The role of fire in the Earth System

2017 Decadal Survey
Response for Information #2

Authors:
E. Natasha Stavros (Jet Propulsion Laboratory, California Institute of Technology)
A. Anthony Bloom (Jet Propulsion Laboratory, California Institute of Technology)
Timothy Brown (Desert Research Institute)
Janice Coen (National Center for Atmospheric Research)
Philip Dennison (University of Utah)
Louis Giglio (University of Maryland)
Robert Green (Jet Propulsion Laboratory, California Institute of Technology)
Everett Hinkley (USDA Forest Service)
Zachary Holden (University of Montana/ USDA Forest Service)
Simon Hook (Jet Propulsion Laboratory, California Institute of Technology)
William Johnson (Jet Propulsion Laboratory, California Institute of Technology)
Mary Ellen Miller (Michigan Technology University)
Birgit Peterson (US Geological Survey, EROS)
Brad Quayle (USDA Forest Service)
Carlos Ramirez (USDA Forest Service)
James Randerson (University of California, Irvine)
David Schimel (Jet Propulsion Laboratory, California Institute of Technology)
Wilfred Schroeder (University of Maryland)
Amber Soja (NASA Langley Research Center, National Institute of Aerospace)
Mike Tosca (Jet Propulsion Laboratory, California Institute of Technology)

Table of Contents

Question 1, Part (A) – Fire Science and Application targets 1
Question 1, Part (B) – Importance of Targets to the Themes 1
Question 1, Part (C) – Advancing Themes by addressing Targets 2
Question 2 – Utility of Geophysical Variables 3
Question 3 – Measurement and Observation Requirements 3
Question 4, Part (A) – Feasibility and Affordability 4
Question 4, Part (B) – Synergistic Measurements 5
Figures 6
References 10

Question 1, Part (A) – Fire Science and Application targets

Key questions regarding the role of fire in the Earth system (Figure 1) include:

A. How does fire affect ecosystem services (e.g., clean air and water, habitat, and biodiversity) and which ecosystems are the most vulnerable to changes?
B. What is the radiative forcing of wildfire globally accounting for greenhouse gas and aerosol emissions, post-fire recovery, and changes in surface albedo?
C. How do fuel type, structure, amount, and condition influence fire?
D. How do these smoke emission influence atmospheric dynamics and health and air quality as they are globally transported?

Answering these questions will improve understanding of fire in the Earth system, and will require continued and improved coverage of observations of ecosystems pre- and post-fire. To address these questions, the following science and application targets ("objectives"):

1. Monitoring post-fire recovery using ecosystem composition and 3-D structure
2. Mapping vegetation carbon and nitrogen
3. Mapping ecosystem condition: soil moisture and vegetation productivity, moisture, stress and mortality
4. Mapping fire emissions and smoke transport

require global observations with frequent revisit to capture before and after disturbance conditions. **To accomplish these objectives, it is imperative for continuity of observations not only to provide long-term analyses of fire's role in the Earth system, but also to sustain integration into operational decision support systems.**

Question 1, Part (B) – Importance of Targets to the Themes

The aforementioned objectives "cross-cut" Themes 2-4 as wildfires can be *extreme events* that directly affect the *carbon cycle* and have direct implications for *applications' science*.

These objectives are important to Theme 2 because smoke emissions from fire are directly injected into the atmosphere, acting as air pollutants, altering atmospheric chemistry downwind of fire (gases and aerosols), and atmospheric thermodynamics, affecting local-to-regional weather and larger-scale climate systems (Figure 1). Fire emissions feedback to the climate system by producing cloud condensation nuclei (CCN)[1–3], aerosols that directly and indirectly affect radiative forcings[2,4–6], and altering the radiation balance (vegetation change, deposition on ice)[7–10]. Emissions also act as sources of pollution that are transported beyond localities and have the potential to affect global atmospheric chemistry and the hydrologic cycle[11–18]. Aerosols can influence the micro- and macro-physical and properties of clouds thus impacting the energy balance and the hydrological cycle. Smoke also contains limiting nutrients that provide necessary nutrients at both land and ocean interfaces[19,20].

These objectives are important to Theme 3 because climate influences fire regimes[21,22], which act as a catalyst expediting terrestrial ecosystem change across climatic gradients[23–25] (i.e., temperate, boreal, and tropical). Thus fire has implications for biogeochemical cycles and ecosystem function (e.g., nutrient cycling), biodiversity and ecosystem health[25]. Specifically, mapping post-fire recovery (Objective 1) informs natural resource management as decision makers balance land use objectives such as biodiversity (which can be influenced by fire[26]), species protection and mitigating fire effects[27]. Fire influences ecosystem health[28] by affecting biogeochemistry (Objective 2), specifically carbon and nitrogen[29], cycles through nutrient cycling[30] and ecosystem productivity[31]. Furthermore, ecosystem condition (Objective 3), an indicator of ecosystem health[28], can influence the likelihood of fire[32].

As fire affects atmospheric thermodynamics and local-to-regional weather (Theme 2) and terrestrial ecosystems (Theme 3), these objectives are also relevant to Theme 4 as carbon cycling and energy exchange link the terrestrial, atmospheric, and hydrologic systems to influence the global climate system[33]. Specifically, fires contribute to increasing atmospheric carbon, which can have countering feedbacks on the climate system. Fire emissions (e.g., greenhouse gases and aerosols discussed above) have made significant contributions to atmospheric carbon[34] in relation to anthropogenic emissions[35], yet confounding impacts of fire necessitate representation of fire in global studies beyond simple carbon emission estimates[36]. Specifically, although carbon is lost to the atmosphere during fire, fire plays an important role in nutrient cycling[30] and regrowth[37] which affects carbon uptake by the biosphere that impose constraints on how the carbon cycle responds to variations in climate[31]. The incomplete combustion of biomass produces varying forcing agents including changed surface albedo from remaining charcoal[17] and aerosols[38], which can absorb and scatter solar radiation[39], deposit on snow and ice to change surface albedo[8], and effects on cloud properties and formulation[40]. Also affecting climate are changes in surface roughness and altered atmospheric mixing[41].

Question 1, Part (C) – Advancing Themes by addressing Targets

The aforementioned objectives can advance Themes 2-4 as follows.

- Terrestrial ecosystems will be better characterized (vegetation composition and vertical and horizontal structure) before and after fire, thus improving understanding of ecosystems (in their current state) and how they relate to current bioclimatic conditions, which can improve benchmarking for predicting changes. The current earth observations with limited resolutions and extent are not sufficient to resolve these relationships beyond the current state of knowledge[42].
- Improved understanding of terrestrial ecosystems, has the potential to resolve the varying functional role of fire and how that relates to biodiversity[26] and ecosystem health (e.g., water quality[28]). Mapping vegetation composition, structure and amount (e.g., biomass) are essential to characterizing habitats for protected species[43–45], resolving models of erosion, hydrologic runoff, and water quality[46,4748], informing predictive models of landslide potential[49], quantifying emissions that degrade air quality[50], and predicting fire behavior[51].
- Current practices for fire emission estimation use models and emission factors to infer transition of biogeochemical cycles (e.g., carbon) between the biosphere and atmosphere. However, continuing observations of forest structure (e.g., NISAR, GEDI and BIOMASS) and improved mapping of ecosystem composition (e.g. image spectroscopy outperforms broadband sensors[42]), can refine estimates of above ground biomass before and after fire[52].
- Increased knowledge of structure and composition (species, age) can improve estimates of aboveground biomass, while mapping ecosystem condition can provide estimates of the total available carbon for burning[32,53], particularly in ecosystems with high belowground carbon reserves that are released during burning. Thus, such observations can refine emissions estimates and combustion efficiency useful for understanding plume injection height and smoke transport.
- Mapping post-fire recovery will resolve uncertainty to local (with respect to the fire) changes in surface albedo, while improved mapping of carbon before and after can inform emissions modeling and thus resolve uncertainty in regional and global effects of black carbon[54] and changed snow and ice albedo from deposition[8] .

Question 2 – Utility of Geophysical Variables

All four objectives require sustained satellite observations of fire activity (e.g., *fire occurrence, fire area, temperature,* and *fire radiative power (FRP))* as fires have global impacts even when occurring in remote areas. Specific to each objective, required observations include:

Objective 1 – mapping forest recovery: Vegetation composition can be represented by *vegetation functional types*, defined as assemblages of species by structure, physiology, and phenology[55] that characterize ecosystem response to environmental conditions or *disturbance severity*[56]. Current practice uses discrete functional types, however new technologies provide continuous characterization of *optical types* that increase functional type classifications[57] (**Figure 2**) and map vegetation functional diversity that can link biodiversity to ecosystems functions[58].

Vegetation structure requires observations of mean and variation of *canopy height, canopy base height*, *stem density, stem volume, basal area,* and *fractional canopy cover*.

Objective 2 – mapping carbon and nitrogen: Mapping *canopy chemical composition* identifies the occurrence and the percentage composition of each in the canopy, while mapping *canopy fuel load* using *aboveground biomass* and *leaf area index* is essential for refining estimates of fire carbon fluxes[59], and pre- and post- carbon and nitrogen stocks[60].

Objective 3 – mapping ecosystem condition: There are many characteristics of ecosystem condition including:

- Discrimination between *live, senescent/scorched, and charred vegetation* can inform the health of the ecosystem (i.e., burn fraction – which performs equally as well as, but with advantages over, historically used indices of burn severity[61]).
- There is a range of proxies to characterize *vegetation stress*, a critical observation for understanding how flammable an ecosystem is[25], including observations of *precipitation*, *temperature, relative humidity, wind speed and direction, soil moisture, soil temperature, vegetation water content* or *equivalent water thickness.*
- Ecosystem flux affects fuel accumulation (e.g., systems with rapid succession or that are water limited[32,62]) and is relevant to mapping post-fire regeneration. Thus, observations are needed of *gross primary productivity* that can be derived from *fraction of photosynthetic active radiation, leaf area index, vegetation greenness, or solar induced fluorescence*.

Objective 4 – emissions and transport: knowing the *fuel amount*, *condition,* and *stand age* is necessaryto determine the combustion completeness, injection height and the vertical profile of emissions in the atmosphere, which affect smoke transport[53].

Question 3 – Measurement and Observation Requirements

To observe these geophysical variables, **measurements are needed contemporaneously (not simultaneously)** across three payloads: (1) a thermal infrared (TIR) radiometer, (2) a Visible-Shortwave Infrared (VSWIR) imaging spectrometer, and (3) an active sensor as well as observations produced from data assimilation.

Fire detections and land surface temperature need sustained global TIR radiometric retrievals at ≤375 m pixel resolution at nadir +/- 60° with sub-daily observations and an NEdT of 0.2K and ≥9 bands at: ~8.3 μm, ~8.6 μm, ~9.1 μm, ~11 μm, ~12 μm to distinguish land surface temperature (LST) from emissivity[63], ~4 μm with ≥400 K saturation and sufficient thermal range for fire detections[64] (but may require 2-bands to have sufficient sensitivity at the lower temperatures), ~1.6 μm and ~2.2 μm for cloud detection[65], geolocation and flagging false positives[64].

Vegetation functional types, *gross primary productivity,* and *fire severity* need continued coverage of multiple Landsat-like data. To advance Theme 3, a VSWIR imaging spectrometer is needed (Figure 3) with continuous spectral range 0.4-2.5 µm at ≤10 nm spectral sampling, ≤30 m pixel resolution, ≤16 day observation repeat, a 185 km swath, high signal-to-noise and global coverage that provides:

- analogous Landsat observations using spectral-response functions[66–68]
- *canopy chemical composition*[69] (Figure 3a) and *equivalent water thickness*[70], and
- *live, senescent or scorched, and charred vegetation*[71]

Vegetation structure and *aboveground biomass* can be observed using full waveform or discrete return active sensors: Light Detection and Ranging (LIDAR)[72] and single-band microwave synthetic aperture radar (SAR)[73]. Generally, full waveform improves dense canopy penetration[74] and may improve dense vegetation structure characterization[75]. LIDAR can be used vertically in the atmosphere to characterize plumes (e.g., CALIPSO) and horizontally to scan the Earth's surface (e.g., GEDI, GLAS, IscSAT-1/2). However, SAR has the advantages of penetrating cloud cover[76], observing *soil moisture*[77] and *vegetation water content*[78], and global mapping ability (as opposed to sampling). Research and management require a scene area of 75 km with nominal resolution of ~1 ha, which requires measurements at ≤20 m resolution to reduce noise, and ≥2 observations per year to resolve changes in phenology and snow contamination[76]. A repeat-pass InSAR configuration with 2 looks are likely to result in unacceptable levels of interferometric decorrelation[76], thus baseline SAR observations require fully polarimetric (HH, HV, VH, VV) L-band and tandem (single pass) interferometry, while threshold SAR require a dual polarimetric L-band with cross polarization (HH, HV) and repeat-pass interferometry with ≥3 looks to reduce SAR speckle[76].

Data Assimilation: *Meteorological data* derived from the GEOS-5 data assimilation system are needed for model smoke transport[79], fire behavior forecast models[80] with the realistic potential to save lives, and fire danger modeling[81]. Research and development is needed to provide data at higher spatial (≤300 m pixel) and temporal (3 hr) resolution that accounts for regions with complex mountainous topography.

Question 4, Part (A) – Feasibility and Affordability

TIR Radiometer: **Consistent TIR measurements are required across missions or through continued existence of these missions**. It is assumed measurements from MODIS and VIIRS will continue through the NPOESS and JPSS programs; however, in order to advance fire information products from TIR, new global mapping satellites must consider instrument development that increases the saturation temperature while providing sub-daily data with ≤375m pixel resolution. Although there is a trade in spatial and temporal resolution, a new TIR platform meeting this spatial requirement could augment the frequency of TIR observations from VIIRS and MODIS while providing a spatial resolution for LST observations, which are needed to assess *vegetation stress*.

NASA-guided engineering studies (2014,2015) demonstrated the feasibility of a 3-year, Class C mission with TIR radiometer at 60 m pixel resolution, 1200K saturation, and 2-day temporal repeat at the equator. This radiometer would fit with a size, weight and power (SWaP) compatible with a Pegasus class launch (Figure 4) and would use key technologies developed from previous investments (e.g., TIMS[82], PMIRR[83], MASTER[84], TES, MCS/DIVINER, HyTES[85] and PHyTIR[86], and ECOSTRESSS) including the focal plane, cryocoolers and scan mirror assembly (Figure 5). Data rate and volume have been addressed using readily available onboard solid state recorded (SSR) and algorithms for lossless compression[87–90] and real-time cloud screening processes [91], thus enabling Ka band downlink of all terrestrial measurements.

VSWIR Imaging Spectrometer: Providing the needed measurements from an imaging spectrometer requires a different sensor than has been used on Landsat, however it builds on a legacy of previous investments in response to the 2007 NRC Decadal Survey[92] and the 2013 NRC sustainable land imaging report[68]: AIS[93], AVIRIS[94], AVIRIS-NG[95], NIMS[96], VIMS[97], Deep Impact[98], CRISM[99], EO-1 Hyperion[100,101], M3[102], MISE, and the IS now being developed for NASA's Europa mission.

NASA-guided engineering studies (2014, 2015) showed that the needed imaging spectrometer (Section 4a) can be implemented as a 3-yr class C mission (in comparison to the Class B Landsat missions) with SWaP compatible and a Pegasus class launch (Figure 6). Key to the design is an optically fast spectrometer[103], for which a scalable prototype F/1.8[104] has been developed, aligned, and qualified (Figure 5). Data rate and volume have been addressed using a lossless compression algorithm[87–89] and a real-time cloud screening process[91], thus enabling Ka band downlink of all terrestrial measurements (Figure 7). Algorithms for automated calibration[94] and atmospheric correction[105,106] are operational. International partnerships may enhance affordability.

Active Sensor: Many existing and future satellites (Section 4b) prove feasibility and affordability for collecting measurements characterizing the Earth's surface from active sensors; however, more research is needed to translate algorithms to bridge observations across satellite platforms. **Consistent active sensor measurements and respective observations are required across missions or through continued existence of these missions.**

For characterizing emissions and accurately quantifying smoke transport to remote locations, a vertical LIDAR is needed. The successes of the CALIOPE instrument on CALIPSO demonstrate feasibility and affordability for space-based measurements. Future flight projects may consider airborne (e.g., multi-wavelength High Spectral Resolution Lidar (HSRL-2)) campaigns to target specific events and address smoke transport questions relevant for management and research teams.

Question 4, Part (B) – Synergistic Measurements

Current and planned thermal sensors that provide data information products relevant to fire include MODIS, VIIRS, and ECOSTRESS. MODIS and VIIRS provide very similar products (*burned area, fire detection*, and *FRP*), however they are distinct missions and research is needed to bridge the datasets to provide data products available through one record. In 2018, the 1-yr ECOSTRESS mission will provide a base map of vegetation *water-use efficiency* in sub-regions around the world that will be invaluable to assessing ecosystem stress in relation to pre- and post-fire ecology.

Current and future satellites that complement a VSWIR imaging spectrometer with global mapping ability include those from the Landsat constellation (Landsat and ESA's Sentinnel 2/3), which provides frequent observations useful for immediate response to fire. Longer-term management and investigations of fire in relation to terrestrial ecosystems, however, will require more information than can be derived from broadband data[107]. The future DLR hyperspectral pointing instrument EnMAP[108], expected to launch in 2018 and operate for 5 years, and JAXA's ALOS-3 with an imaging spectrometer HISUI and broadband sensor[109] can facilitate ongoing research to improve regional processing of geophysical variables that are both backwards compatible with broadband sensors[66–68] and utilize the full breadth of information available in hyperspectral data.

While there are many existing and planned synergistic active sensors (NASA's IceSAT-2[110,111], GEDI[112], SMAP[113–115], CALIPSO[116], NASA-ISRO's NISAR[117], and ESA's BIOMASS[118] and Sentinnel 1[119]), the fire community needs a continuous record across decadal time scales, thus **consistent production of information products either between missions or through continued existence is essential**.

Figures

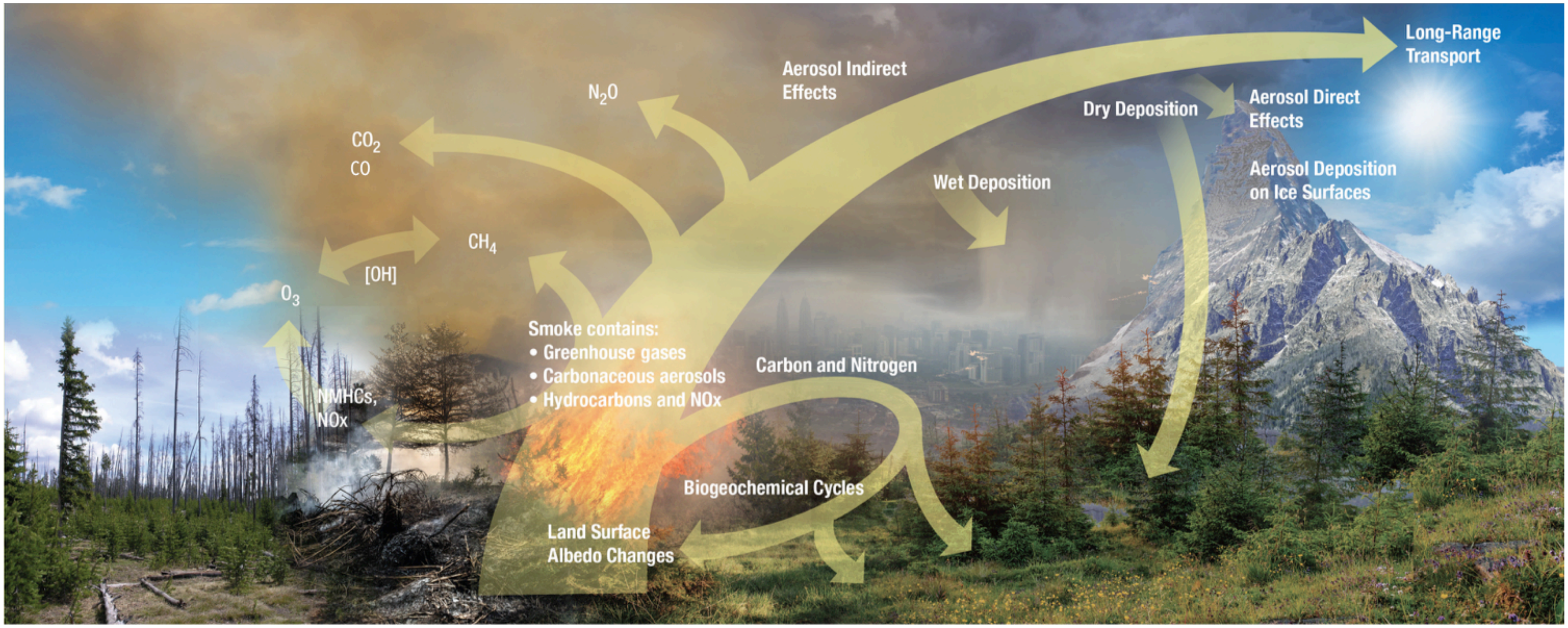

Figure 1. *A schematic of the role of fire in the earth system. Figure modified from Ward et al. (2012)*[33].

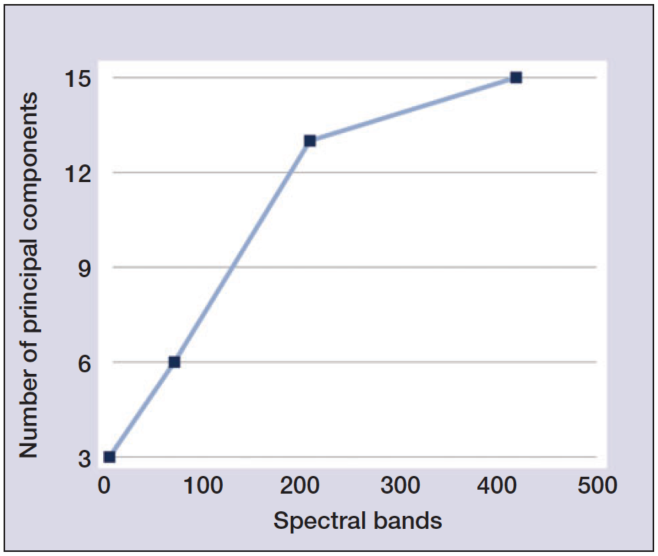

Figure 2. *The number of independent components that can be classified by spectral data depends on the number of spetral bands and the spectral resolution of the data. Underlying spectral features are often broader than a single spectral band and many plant constituents have spectral features across the spectrum, thus there are many fewer independent components than there are spectral bands*[107]*. This figure is reproduced from Scimel et al. (2013)*[107].

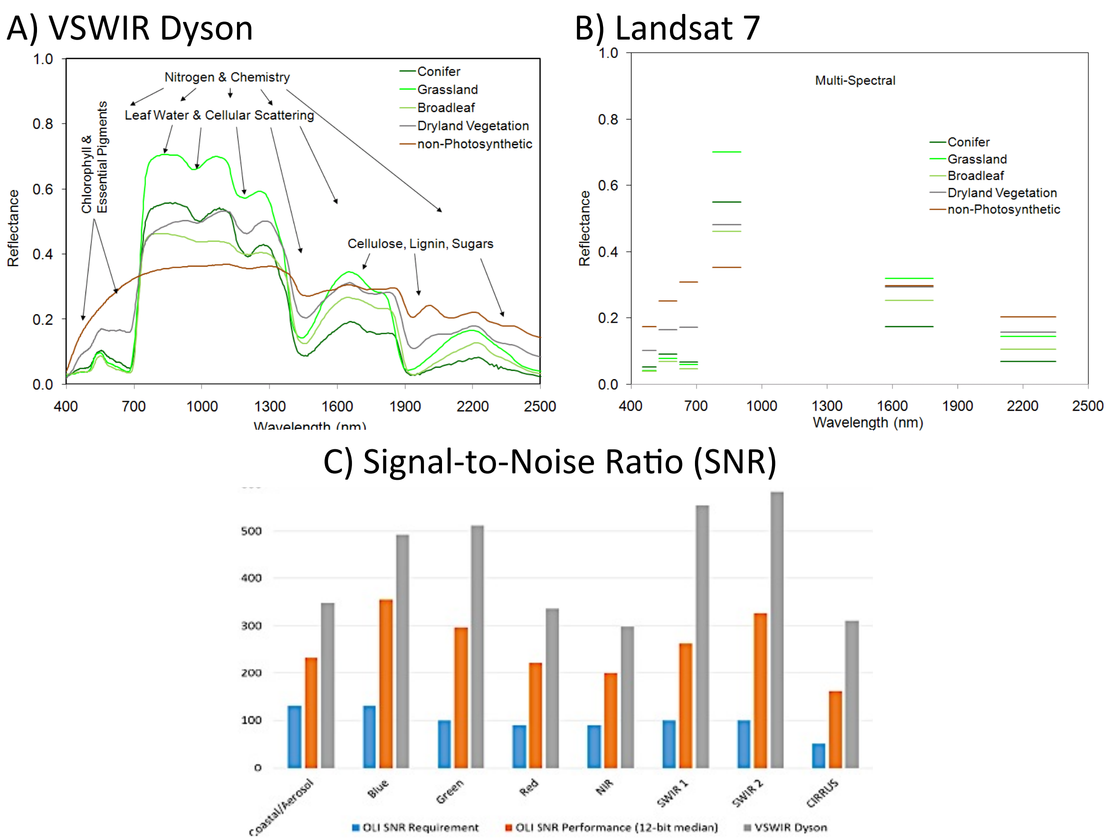

Figure 3. *Comparing imaging spectroscopy to broadband where (a) depicts the contiguous spectral coverage over several key endmembers for fire science from VSWIR Dyson, which shows much more detail of optical traits of each endmember (e.g., lignen and sugar content) compared to (b) broadband sensor Landsat. (c) Demonstrates the different signal-to-noise (SNR) ratios by sensor. In order to compare SNR, the contiguous spectra from VSWIR Dyson were back-transformed into equivalent bands as the broadband sensors using spectral response functions*[66–68] *to convolve the spectra*[67]*. Figure 3c is reproduced from Mouroulis et al. (2016)*[103].

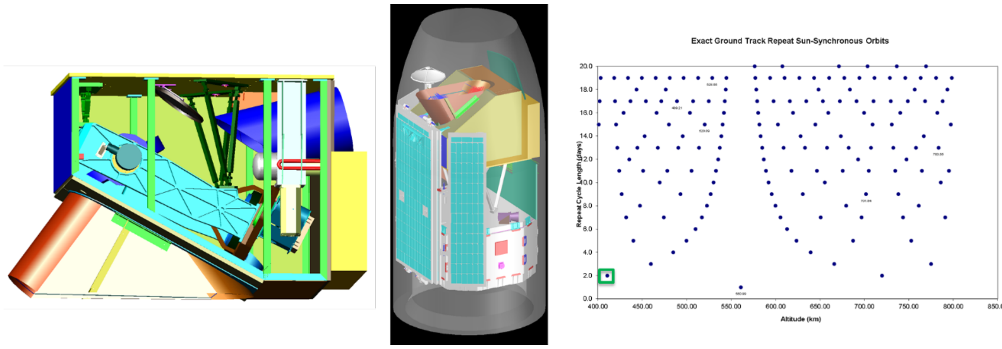

Figure 4. *(left) Opto-mechanical configuration for a wide swath, high resolution TIR imaging radiometer system providing 73-degree swath and 60 m sampling. TIR Imaging radiometer with spacecraft (265 kg, 187 W) configured for launch in a Pegasus shroud for an orbit of 410 km altitude, 97.07 inclination to provide 2-day revisit for three years. (right) Orbital altitude and repeat options. An altitude of 410 km with a fueled spacecraft supports the three-year mission with the affordable Pegasus launch. Higher orbits require a larger launch vehicle.*

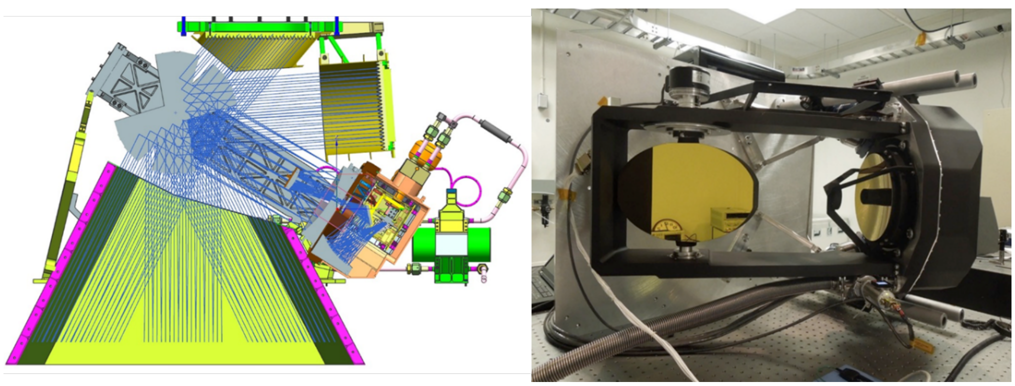

Figure 5. *(left) Design of ECOSTRESS TIR Push-whisk scanning system covering a wide field of view with an 8 band SWIR to TIR sensor. (right) Developed, aligned and qualified PHyTIR push-whisk system with TIR full range multi-band detector array.*

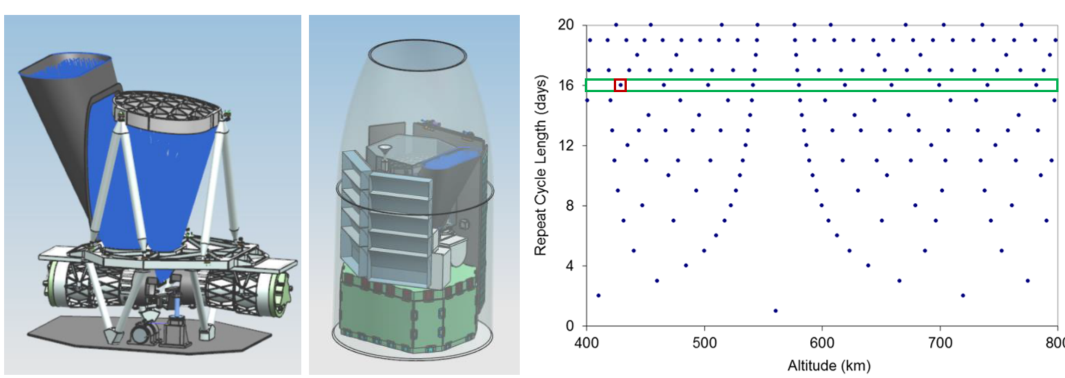

Figure 6. *(left) Opto-mechanical configuration for a high SNR F/1.8 VSWIR imaging spectrometer system providing 185 km swath and 30 m sampling. (center) Imaging spectrometer with spacecraft (265 kg, 134 W)*

configured for launch in a Pegasus shroud for an orbit of 429 km altitude, 97.14 inclination to provide 16 day revisit for three years. (right) Orbital altitude and repeat options. An altitude of 429 km with a fueled spacecraft supports the three-year mission with the affordable Pegasus launch. Higher orbits require a larger launch vehicle.

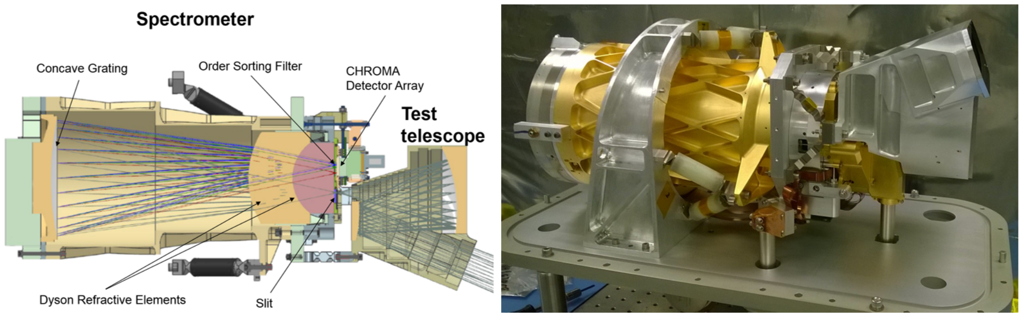

Figure 7. *Design of F/1.8 VSWIR Dyson covering the spectral range from 380 to 2510. (right) Developed, aligned and qualified Dyson with CHROMA full range VSWIR detector array.*

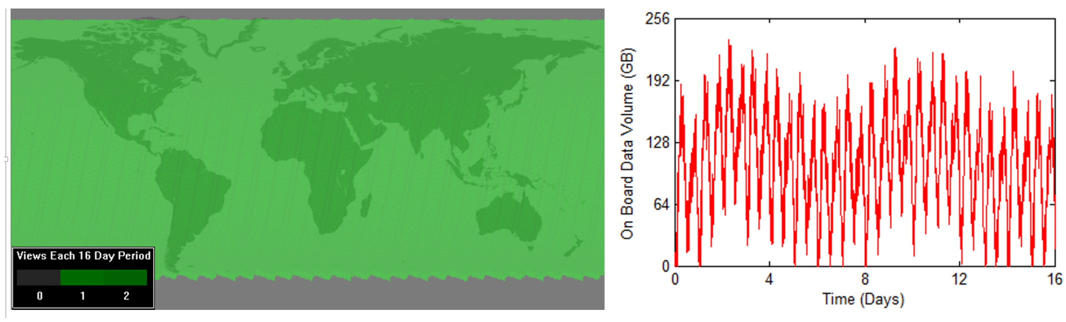

Figure 8. *(left) Global illuminated surface coverage every 16 days. (right) On-board data storage usage for illuminated terrestrial/coastal regions with downlink using Ka Band to KSAT Svalbard and Troll stations. Oceans and ice sheets can be spatially averaged for downlink.*

References

1. Eagan, R. C. R., Hobbs, P. V. & Radke, L. F. Measurements of cloud condensation nuclei and cloud droplet size distributions in the vicinity of forest fires. *J. Appl. Meteorol.* **13,** 553–557 (1974).
2. Hobbs, P. V., Reid, J. S., Kotchenruther, R. A., Ferek, R. J. & Weiss, R. Direct Radiative Forcing by Smoke from Biomass Burning. *Science (80-.).* **275,** 1777–1778 (1997).
3. Hobbs, P. V. & Radke, L. F. Cloud condensation nuclei from a simulated forest fire. *Science (80-.).* 279–280 (1969).
4. Konzelmann, T., Cahoon, D. R. & Whitlock, C. H. Impact of biomass burning in equatorial Africa on the downward surface shortwave irradiance: Observations versus calculations. *J. Geophys. Res. Atmos.* **101,** 22833–22844 (1996).
5. Kaufman, Y. J. *et al.* Potential global fire monitoring from EOS-MODIS. *J. Geophys. Res.* **103,** 32215 (1998).
6. Wild, M. Discrepancies between model-calculated and observed shortwave atmospheric absorption in areas with high aerosol loadings. *J. Geophys. Res.* **104,** 27361 (1999).
7. Bonan, G. B., Chapin, F. S. & Thompson, S. L. Boreal forest and tundra ecosystems as components of the climate system. *Clim. Change* **29,** 145–167 (1995).
8. Randerson, J. T. *et al.* The impact of boreal forest fire on climate warming. *Science* **314,** 1130–2 (2006).
9. Liu, H., Randerson, J. T., Lindfors, J. & Chapin, F. S. I. Changes in the surface energy budget after fire in boreal ecosystems of interior Alaska: An annual perspective. *J. Geophys. Res.* **110,** D13101 (2005).
10. Amiro, B. D. *et al.* The effect of post-fire stand age on the boreal forest energy balance. *Agric. For. Meteorol.* **140,** 41–50 (2006).
11. Fishman, J., Fakhruzzaman, K., Cros, B. & Nganga, D. Identification of widespread pollution in the Southern Hemisphere deduced from satellite analysis. *Science (80-.).* **252,** 1693 (1991).
12. Schultz, M. G. *et al.* On the origin of tropospheric ozone and NOx over the tropical South Pacific. *J. Geophys. Res. Atmos.* **104,** 5829–5843 (1999).
13. Ramanathan, V., Crutzen, P. J., Kiehl, J. T. & Rosenfeld, D. Aerosols, climate, and the hydrological cycle. *Science* **294,** 2119–24 (2001).
14. Andreae, M. O. *et al.* Smoking rain clouds over the Amazon. *Science* **303,** 1337–42 (2004).
15. Kaufman, Y. J. & Koren, I. Smoke and pollution aerosol effect on cloud cover. *Science* **313,** 655–8 (2006).
16. Koren, I., Kaufman, Y. J., Remer, L. A. & Martins, J. V. Measurement of the effect of Amazon smoke on inhibition of cloud formation. *Science* **303,** 1342–5 (2004).
17. Bonan, G. B. Forests and climate change: forcings, feedbacks, and the climate benefits of

forests. *Science* **320,** 1444–9 (2008).

18. Crutzen, P. J., Heidt, L. E., Krasnec, J. P., Pollock, W. H. & Seiler, W. in *A Pioneer Atmos. Chem. Clim. Chang. Anthr.* (Crutzen, P. J. & Brauch, H. G.) **50,** 117–124 (Springer International Publishing, 2016).

19. Schulz, M. *et al.* Atmospheric transport and deposition of mineral dust to the ocean: implications for research needs. *Environ. Sci. Technol.* **46,** 10390–404 (2012).

20. Yu, H. *et al.* The fertilizing role of African dust in the Amazon rainforest: A first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. *Geophys. Res. Lett.* **42,** 1984–1991 (2015).

21. Flannigan, M. D. *et al.* Global wildland fire season severity in the 21st century. *For. Ecol. Manage.* **294,** 54–61 (2013).

22. Moritz, M. A. *et al.* Climate change and disruptions to global fire activity. *Ecosphere* **3,** art49 (2012).

23. Bond, W. J. & Keeley, J. E. Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. *Trends Ecol. Evol.* **20,** 387–394 (2005).

24. Turner, M. G. Disturbance and landscape dynamics in a changing world. *Ecology* **91,** 2833–2849 (2010).

25. Davidson, E. A. *et al.* The Amazon basin in transition. *Nature* **481,** 321–328 (2012).

26. Miller, A. D., Roxburgh, S. H. & Shea, K. How frequency and intensity shape diversity-disturbance relationships. *Proc. Natl. Acad. Sci. U. S. A.* **108,** 5643–5648 (2011).

27. Driscoll, D. A. *et al.* Resolving conflicts in fire management using decision theory: Asset-protection versus biodiversity conservation. *Conserv. Lett.* **3,** 215–223 (2010).

28. Cairns Jr., J., McCormick, P. & Niederlehner, B. R. A proposed framework for developing indicators of ecosystem health. *Hydrobiologia* **263,** 1–44 (1993).

29. Ghimire, B., Riley, W. J., Koven, C. D., Mu, M. & Randerson, J. T. Representing leaf and root physiological traits in CLM improves global carbon and nitrogen cycling predictions. *J. Adv. Model. Earth Syst.* (2016). doi:10.1002/2015MS000538

30. Knicker, H. How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. *Biogeochemistry* **85,** 91–118 (2007).

31. Thornton, P. E., Lamarque, J. F., Rosenbloom, N. A. & Mahowald, N. M. Influence of carbon-nitrogen cycle coupling on land model response to CO2 fertilization and climate variability. *Global Biogeochem. Cycles* **21,** 1–15 (2007).

32. Stavros, E. N., Abatzoglou, J. T., Larkin, N. K., Mckenzie, D. & Steel, E. A. Climate and very large wildland fires in the contiguous Western USA. *Int. J. Wildl. Fire* **23,** 899–914 (2014).

33. Ward, D. S. *et al.* The changing radiative forcing of fires: Global model estimates for past, present and future. *Atmos. Chem. Phys.* **12,** 10857–10886 (2012).

34. Tosca, M. G., Randerson, J. T. & Zender, C. S. Global impact of smoke aerosols from

landscape fires on climate and the Hadley circulation. *Atmos. Chem. Phys.* **13,** 5227–5241 (2013).

35. Page, S. E. *et al.* The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* **420,** 61–65 (2002).

36. Landry, J.-S. & Matthews, H. D. Non-deforestation fire vs. fossil fuel combustion: the source of CO2 emissions affects the global carbon cycle and climate responses. *Biogeosciences* **13,** 2137–2149 (2016).

37. Ghimire, B., Williams, C. A., Collatz, G. J. & Vanderhoof, M. Fire-induced carbon emissions and regrowth uptake in western U.S. forests: Documenting variation across forest types, fire severity, and climate regions. *J. Geophys. Res.* **117,** G03036 (2012).

38. Veira, a., Kloster, S., Schutgens, N. a. J. & Kaiser, J. W. Fire emission heights in the climate system – Part 2: Impact on transport, black carbon concentrations and radiation. *Atmos. Chem. Phys.* **15,** 7173–7193 (2015).

39. Liu, Y. Enhancement of the 1988 northern U.S. drought due to wildfires. *Geophys. Res. Lett.* **32,** L10806 (2005).

40. Langmann, B., Duncan, B., Textor, C., Trentmann, J. & van der Werf, G. R. Vegetation fire emissions and their impact on air pollution and climate. *Atmos. Environ.* **43,** 107–116 (2009).

41. Chambers, S. D. & Chapin, F. S. Fire effects on surface-atmosphere energy exchange in Alaskan black spruce ecosystems: Implications for feedbacks to regional climate. *J. Geophys. Res.* **108,** 17 (2002).

42. Thenkabail, P. S., Enclona, E. A., Ashton, M. S., Legg, C. & De Dieu, M. J. Hyperion, IKONOS, ALI, and ETM+ sensors in the study of African rainforests. *Remote Sens. Environ.* **90,** 23–43 (2004).

43. Tews, J. *et al.* Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. *J. Biogeogr.* **31,** 79–92 (2004).

44. Nagendra, H. *et al.* Remote sensing for conservation monitoring: Assessing protected areas, habitat extent, habitat condition, species diversity, and threats. *Ecol. Indic.* **33,** 45–59 (2013).

45. Turner, W. *et al.* Remote sensing for biodiversity science and conservation. *Trends Ecol. Evol.* **18,** 306–314 (2003).

46. Williams, C. J., Pierson, F. B., Robichaud, P. R. & Boll, J. Hydrologic and erosion responses to wildfire along the rangeland–xeric forest continuum in the western US: a review and model of hydrologic vulnerability. *Int. J. Wildl. Fire* **23,** 155 (2014).

47. Moody, J. A., Shakesby, R. A., Robichaud, P. R., Cannon, S. H. & Martin, D. A. Current research issues related to post-wildfire runoff and erosion processes. *Earth-Science Rev.* **122,** 10–37 (2013).

48. Smith, H. G., Sheridan, G. J., Lane, P. N. J., Nyman, P. & Haydon, S. Wildfire effects on

water quality in forest catchments: A review with implications for water supply. *J. Hydrol.* **396,** 170–192 (2011).

49. Varnes, D. J. *Landslide Hazard Zonation: A Review of Principles and Practice*. *Nat. Hazards* (1984).

50. French, N. H. F. *et al.* Model comparisons for estimating carbon emissions from North American wildland fire. *J. Geophys. Res.* **116,** G00K05 (2011).

51. Keane, R. E., Burgan, R. & van Wagtendonk, J. Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. *Int. J. Wildl. Fire* **10,** 301–319 (2001).

52. Lu, D. The potential and challenge of remote sensing-based biomass estimation. *Int. J. Remote Sens.* **27,** 1297–1328 (2006).

53. Gonzalez-Perez, J. A., Gonzalez-Vila, F. J., Almendros, G. & Knicker, H. The effect of fire on soil organic matter - a review. *Environ. Int.* **30,** 855–870 (2004).

54. Lehmann, J. *et al.* Australian climate-carbon cycle feedback reduced by soil black carbon. *Nat. Geosci.* **1,** 832–835 (2008).

55. Gitay, H. & Nobel, I. R. in *Plant Funct. Types Their Relev. to Ecosyst. Prop. Glob. Chang.* (Smith, T. M., Shugart, H. H. & Woodward, F. I.) 1–19 (Cambridge University Press, 1997).

56. Hooper, D. U. & Vitousek, P. The effects of plant composition and diversity on ecosystem processes. *Science (80-.).* **277,** 1302–1305 (1997).

57. Ustin, S. L. & Gamon, J. A. Remote sensing of plant functional types. *New Phytol.* **186,** 795–816 (2010).

58. Jetz, W. *et al.* Monitoring plant functional diversity from space. *Nat. Plants* **2,** 16024 (2016).

59. Bloom, A. A. *et al.* Remote-sensing constraints on South America fire traits by Bayesian fusion of atmospheric and surface data. *Geophys. Res. Lett.* **42,** 1268–1274 (2015).

60. Bloom, A. A., Exbrayat, J.-F., van der Velde, I. R., Feng, L. & Williams, M. The decadal state of the terrestrial carbon cycle: Global retrievals of terrestrial carbon allocation, pools, and residence times. *Proc. Natl. Acad. Sci.* 1–6 (2016). doi:10.1073/pnas.1515160113

61. Veraverbeke, S. & Hook, S. J. Evaluating spectral indices and spectral mixture analysis for assessing fire severity, combustion completeness and carbon emissions. *Int. J. Wildl. Fire* **22,** 707–720 (2013).

62. Littell, J. S., McKenzie, D., Peterson, D. L. & Westerling, A. L. Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003. *Ecol. Appl.* **19,** 1003–1021 (2009).

63. Gillespie, A. *et al.* A temperature and emissivity separation algorithm for advanced spaceborne thermal emission and reflection radiometer (ASTER) images. *IEEE Trans. Geosci. Remote Sens.* **36,** 1113–1126 (1998).

64. Schroeder, W., Oliva, P., Giglio, L. & Csiszar, I. A. The New VIIRS 375m active fire

detection data product: Algorithm description and initial assessment. *Remote Sens. Environ.* **143,** 85–96 (2014).

65. Hulley, G. C. & Hook, S. J. A new methodology for cloud detection and classification with ASTER data. *Geophys. Res. Lett.* **35,** 1–6 (2008).

66. Veraverbeke, S., Stavros, E. N. & Hook, S. J. Assessing fire severity using imaging spectroscopy data from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and comparison with multispectral capabilities. *Remote Sens. Environ.* **154,** 153–163 (2014).

67. Lee, C. M. *et al.* An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities. *Remote Sens. Environ.* **167,** 6–19 (2015).

68. NRC. *Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program*. (2013).

69. Asner, G. P., Martin, R. E., Anderson, C. B. & Knapp, D. E. Remote Sensing of Environment Quantifying forest canopy traits : Imaging spectroscopy versus fi eld survey. *Remote Sens. Environ.* **158,** 15–27 (2015).

70. Li, L., Cheng, Y. B., Ustin, S., Hu, X. T. & Riaño, D. Retrieval of vegetation equivalent water thickness from reflectance using genetic algorithm (GA)-partial least squares (PLS) regression. *Adv. Sp. Res.* **41,** 1755–1763 (2008).

71. Roberts, D. A., Smith, M. O. & Adams, J. B. Green vegetation, nonphotosynthetic vegetation, and soils in AVIRIS data. *Remote Sens. Environ.* **44,** 255–269 (1993).

72. Lefsky, M. A., Cohen, W. B., Parker, G. G. & Harding, D. J. Lidar Remote Sensing for Ecosystem Studies. *Bioscience* **52,** 19–30 (2002).

73. Saatchi, S., Halligan, K., Despain, D. G. & Crabtree, R. L. Estimation of forest fuel load from radar remote sensing. *IEEE Trans. Geosci. Remote Sens.* **45,** 1726–1740 (2007).

74. Neuenschwander, A. L., Gutierrez, R., Schutz, B. E. & Urban, T. J. Comparison of small-footprint and large-footpring waveform LiDAR for terrestrial surface characterization. in *Geosci. Remote Sens. Symp. 2006. IGARSS 2006. IEEE Int. Conf.* **1,** 3741–3744 (2006).

75. Hermosilla, T., Ruiz, L. a., Kazakova, A. N., Coops, N. C. & Moskal, L. M. Estimation of forest structure and canopy fuel parameters from small-footprint full-waveform LiDAR data. *Int. J. Wildl. Fire* **23,** 224 (2014).

76. Bergen, K. M. *et al.* Remote sensing of vegetation 3-D structure for biodiversity and habitat: Review and implications for lidar and radar spaceborne missions. *J. Geophys. Res. Biogeosciences* **114,** 1–13 (2009).

77. Bindlish, R. & Barros, A. P. Subpixel variability of remotely sensed soil moisture: An inter-comparison study of SAR and ESTAR. *IEEE Trans. Geosci. Remote Sens.* **40,** 326–337 (2002).

78. Steele-Dunne, S. C., Friesen, J. & Van De Giesen, N. Using diurnal variation in backscatter to detect vegetation water stress. *IEEE Trans. Geosci. Remote Sens.* **50,** 2618–2629 (2012).

79. Goodrick, S. L., Achtemeier, G. L., Larkin, N. K., Liu, Y. & Strand, T. M. Modelling smoke

transport from wildland fires: A review. *Int. J. Wildl. Fire* **22,** 83–94 (2012).

80. Coen, J. L. *Modeling Wildland Fires: of the Coupled Atmosphere- Wildland Fire Environment Model (CAWFE)*. (2013).

81. Tian, X. *et al.* Comparisons and assessment of forest fire danger systems. *For. Stud. China* **7,** 53–61 (2005).

82. Palluconi, F. D. & Meeks, G. R. Thermal Infrared Multispectral Scanner (TIMS): An investigator's guide to TIMS data. (1985).

83. Chrisp, M. P. The PMIRR Optical System for Mars Observer. *SPIE Proceeding, Opt. Syst. Sp. Appl.* **810,** 44–51 (1987).

84. Hook, S. J., Myers, J. J., Thome, K. J., Fitzgerald, M. & Kahle, A. B. The MODIS/ASTER airborne simulator (MASTER) -- a new instrument for earth science studies. *Remote Sens. Environ.* **76,** 93–102 (2001).

85. Johnson, W. R. *et al.* HyTES: Thermal imaging spectrometer development. *IEEE Aerosp. Conf. Proc.* **91109,** 1–8 (2011).

86. Hook, S. J., Johnson, W. R., Foote, M. C., Eng, B. T. & Jau, B. M. The Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR): A high speed, multispectral, thermal instrument development in support of HyspIRI-TIR. in *Earth Sci. Technol. Forum* (2011).

87. Aranki, N., Keymeulen, D., Bakshi, A. & Klimesh, M. Hardware implementation of lossless adaptive and scalable hyperspectral data compression for space. in *NASA ESA Conf. Adapt. Hardw. Syst.*

88. Keymeulen, D., Aranki, N., Bakhshi, A., Sarture, C. & Dolman, D. Airborne demonstration of FPGA implementation of Fast Lossless hyperspectral data compression system. in *2014 NASA/ESA Conf. Adapt. Hardw. Syst.* 278–284 (IEEE, 2014). doi:10.1109/AHS.2014.6880188

89. Aranki, N., Bakshi, A., Keymeulen, D. & Klimesh, M. Fast and adaptice lossless onboard hyperspectral data compression system for space applications. in *IEEE Aerosp. Conf.*

90. CCSDS. *Lossless multispectral and hyperspectral image compression infromational report, 120.2-G-1, Green Book*. (2015).

91. Thompson, D. R. *et al.* Rapid Spectral Cloud Screening Onboard Aircraft and Spacecraft. *IEEE Trans. Geosci. Remote Sens.* **52,** 6779–6792 (2014).

92. NRC. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. *J. Chem. Inf. Model.* **53,** (2008).

93. Vane, G., Goetz, A. F. H. & Wellman, J. B. Airborne imaging spectrometer: A new tool for remote sensing. *IEEE Trans. Geosci. Remote Sens.* **GE-22,** 546–549 (1984).

94. Green, R. O. *et al.* Imaging spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). *Remote Sens. Environ.* **65,** 225–248 (1998).

95. Hamlin, L. *et al.* Imaging spectrometer science measurements for Terrestrial Ecology:

AVIRIS and new developments. in *2011 Aerosp. Conf.* 1–7 (IEEE, 2011). doi:10.1109/AERO.2011.5747395

96. Carlson, R. W. *et al.* Near-Infrared Mapping Spectrometer experiment on Galileo. *Space Sci. Rev.* **60,** 457–502 (1992).

97. Brown, R. H. *et al.* The Cassini Visual and Infrared Mapping Spectrometer (VIMS) Investigation. *Space Sci. Rev.* **115,** 111–168 (2004).

98. Hampton, D. L. *et al.* An Overview of the Instrument Suite for the Deep Impact Mission. *Space Sci. Rev.* **117,** 43–93 (2005).

99. Murchie, S. *et al.* Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO). *J. Geophys. Res.* **112,** E05S03 (2007).

100. Middleton, E. M. *et al.* The Earth Observing One (EO-1) Satellite Mission: Over a Decade in Space. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **6,** 243–256 (2013).

101. Ungar, S. G., Pearlman, J. S., Mendenhall, J. A. & Reuter, D. Overview of the earth observing one (eo-1) mission. *IEEE Trans. Geosci. Remote Sens.* **41,** 1149–1159 (2003).

102. Green, R. O. *et al.* The Moon Mineralogy Mapper (M3) imaging spectrometer for lunar science: Instrument description, calibration, on-orbit measurements, science data calibration and on-orbit validation. *J. Geophys. Res. E Planets* **116,** 1–31 (2011).

103. Mouroulis, P. R. *et al.* Landsat swath imaging spectrometer design. *Opt. Eng.* **55,** 015104 (2016).

104. Design of the Compact Wide Swath Imaging Spectrometer (CWIS) | (2014) | Van Gorp | Publications | Spie. at <http://spie.org/Publications/Proceedings/Paper/10.1117/12.2062886>

105. Thompson, D. R. *et al.* Atmospheric correction for global mapping spectroscopy: ATREM advances for the HyspIRI preparatory campaign. *Remote Sens. Environ.* **167,** 64–77 (2015).

106. Gao, B.-C., Montes, M., Davis, C. & Goetz, A. Atmospheric correction algorithms for hyperspectral remote sensing data of land and ocean. *Remote Sens. Environ.* **113,** 17–24 (2009).

107. Schimel, D. S., Asner, G. P. & Moorcroft, P. Observing changing ecological diversity in the Anthropocene. *Front. Ecol. Environ.* **11,** 129–137 (2013).

108. Kaufmann, H. *et al.* EnMAP - A hyperspectral sensor for environmental mapping and analysis. *Int. Geosci. Remote Sens. Symp.* 1617–1619 (2006). doi:10.1109/IGARSS.2006.417

109. Iwasaki, A., Ohgi, N., Tanii, J., Kawashima, T. & Inada, H. Hyperspectral Imager Suite (HISUI)-Japanese hyper-multi spectral radiometer. *Int. Geosci. Remote Sens. Symp.* 1025–1028 (2011). doi:10.1109/IGARSS.2011.6049308

110. Yu, A. W. *et al.* Space laser transmitter development for ICESat-2 mission. in *SPIE LASE* (Clarkson, W. A., Hodgson, N. & Shori, R. K.) 757809 (International Society for Optics and

Photonics, 2010). doi:10.1117/12.843342

111. Herzfeld, U. C. *et al.* Algorithm for Detection of Ground and Canopy Cover in Micropulse Photon-Counting Lidar Altimeter Data in Preparation for the ICESat-2 Mission. *IEEE Trans. Geosci. Remote Sens.* **52,** 2109–2125 (2013).

112. Dubayah, R. *et al.* The Global Ecosystem Dynamics Investigation. in *Am. Geophys. Union Fall Meet.* U14A–07 (2014).

113. Entekhabi, D., Njoku, E. & O'Neill, P. Soil Moisture Active and Passive (SMAP) Mission: Science and Applications. *IEEE* 1–2 (2009).

114. Konings, A. G. *et al.* Vegetation optical depth and scattering albedo retrieval using time series of dual-polarized L-band radiometer observations. *Remote Sens. Environ.* **172,** 178–189 (2016).

115. Akbar, R. & Moghaddam, M. A combined active–passive soil moisture estimation algorithm with adaptive regularization in support of SMAP. *IEEE Trans. Geosci. Remote Sens.* **53,** 3312–3324 (2015).

116. Winker, D. M., Pelon, J. R. & McCormick, M. P. The CALIPSO mission: spaceborne lidar for observation of aerosols and clouds. in *Third Int. Asia-Pacific Environ. Remote Sens. Remote Sens. Atmos. Ocean. Environ. Sp.* (Singh, U. N., Itabe, T. & Liu, Z.) 1–11 (International Society for Optics and Photonics, 2003). doi:10.1117/12.466539

117. Rosen, P. A., Hensley, S. & Shaffer, S. The NASA-ISRO SAR Mission – An International Space Partnership for Science and Societal Benefit. *IEEE Radar Conf.* 1610–1613 doi:10.1109/RADAR.2015.7131255

118. Le Toan, T. *et al.* The BIOMASS mission: Mapping global forest biomass to better understand the terrestrial carbon cycle. *Remote Sens. Enivornment* **115,** 2850–2860 (2011).

119. Torres, R. *et al.* GMES Sentinel-1 mission. *Remote Sens. Environ.* **120,** 9–24 (2012).