1e) and changes in polar ice mass due to glacier melting. Changes in ice cap elevation are also monitored by the polar-orbiting Ice, Cloud, and Land Elevation Satellite (ICESat) and other altimetry satellites. Geoid and elevation changes over polar ice caps include both ice changes and GIA response to current and past melting. Ground-based GPS measurements are essential for determining mass changes due to GIA-induced crustal uplift, allowing improved estimates of polar ice cap melt rate.

In addition to monitoring changes to the surface of Earth, many continental-scale atmospheric and ionospheric phenomena can be measured through satellite geodesy. GPS and other GNSS techniques can monitor changes in atmospheric precipitable water (Figure 1f) and ionospheric total electron content (TEC). Such changes can be monitored because signals transmitted from the GNSS satellites are sensitive to the water content in the atmosphere and to TEC in the ionosphere. Precipitable water retrievals have been shown to improve the representation of atmospheric water vapor in numerical weather prediction systems, increasing their ability to forecast heavy rain and hurricane intensity. TEC retrievals can help scientists forecast adverse space weather.

Satellite Geodesy on Local Scales

Changes in the Earth's surface at local scales (<100 kilometers) are best measured by a combination of high temporal resolution (GPS) and high spatial resolution (InSAR) observations. In tectonically active areas, utilization of both techniques has revealed details of crustal deformation during, after, and between moderate and large earthquakes (Figure 2a) as well as magma-induced deformation beneath volcanoes and continental rifts (Figure 2b). In the cryosphere, these two methods provide a new understanding of the kinematics of glacier flow (Figure 2c).

InSAR is very effective in detecting localized subsidence and uplift of land surfaces in response to natural or anthropogenic causes. Some of the more successful applications are monitoring subsidence due to compaction of sediments (Figure 2d), aquifer-system response to groundwater pumping and artificial recharge (Figure 2e), extraction of fluids in oil fields, and excavation in mines and tunnels. InSAR and GPS are also powerful tools in studying surficial processes such as landslides (Figure 2f) and soil moisture content.

Space geodesy also measures changes in water surfaces on continents. InSAR combined with water level gauges provides information on wetland water level changes (Figure 2g). Altimetry observations are used for detecting water levels in rivers and lakes (Figure 2h), especially in remote regions.

The observations are local at points where ground tracks of satellite orbits intersect rivers or lakes and can be combined to provide regional information.

Though not space-based, airborne lidar and TLS instruments are very effective geodetic techniques—both are used in geomorphological studies, such as determining fault slip rates across offset topographic features. Airborne lidar can map subtle elevation changes in extremely flat areas, such as south Florida, where it is used for determining flood zones.

Societal Implications

Natural hazard mitigation, the effects of global warming, and optimum use of water resources are areas of major concern for humankind today. The implications of space geodesy when applied to natural hazards associated with earthquakes and volcanoes are well known in the geoscience community, but space geodesy also has an impact

beyond these traditional solid Earth hazards. Sea level rise, glacial melting, and hurricane forecasts are of immediate interest to communities around the world, particularly in the context of global climate change. Geodesy can also reveal the overlapping threats from multiple hazards—for example, in areas of coastal subsidence such as Bangkok, Thailand, the effect of continued sea level rise amplifies flooding hazards.

One of the greatest global challenges of the 21st century is securing fresh water for the increasing worldwide population and for sustaining natural ecosystems. Geodetic monitoring of subsidence in depleted aquifers and water level changes in wetlands, rivers, and lakes yields important constraints for hydrological models that can serve as decision support tools for water resource managers.

The varied scales and high precision of space geodetic observations are helping to push the frontiers of knowledge regarding many Earth processes. Because space geodetic measurements have many

applications, geodesy today brings scientists together for interdisciplinary research that helps mitigate the influence of the forces of nature on our growing population as well as the effect of the population on Earth's fragile surface.

For more information on space geodetic techniques and their applications, please visit <http://www.unavco.org/geodesy21century>.

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NASA Mission to Explore Forcing of Earth's Space Environment

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The Global-Scale Observations of the Limb and Disk (GOLD) mission has been selected as a mission of opportunity by NASA's Small Explorer program. This mission, with an anticipated 2014 launch date, is an opportunity to significantly advance thermosphere-ionosphere (TI) science and to provide answers to key elements of an overarching question for heliophysics science: What is the global-scale response of the thermosphere and ionosphere to forcing (e.g., by geomagnetic storms or atmospheric tides) in the integrated Sun-Earth system?

Understanding the response of the TI region to forcing is important for scientific as well as societal reasons. Scientifically, understanding how Earth's TI responds to forcing provides insights into the response of similar regions on other planets. Societal impacts that arise from an inadequate understanding of this region include unnecessary delays in air travel and unanticipated interruptions in satellite services such as the Global Positioning System. The GOLD mission promises to lead to a decrease in such problems.

Scientific Objectives

The TI region contains the transition between the plasma-dominated region of the atmosphere and the neutral, fluid-dominated atmosphere at lower altitudes. External forcing by the solar extreme ultraviolet (EUV) normally dominates in this region, but internal forcing from magnetosphere-ionosphere (MI) coupling or from atmospheric tides can have a critical or even dominant influence, as MI coupling frequently does during geomagnetic

storms. The relative importance of each forcing source varies with time, geographic location, and altitude; consequently, our understanding of the TI region is best advanced by considering its global-scale behavior, an approach often used in modeling.

GOLD will provide, for the first time, a near-simultaneous global-scale "snapshot" of the temperature and composition in the lower thermosphere, allowing one to see how these two major parameters, shown in Figure 1, react to external and internal

forcing. Following their temporal development across a hemisphere of the Earth, GOLD measurements are expected to resolve critical aspects of the forcings that drive the transition region. Using these two key parameters, theories and models of TI forcing are tested and understanding of the system is advanced.

The GOLD mission will address the following four key science questions, which are a subset of the overarching question:

1. How do geomagnetic storms alter the temperature and composition structure of the thermosphere; how does the low-latitude nighttime ionosphere respond to geomagnetic storms; and is the initial state of the

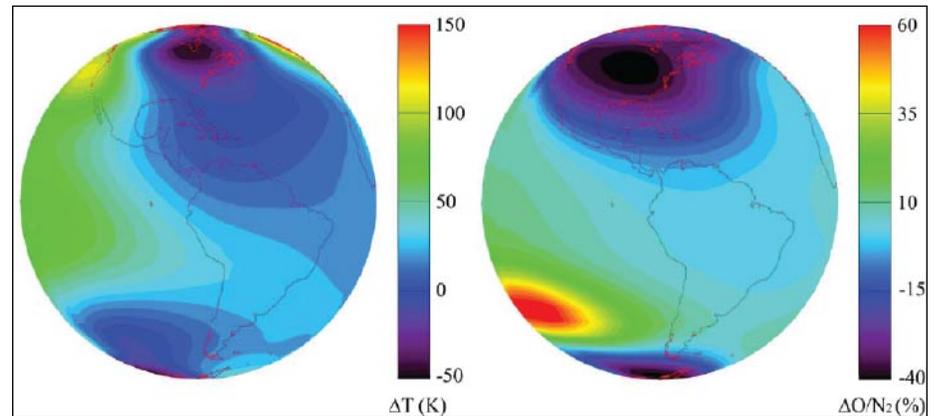


Fig. 1. Storm-time changes in thermospheric temperature and composition. Differences between storm-time and quiet-time calculations from the National Center for Atmospheric Research's thermosphere-ionosphere electrodynamics general circulation model (TIEGCM) are shown (left) for the temperature (K) and (right) for the column density ratio of atomic oxygen to molecular nitrogen (O/N_2 , in percent). Both are on a constant-pressure surface at an altitude of approximately 160 kilometers. After averaging from an intrinsic, approximately 625-square-kilometer resolution to the $5^\circ \times 5^\circ$ grid typically used by the TIEGCM, the Global-Scale Observations of the Limb and Disk (GOLD) mission is expected to resolve differences of less than 15 K in temperature or less than 10% in O/N_2 column density in 2-hour averages. The spatial resolution and the viewing geometry used for these images approximate those of the GOLD imager.