**Enabling a global perspective for deterministic modeling of volcanic unrest**

JPL Volcano Science Team and Colleagues

*Science Target: The greatest challenge facing volcano science today is to understand how underground magmatic systems evolve at restless volcanoes to determine if they will erupt.*

## Science Application Targets

Volcanic systems become eruptible through the injection and ascent of gas-rich magma, and the saturation, exsolution, and accumulation of gases and heat prior to eruptions [1, 2]. In restless volcanoes, these processes can generate variable signals of ground deformation and gas and thermal emission for weeks to months before eruptions [1, 2]. Thus surface gas and thermal signatures reflect inferred subsurface magmatic heat and gas loss hidden from direct observation. The individual signals, and processes generating these signals, may be understood at a limited number of volcanoes. However, physical modeling is required to understand the systematic interdependence between the processes, establish frames of reference for the comparison of volcanic systems on a global scale [3, 4, 5, 6], and achieve deterministic forecasts of volcanic behavior.

**Info Box 1: Volcanic eruptions occur incessantly.**

Large explosive eruptions occur annually at 50-60 of the world's ~1,500 potentially active volcanoes [46, 17], posing significant health and economic risks for close to 1 billion people [53, 43, 41, 44, 40], and their atmospheric impacts include climate forcing and aviation hazards [2, 17]. The week of March 23-29, 2016 alone, over 26 volcanoes erupted [54] and VAACs issued aviation ash advisories for 15 volcanoes (AFWA issues on average 40 advisories each week), including Pavlof Volcano (Alaska) which led to airspace warnings (SIGMETs and NOTAMs) and U.S. flight disruptions. Timely and accurate eruption forecasts would help mitigate annual losses of up to US$ 6 billion [43] and the displacement of up to 400,000 people per year [40, 44, 53]. *See Table 1 and Figures 2a and 2b in Appendix 2.*

The science objective for the next decade is to reduce uncertainty in volcano forecasts. Deterministic dynamic models have the potential to improve volcano forecasts over currently used alert level [7] (and/or other probabilistic event tree [6]) methods. These models incorporate the physical and chemical evolution of magmatic and hydrothermal systems, the locations and geometries of magma bodies and conduits, and the principles governing their dynamics. The forecasting skill of the alert level models currently in use is less than 50% for time periods greater than 2-weeks prior to eruptions [7] *(See figure 3 in Appendix 3)*. Deterministic models will improve forecast lead times because they can be initialized with the state of the system at *any* time prior to an eruption and can be trained with eruption event data. In addition, alert level models can only be applied at well-monitored volcanoes, while deterministic models can be applied at any volcano. To advance deterministic forecasting, the models must accommodate wide ranges of volcanic composition, geologic and tectonic settings, and eruption styles, necessitating a global perspective.

This science objective has broad support within the science community as evidenced by:

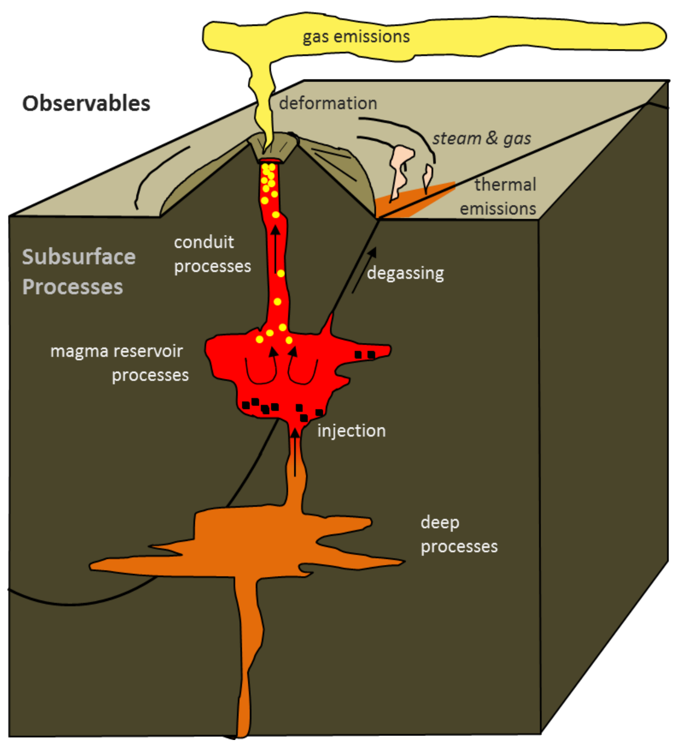


**Fig. 1.** Volcanoes give surface signals, which reflect subsurface processes.

- the NRC's 2007 Earth Science Decadal Survey, which states: "… *direct observational constraints on the style and dynamics of magma ascent are still lacking. Such constraints are crucial for forecasting the replenishment and pressurization of shallow magma chambers that may potentially feed volcanic eruptions. Volcanic unrest episodes for any given magmatic system may be quite infrequent, and only a few volcanic systems around the world are closely monitored. Therefore, a global observation system capable of detecting ongoing magmatic unrest will result in dramatic improvements in the understanding of volcanic activity and associated societal hazards*. [8].
- The objective of investigating processes of volcanic unrest through their observable signals and processed-based models is of decisive scientific importance and an expressed goal of the volcanological science community [2, 4, 9, 3, 5, 10, 11, 12].
- the strategic goals of NASA's Earth Surface & Interior focus area, as defined by the CORE report: "*How do magmatic systems evolve, under what conditions do volcanoes erupt, how do eruptions and volcano hazards develop?*" [13].
- the Applied Sciences & Disasters strategic goal to enhance natural hazards response [14].

The science target addresses the 2017 Decadal Survey Theme V--*Earth Surface and Interior: Dynamics and Hazards,* which will be advanced by systematically *addressing global volcanism to substantially improve knowledge of how volcanoes work*.

**Utility of Geophysical Variables** Geophysical variables driving these models include the geometry, pressurization, mass flux, and properties of the magmatic system and its host environment. As magmatic systems evolve, changing system properties lead to potentially different evolution pathways. Accuracy of the forecast is a function of the quality and frequency of our knowledge of these variables. When magma rises and depressurizes, gases exsolve leading to changes to melt properties such as viscosity, crystal content, and changes in the state of stress in the host rock and overlying hydrothermal systems (Info Box 2).

Mass flux from the system, such as dome extrusion, degassing, lava effusion, ash emission, results in feedback mechanisms that modulate the evolution of the system through changes in pressure and mass balance.

**Info Box 2: How volcanoes become detectably restless.**

Volcanic eruptions are preceded by subsurface magma ascent, often resulting in an addition of deep basaltic magma into shallow magma reservoirs, and deformation-induced opening of pathways [2]. $CO_2$ and helium are the first gases to exsolve from ascending magma upon depressurization, with $CO_2$ accounting for ~50 to ~98 mol % of these species in dry volcanic gases depending on magma composition, degassing history and exsolution pressure [49]. Continuous volcanic $CO_2$ surface emissions are consequently expected to increase prior to eruptions.

$SO_2$ evolves from magma at much shallower levels than $CO_2$, but it is the dominant precursory gas signal in the weeks directly preceding eruptions, indicating that magma is close to the surface [48, 49]. Multiple signals of degassing, deformation, and thermal activity begin to coevolve before an eruption (e.g., [52, 6, 27]).

Some volcanoes dissipate magmatic heat through hydrothermal systems, which produce reduced gas species ($CH_4$, $H_2S$) at the expense of soluble oxidized gas species ($CO_2$, $SO_2$) [50]. Increased thermal energy speeds up reaction rates speed and produces more $CH_4$, $H_2S$ emissions until the hydrothermal system begins to dry out and $CO_2$ and $SO_2$ increase again [51]. *(See figure 3 in Appendix 3)*

**Key geophysical variables** incorporated into the deterministic models include:

- Composition of the melt, separated fluid and gas phases, and hydrothermal systems;
- Geometry, depth, and location of the magma reservoirs and conduits;
- Changes in volume and mass within and out of the system;
- Changes in the stress field and thermal evolution of the system;

**Key observations** of phenomena, from which knowledge of these variables is derived from, include:

- Variations in the rate and composition of gas emissions (e.g., $CH_4$, CO, $CO_2$, $H_2O_{vap}$, $H_2S$, $SO_2$);
- Variations in the composition and abundance of volcanic ash and aerosols (e.g., dissolved $H_2SO_4$);
- Variations in thermal emissions from summit craters, lava lakes and flows;

- Variations in the composition of lava domes and flows;
- Changes in surface topography resulting from the extrusion of lava domes, effusion of lava flows, and deposition of ash and pyroclastic material;
- Surface deformation resulting from changes in stress and volume of the system, as well as the geometry, depth, location of magma reservoirs and conduits;
- Dielectric contrasts between magma bodies and host environment.

**Case studies.** The use of satellite-based remote sensing techniques to detect, quantify, and track many of these phenomena has been demonstrated by a large number of case studies:

- $SO_2$ and ash emissions have been measured at ultraviolet (UV) and thermal infrared (TIR) wavelengths [15, 16, 17];
- $CO_2$ emissions have been measured in the short wavelength infrared (SWIR) [18, 19];
- Mass effusion rates have been inferred from measurements of radiant emissions from lava domes and flows in the SWIR and TIR [12, 20];
- Surface composition and texture of lava domes and flows have been mapped in the TIR [21, 20, 22];
- Topographic change has been documented through comparisons of digital elevation models (DEMs) from single-pass, dual-antennae synthetic aperture radar (SAR) interferometry (InSAR) [23];
- Surface deformation has been measured with multi-pass InSAR [24];

In addition, recent experiments with Rayleigh resonance radar imaging (RRRI) suggest that the dielectric contrast between magma bodies and host rocks could be used to map their geometries [25].

**Measurement Requirements**

To advance deterministic forecasting, models must accommodate wide ranges of volcanic composition, geologic and tectonic settings, and eruption styles. In addition, surface phenomena must be measured at temporal resolutions on a par with timescales of critical processes (e.g., every 2-3 days) to provide multiple successful data points throughout the weeks to months of precursory signals [5, 11, 4]. A space-based targeted observation strategy is the only practical way to achieve this frequency and variety of observations globally, especially for volcanoes (e.g., remote and/or very hazardous sites) where ground-based observations are not readily available, or are not available at all.

While multispectral TIR remote sensing has proven to be an effective tool for the measurement of the $SO_2$ content of homogeneous volcanic plumes, hyperspectral TIR measurements are required to identify and quantify the components of heterogeneous volcanic plumes, map quantities of important gas species, such as $H_2S$, with spectral features in regions affected by strong $H_2O$ absorption, and estimate the dimensions of gas plumes based on atmospheric sounding techniques. In addition, hyperspectral TIR measurements can be used to map the column density of water vapor, and thus correct TIR and microwave (radar and GPS) measurements for the effects of water vapor absorption. *(See Figures 4, 5, 6 in Appendix 3.)*

In the next decade (2017-2027) we assume that NISAR will be available to measure ground deformation, and ASTER, ECOSTRESS, MODIS, and VIIRS will provide multispectral TIR data. However, none of these missions will provide data with the spatial, spectral and temporal resolution needed for modeling. HyspIRI may be another source of multispectral TIR data, but this mission is still in the pre-formulation stage. These TIR measurements do not provide the combination of fine spectral and temporal resolution required for modeling.

**Key requirements** on the hyperspectral TIR measurements include:

A. <u>Quantitatively determine main trace gas abundances and time variability</u> of such emissions during volcanic unrest ($SO_2$, $H_2S$, $CH_4$) to ~1% accuracy, to constrain the volatile content of magma, to detect, and to quantify rates of magma ascent. A secondary focus is on volcanic ash particles and sulfate ($SO_4$) aerosols. $CO_2$ at 10-60 kt/day [26, 27, 28, 29] and $SO_2$ at 0.5-10 kt/day [30, 31, 32], are now globally detectable [33, 31], and limitations in data quality from water vapor interferences can also now be addressed [34, 15, 35, 36]. Generally, spectral delineation (e.g., minimal spectral mixing) of individual volcanic features (e.g., gas species, airborne ash size-frequency distributions) requires sub-200m spatial resolution (0.01 to 0.1 characteristic feature dimension), with SNR optimally of 150-1000, TIR NEΔT ~0.1K or better, spectral resolution of ~20nm, and ability to accommodate a dynamic range of 500-800K (depending on spatial resolution) across the TIR band-passes. Trace gas measurements can be correlated with available $CO_2$ observations, in situ and orbital. Also, measurement of surface material composition (i.e. ashfall spectral response) constrains the composition of source magmas.

B. <u>Determine the dynamics of intrinsic volcanic thermal emissions</u> from eruption-related anomalies, and the characteristic spatial domain size of thermal differences on the order of ≤ 100m, at < 5K [16].

C. <u>Improve detectability, accuracy and precision</u> by significantly improving the characterization of water vapor signature which obscures the desired gas and thermal signals – i.e., lifting the water veil. The recognition and removal of water vapor is like the *defogging of a windshield*-- dramatically reducing the impact of confounding water vapor increases definition of spectral detail. The $H_2O$ column density estimates will be used to “correct” the radiance measurements for atmospheric emission and absorption, thus increasing the accuracy and precision of our maps of gas species, surface composition, and surface temperature *(See Figures 4, 5, 6 in Appendix 3).*

Measurements that meet these requirements can be used to test if forecasting skill improvements can be applied to any volcano, by comparing new data to predictions generated iteratively by process-based forward numerical/analytical models, constrained by previous data inputs, thus tying observations of known processes to predicted outcomes.

| Spaceborne - HyTES System Design Parameters | |
|---|---|
| **PARAMETER** | **Spaceborne - HyTES** |
| Sensor scanning geometry | Pushbroom:hyperspectral |
| Detector technology (T = 65K) | Barrier InfraRed Detector |
| Spectrometer design (T = 100K) | Transmissive Dyson and relay |
| Telescope design (T = Ambient) | 2-Mirror metal alloy |
| Pointing mirror (T = Ambient) | Metal alloy with stepper motor |
| On-board calibration | Full aperture blackbody |
| Instrument mass (CBE + selective contingency) | 88 kg |
| Instrument power (CBE + selective contingency) | 143 W |
| Single scene frame storage (100km x 100km) | 537 MB |
| Time to acquire single scene | 15s |
| # of potential scenes per orbit | 40 |
| Orbital average data rate for 10 min/orbit | 32 Mbps (x-band) |
| Instrument 50% NICM cost | $60M |
| Science investigation | 2 years, fuel for 5 |
| Orbit characteristics | Sun-Synchronous / Descending |

Cost assumptions: The instrument will utilize passive cooling in conjunction with a pulse tube cryocooler. The cryocooler is already **in-hand.** The mass of this cryocooler is accounted for in the thermal estimate. A pointing mirror is used to calibrate the spectrometer once per orbit (one on-board blackbody + one space view).The cost estimate assumes the detectors are at TRL 6 by PDR. The cost estimate assumes selective redundancy as opposed to fully single string – required by instrument class.

**Feasibility and Affordability**

It is very likely that the **remote measurements required to substantially improve our understanding of volcanic processes and paths to eruptions can be affordably achieved between 2017-2027, although they are not currently planned.** This is primarily because of recent improvements and experience in observational technologies over the last decade. The key missing measurement or gap is hyperspectral TIR spectral imaging. The observational capabilities and approaches, discussed above, address the rationale and benefits of collecting data in the volcanological context, which can be extended to other fields where such observations are useful, like hydrology and agriculture. We feel there will be a substantial benefit in assuring the accessibility and continuity of multispectral and hyperspectral TIR data, of the type collected by NASA, NOAA, and partners (e.g., ASTER, MODIS, VIIRS), especially as these very mature tools are decommissioned in the coming decade. While these legacy efforts have been important in illustrating the value of such measurements, they have inherent instrumental and mission limitations that can be overcome by newly available technologies, and by planning for new missions based on experience with these legacy systems. In particular, the ability to improve both spatial and spectral resolution, and revisit frequency, beyond what’s now available, will be key.

| Spaceborne - HyTES System Design Parameters | |
|---|---|
| **PARAMETER** | **Spaceborne - HyTES** |
| Ground resolution (m) @ NADIR | 100 |
| Orbit altitude (km) | 720 |
| Equatorial revisit with pointing (days) | 2 |
| Cross track FOV (degrees) | 8.1 |
| NADIR swath width (km) | 100 |
| Noise equivalent delta temperature (K) at 300K | <0.2 |
| Absolute accuracy (K) at 300K | 0.5 |
| Saturation temperature (K) | 500 |
| Nominal dwell time (ms) | 10 |
| Daytime overpass time (hh:mm) | 11:00AM +/-30 min |
| Nighttime imaging | Yes |
| Number of bands spectral range: 7.5 – 12 μm | 256 |
| Off NADIR pointing | +/- 40 degrees |
| Data latency | < 3 days |

Current operational and near-term missions similar to what is envisioned for the next decade, by analogy, can provide insight into what may be affordably achievable within the next decade. For instance, the yearlong ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), will provide multispectral TIR measurements at spatial resolution finer than 100m. It is designed specifically as a multispectral pointing mission to investigate thermal stresses on plants. It is currently on cost, and on schedule, and thus provides a high confidence roadmap as to low-cost mission architecture and required resources. Based on cost estimates for ECOSTRESS, it is estimated the cost of the needed TIR instrumentation will be <$60M.

Confidence that an expansion to a spaceborne thermal infrared hyperspectral capability is strengthened by the recent demonstrated successes of the Hyperspectral Thermal Emission Spectrometer (HyTES) airborne deployments. It is currently operational and at NASA Technology Readiness Level 9 (i.e., "flight qualified through test and demonstration" for airborne operations, and is thus relatively mature). We provide here the System Design Parameters for a Spaceborne HyTES. The cost of a similar instrument would likely be <$60M in the next decade.

The situation is robust for deformation measurements, since continuous GPS is a mature technology. InSAR from NISAR (2021-2024) is in its formulation stage and is expected to be operational during the relevant time period. Much of the technology necessary to achieve the goals outlined here is in hand; the likelihood of affordably realizing the required measurements is high, and risk is relatively low. Based on airborne and orbital capabilities already realized or in advanced development, there are no apparent technological hurdles. Such technology should easily be at a maturity appropriate for deployment to orbit within the next decade.

**Synergistic measurements**

A multitude of volcano observatories provide existing and potential partnerships for ground-based validation data to space-borne measurements, and to deterministic model outcomes. Over 70 volcano observation agencies perform ground based measurements at a subsample of Earth's active volcanoes [17]. Under the auspices of their umbrella organization, the World Organization of Volcano Observatories (WOVO) archives data of unrest in its database WOVOdat [17, 2]. Among these agencies contributing to WOVOdat is the *Istituto Nazionale di Geofisica e Vulcanologia* (INGV – Italy) with a longstanding interest in undertaking spaceborne observations in the short wave infrared (SWIR: 1-2.5 µm), the mid-range infrared (MIR: 3-5µm), and the thermal infrared (TIR: 8-12µm). INGV is a cabinet-level agency in Italy that has chartered responsibility to detect and mitigate geological hazards, particularly with respect to volcanoes and earthquakes. INGV actively collaborates with NASA colleagues, the United States Geological Survey, the ASTER Science Team and with Principal Investigators in the NASA Earth Surface and Interior Focus Area programs.

Likewise, leveraging designs and development of other prospective NASA instruments proposed under Earth Ventures and related NASA Science Mission Directorate instrument development programs promise relevant advances supporting goals expressed here.

*n.b., The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or the California Institute of Technology.*

# Appendices

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### A3. Additional Tables and Figures

**Table 1.**
**Increased observations and process knowledge reduce fatalities.**

| Example | | evacuated | killed |
|---|---|---|---|
| Mayon, Philippines | 2014 | 12,000 | 0 |
| Kelut, Indonesia | 2014 | 100,000 | 3 |
| Sinabung, Indonesia | 2010-now | 20,000 | >14 |
| Merapi, Indonesia | 2010 | 400,000 | 353 |
| Eyjafjallajökull, Iceland | 2010 | 800 | 0 |
| Pinatubo, Philippines | 1991 | >1,000,000 | 847 |
| | *loss of 2 largest US overseas bases* | | |
| N. del Ruiz, Colombia | 1983 | 0 | 25,000 |

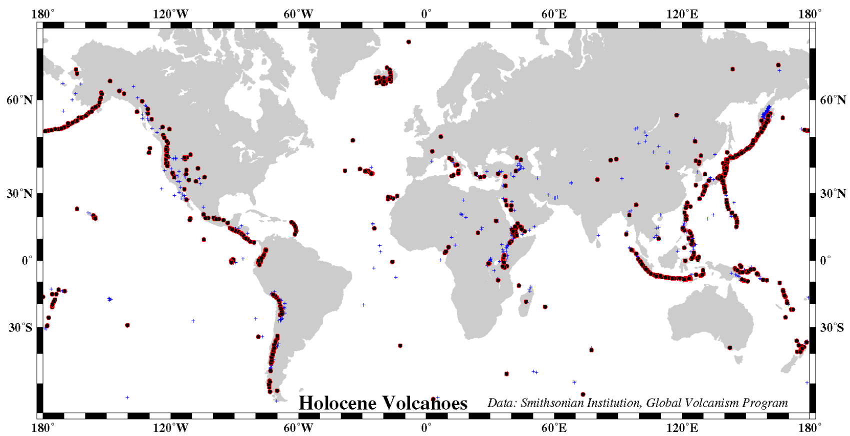


**Figure 2a.**

**Distribution of the World's Active Volcanoes**: Most volcanoes occur within zones of tectonic plate margins, or within tectonic rift zone. Others occur within interior regions of both continental and oceanic plates.

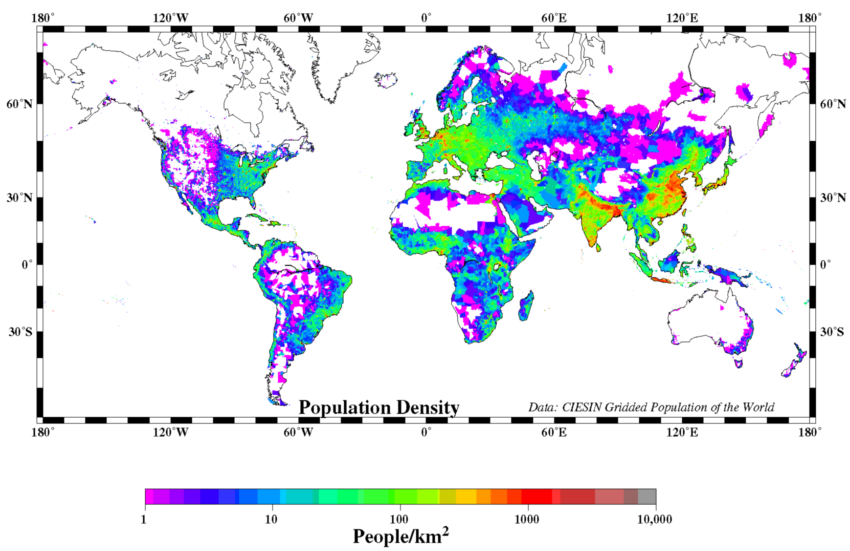


**Figure 2b.**

**Distribution of the World's Population:** More than 800,000,000 people live within the hazard zones of the world's active volcanoes. Air routes are often affected by volcanic emissions, especially drifting ash clouds, which pose a serious hazard to flight.

**Figure 3.** A notional illustration of the stages of volcanic unrest. Eruption precursor phenomena will be detected earlier when increased instrument sensitivity permits lowered detection thresholds. Sensitivity will be increased in critical thermal infrared (TIR) band-passes when future hyperspectral TIR data allow more precise spectral characterization and removal of confounding water vapor, which masks the spectral signal of precursory gas emissions. [In the magma reservoir, arrows indicate paths of movement, black dots indicate crystalized phases, and yellow dots indicate buoyant rising bubbles of gas, exerting pressure that drives the eruption.]

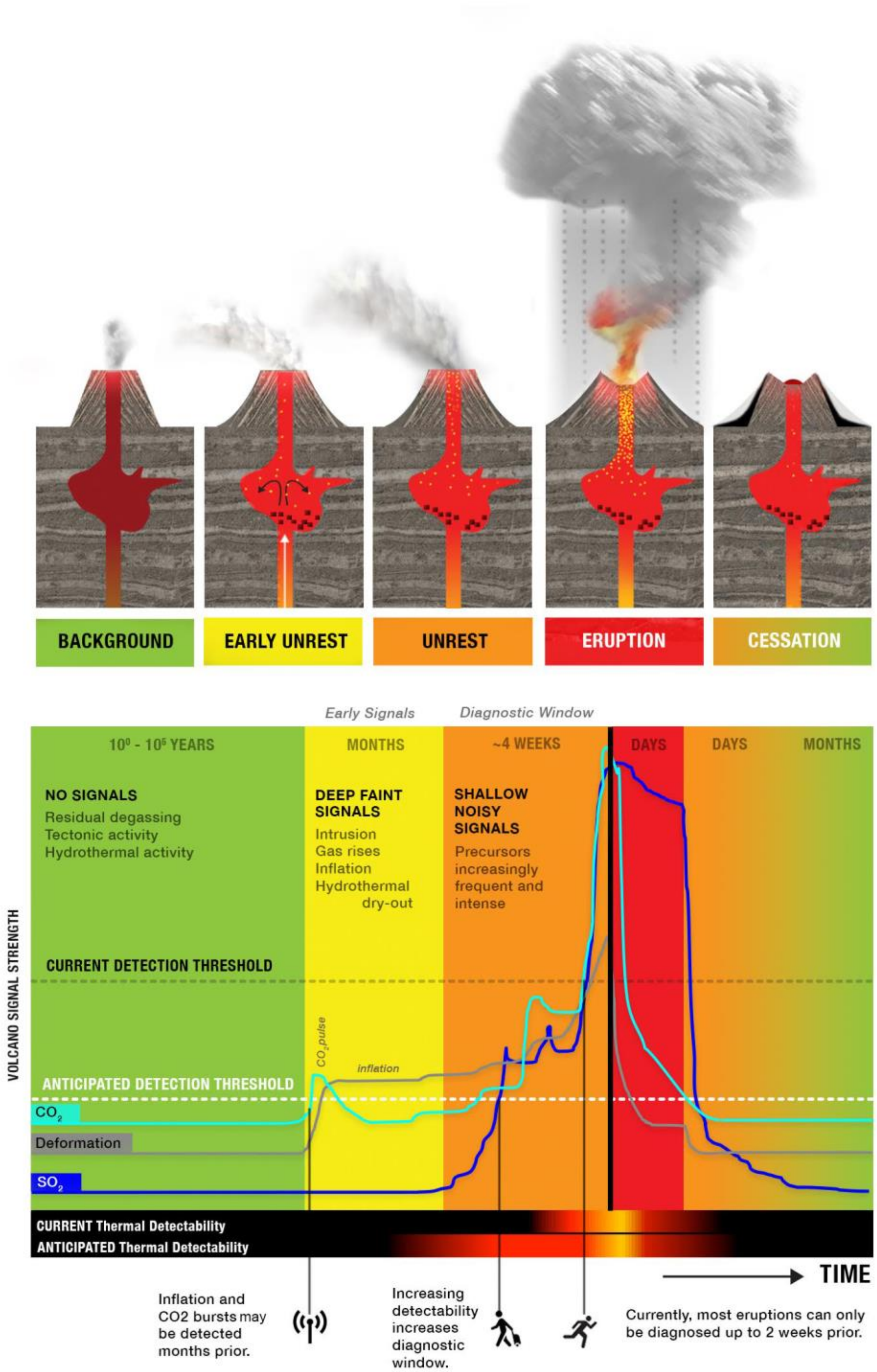

**Figure 4.**

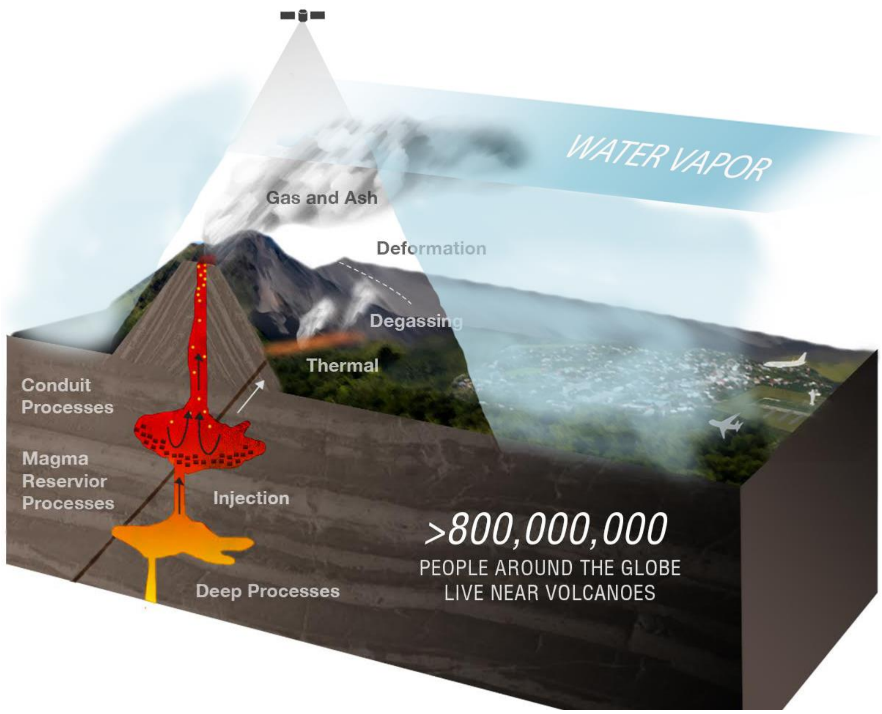


**Figure 4** graphically shows the relationship between the observing satellite, volcanic activity, and obscuration caused by intervening atmospheric water vapor. When the water vapor spectrum can be accurately determined, its degradation of volcanic trace gas spectra and geothermal anomalies can be dramatically mitigated. Hyperspectral thermal observations will enable these techniques to improve volcanic precursor detection.

**Figure 5.**

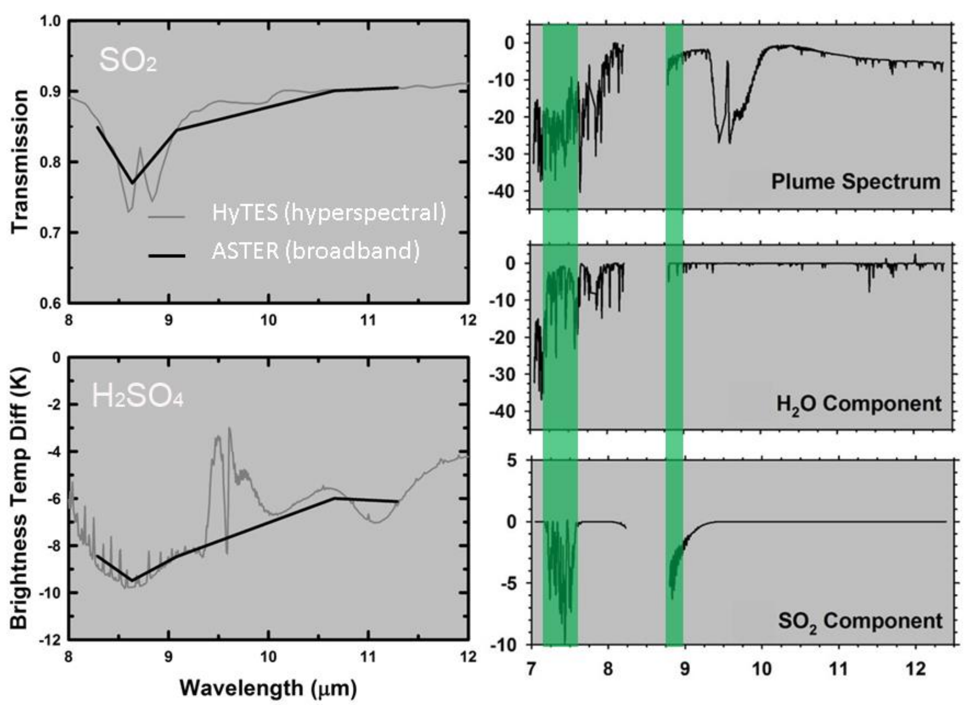


**Figure 5 (left)** compares hyperspectral TIR data from the airborne hyperspectral HyTES with broadband TIR data from ASTER for $SO_2$ and $H_2SO_4$, two typical components of volcanic plumes. Spectral detail is clearly enhanced in the HyTES data.

**Figure 5 (right)**, shows two bands (green) of the $H_2O$ component subtracted from a volcanic plume spectrum to retrieve a residual $SO_2$ component, using hyperspectral TIR data.

**Figure 6.**

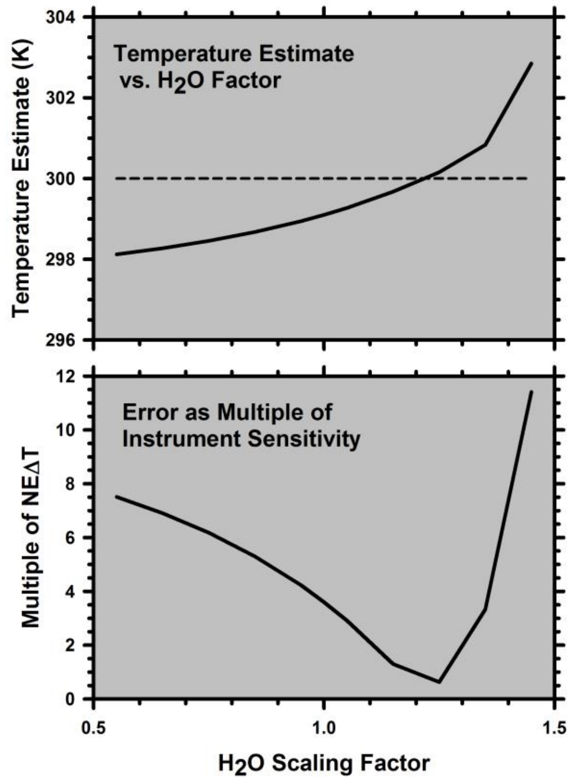


**Figure 6.**

The results of a forward model simulation above quantitatively show how detailed knowledge of water vapor abundance impacts the accuracy of the spectrum of surface temperature retrievals, and improves detectability. Accurate temperature retrieval across the thermal infrared spectrum is fundamental to accurate retrievals of gas concentrations and detection and precise characterizations of thermal anomalies. Here, a synthetic thermal spectrum was generated using a forward model, which was then used as input to the temperature retrieval procedure. “Scaling Factor” indicates knowledge of $H_2O$ vapor abundance: a factor of 1 indicates perfect knowledge, < 1 indicates under-representation, > 1 indicates that water was over-represented. The top graph shows that even with perfect knowledge of the $H_2O$ (Scaling Factor = 1), least squares-based retrievals used in most models under-represent temperature.

The bottom graph portrays the estimation error in multiples of instrument sensitivity, or NEΔT (noise-equivalent change in temperature, or the smallest temperature change that can be measured in the presence of noise). The impact of uncertainty in our knowledge of $H_2O$ is significant. With the very modest 5% under-representation of $H_2O$ (Scaling Factor = 0.95), the temperature estimation error is 4X larger than the NEΔT (0.20 K). A 45% over-representation of $H_2O$ (Scaling Factor = 1.45) results in a temperature estimation error 11X larger than the NEΔT. In other words, hyper-fine instrument sensitivity will not ensure comparable accuracy of temperature estimates unless $H_2O$ vapor abundance is known. Hyperspectral TIR observations will allow us to resolve $H_2O$ vapor in the observed spectra, and thus estimate its column abundance at each pixel, resulting in significantly improved detectability. In the case shown, NEΔT uncertainty is minimized at an $H_2O$ scaling factor of 1.25 which, in this context, would be extremely difficult or impossible to determine accurately by remote sensing without hyperspectral data.