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MetNet™ Small Weather Satellite Network: An Alternative System for Global Meteorological Observations

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ABSTRACT

Individual small weather satellites have been previously presented including GPS-Radio Occultation, Infrared Sounding, Microwave Radiometry, Multispectral Imaging, and Gas-Filter Correlation Radiometry, but to our knowledge not as a comprehensive on-orbit system. In this paper, for the first time, we describe a new global Meteorological Network - ***MetNet™*** using multiple electro-optical and microwave satellite constellations. We shall provide a brief overview of several candidate small weather satellites including Doppler Wind Temperature Sounder (DWTS™), Moderate Resolution Imaging Spectro-Radiometer in 3U (MODIS-3U), the Compact Microwave Sounder (CMS), the Compact Infrared Sounder CIS), the stellar occultation temperature retrieval CubeSat (T-STAR), the Aerosols and Cloud Characterization Imaging Polarimeter (ACCIP), and the High-Altitude Temperature Sounder (HATS™). These instrument constellations when combined shall cover the full range of altitudes from surface to thermosphere, at significantly higher spatial resolutions than available from GEO satellites, with improved retrievals through synergistic data techniques. The disaggregation of instruments onto several spacecraft simplifies the production flow, as well as allowing more flexibility in calibration maneuvers such as lunar scans and cross-calibrations. The full range of measurements shall include horizontal wind speeds, 3D temperature soundings, humidity, precipitation, sea surface temperature, cloud characterization, aerosol size distributions, and atmospheric chemistry.

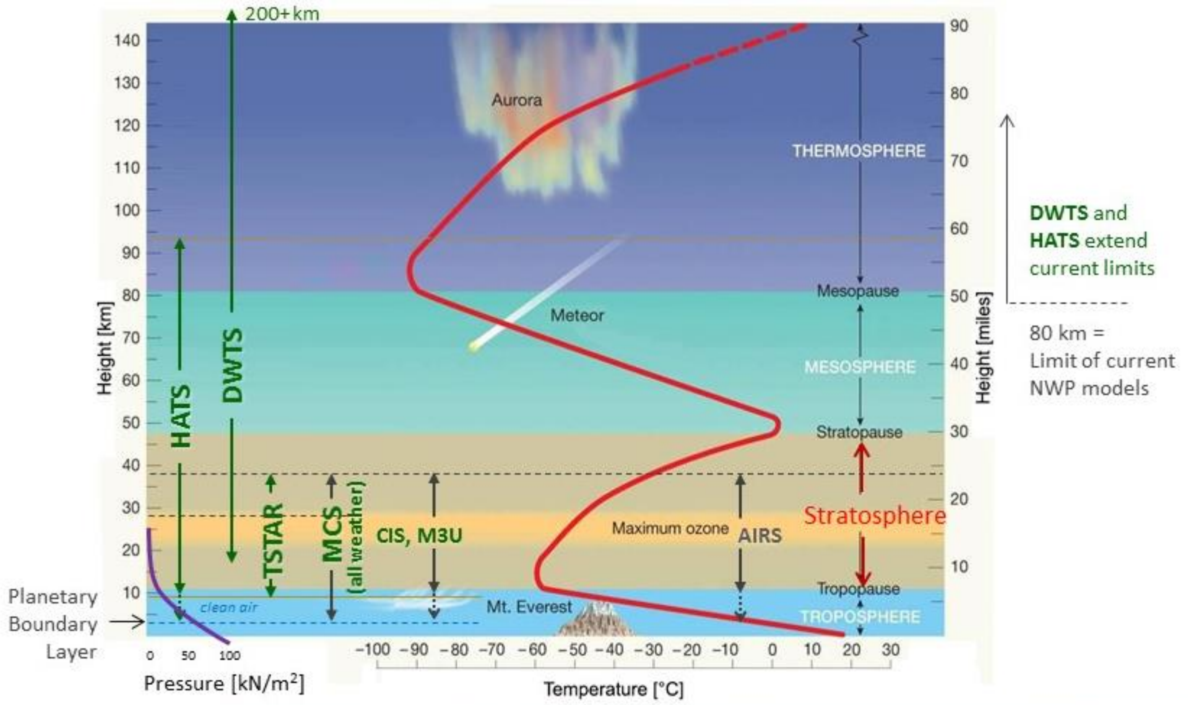

Figure 1 MetNet™ Extended atmospheric coverage, measuring Winds, Temperatures, and Cloud Properties

BACKGROUND

Atmospheric thermal sounding is accomplished by observing emission in multiple spectral intervals of varying absorption strengths. Using the known functional dependences of the emissions on the temperature profile, the temperature profile can be retrieved. This method has been used successfully for decades to process data from the MSU and AMSU instruments, AIRS, and GOES broadband instruments in geostationary orbit. Radiation received by a down-looking spacecraft emanates from various depths in the atmosphere. To infer the temperature at a specific altitude, the instrument must measure and distinguish emission that predominantly emanates from that altitude. However, spectral absorption lines from gases at high altitude and low pressure are very narrow, which makes for challenging spectrometer designs. Large satellite programs such as Suomi National Polar-orbiting Partnership (Suomi-NPP), Defense Military Satellite Program (DMSP), and MetOp satellites have provided this vital data for Numerical Weather Prediction (NWP) models. Soon to be launched Joint Polar Satellite System (JPSS-1) will continue in making these meteorological observations using Cross-track Infrared Sounder (CrIS) Advanced Technology Microwave Sounder (ATMS), Ozone Mapping Profiling Suite (OMPS), Visible Infrared Imaging Radiometer Suite (VIIRS).

Advantages

Although comprehensive in many respects, these satellites have known risks not only due to launch or satellite loss (DMSP-19), but also have risk of cancellation (NPOESS) and budget cuts (Weather Satellite Follow-on.) The loss of either JPSS-1 or JPSS-2 would lead to a 2-year gap in data continuity of high resolution LEO data. The disaggregated SmallSat approach not only improves resiliency against launch or satellite failure, but secondly can reduce cost and delivery by using high volume production spacecraft. The third advantage of SmallSats is in exploiting the advantages in rapidly changing technologies such as larger format Focal Plane Arrays (FPAs), freeform optics, new compact microwave receivers, and improved vicarious calibration methods.

Measurement Techniques

Traditional instruments which will be included in MetNet™ include Multispectral measurements from the UV-VIS, SWIR, MWIR, and LWIR. These will be advanced through new detector technologies such as auto-zeroing for eliminated bias drift, reduced noise through on-chip Correlated Double Sampling, and on-chip digitization for reducing noise pickup. Midwave infrared spectrometers will continue to have a role, with advances in optics, coolers, and detectors. High Operating Temperature detectors (nBn and Type-2 Strained Layer Superlattice) will allow detectors operating temperatures at >150 K, with better uniformity compared to HgCdTe. Longwave Infrared for temperature sounding and CO_2 retrievals will also be advanced through T2SLS detectors, with recent results showing significant dark current performance exceeding the gold standard - "Rule-07".

Stellar occultation can provide temperature profiles without gas concentration knowledge. The resulting profiles can act as calibration data for limb thermal imagers. Attitude control systems allow static sensors to be scanned over and around vicarious calibration sources such as surface target areas, moon, sun and limb, accurately calibrating stray light and background effects. Limb observations produce temperature and moisture profiles that can be used for *a priori* profiles for inversion of nadir observations to vertical profiles. Deconvolution techniques can partially restore resolution of profiles retrieved from vertical sounders. Attitude control systems make the vicarious calibration strategies possible as well as laser communication by open–loop lock onto high altitude receivers. Relative to past sensors, the MetNet constellation instruments will be remarkably simple, while forging new capabilities in weather forecasting.

Applying CubeSats to address these weather observations has been discussed in Pagano,[1] Blackwell,[2] Schutz,[3] and others.[4-5] These new missions cover the range of IR sounding, Microwave Sounding, GPS-Radio Occultation, Cloud and Aerosols Polarimetry, and Millimeter wave sounding, all from CubeSats in either 3U or 6U form factors. Cyclone Global Navigation Satellite System may be considered the first weather MicroSat constellation, using Delay Doppler Mapping Instrument to measure cyclone winds from 8-spacecraft.[6] Bevilacqua described a similar SmallSat mission concept for a trace gas mission, Solar Occultation Constellation for Retrieving Aerosols and Trace Element Species (SOCRATES).[7] It is evident from the early successes, and rigorous analysis of planned NASA Earth Venture SmallSats that these missions show great promise to provide critical atmospheric measurements. This MetNet™ constellation goes further through exploiting synergies between observations to create a single commercial or government weather observation network.

Data Assimilation

To improve weather forecasting over the intermediate to long-term (5 to 30 days) time scales requires global models, plus data that accurately captures the current temperature, wind vectors, and water content of the atmosphere. Observing high-energy, rapidly changing states from orbit is a challenge due to their small scales and time evolution.[8-10] Sensors that sound the atmosphere through occultation or thermal limb observations (e.g. GPSRO and thermal imagers) are inherently limited to resolutions of 100 to 200 kilometers in the horizontal. Temperature and moisture fields that drive very dynamic weather conditions are often smoothed to the point of limited value to forecasting of high-energy systems. However, like a pot of boiling soup, these dynamic weather systems radiate their signature into the upper atmosphere with expanding scales, producing waves and winds that can be observed and used to infer the underlying state. It has been shown by a variety of groups that the wave and wind fields in the upper atmosphere can act as a powerful boundary condition on the evolution of weather systems. Satellite related sensor technology now makes it possible to observe these parameters at the resolution required to fill the deficiency of limb observations. However, limb sensors must still play an essential role in removing the observation deficiency.

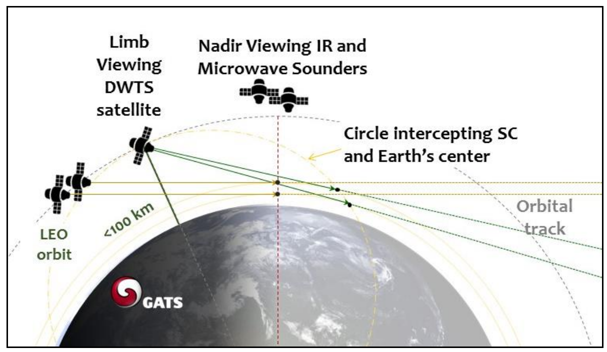

Figure 2 Limb sounders, including GPSRO and DWTS™ providing provide *a priori* solution profiles for nadir sounding observations

SATELLITE CONSTELLATIONS

The approach for the MetNet constellation has been to focus primarily on two form factors which satisfy the following conditions: low-cost to orbit from several launch providers, standardized interfaces, and advanced capabilities (pointing, power, and communications). For a given constellation, 3U form factor was chosen for small imagers with low resolution, for technology testing, and for large constellations of >50 satellites to achieve desired revisit rate. The majority of the science will be in MicroSat 50-75 Kg class which can support the rest of the planned instruments. The reason for spacecraft larger than 6, 12, or 27U is not so much to support requirements such as aperture and volume, as many instruments can fit into these form factors, but for operational requirements. The spacecraft must support thermal control systems, high speed down link communications (preferrably Ka band or Optical), and high pointing accuracy for some optical measurements (goal <10 arcsec rms stability). Several launch opportunities exist or are planned for this class including both dedicate launch (Rocket Labs, Gilmore, zero2infinity) and rideshares (ISRO PSVL, SpaceX, BlueOrigin).

The guidelines for reducing the size and mass of the proposed instruments was the elimination of scanning mechanisms through the use Focal Plane Arrays and spacecraft pointing, elimination of on-board calibration mechanisms through the used of vicarious and lunar calibrations, and continueing progress in electronics miniaturization. We have also separated the infrared and microwave sounders into separate spacecraft - the most signficant complexity reduction. The goal of these instruments will not be climate monitoring of radiance balance, as that will be the venue of the JPSS flagship mission and other similar dedicated missions.

Instrument	**Primary mission**
T-Star (Stellar Occultation)	Upper altitude temperatures
MODIS-3U (Multispectral)	Cloud Characterization
Microwave Compact Sounder	Temperature, Water-vapor
Aerosol Cloud Char. Imaging Polarimeter	Cloud Characterization
Doppler Wind & Temperature Sounder	Upper altitude winds & temperature
High Altitude Temperature Sounder	Temperature Sounding
Compact Lightning Imager	Lighting mapping
Global Limb Observer (GFCR)	Atmospheric Chemistry,

Figure 3 MetNet^{TM} Proposed Instrument List

The classes of satellites are separated into limb and nadir viewers, and then further separated into multispectral, gas-filter correllation radiometry (GFCR), polarimetry, infrared spectrometry, and passive microwave measurement modalities. Although the sensing modalities are greatly varied, one key recurring component for the optical and infrared measurements is the Focal Plane Array (FPA.) A benefit of considering production of a MetNet system rather than individual instruments is the ability to share technology development resources of one FPA across multiple instruments. IP cores such as on-chip ADCs, radiation tolerance structures, and auto-zero features can be shared across sensors. The software and FPGA firmware can be reused reducing development time and improving reliability. Similarly, synergies exist when multiple instrument developments can share instrument performance and environmental tests. Most importantly the experience and skills of the technical staff will grow rapidly with each batch of spacecraft with slightly different configurations, optics, and detectors.

MODIS-3U– Brandywine Photonics

The first instrument in development is the MODIS-3U instrument, which is a multispectral imager that utilizes the full MODIS bandset and resolution for cloud characterization, water vapor, and sea surface temperature. Similar to the way that the Seahawk CubeSat targeted the SeaWifs bands for Ocean Color, this instrument matches the MODIS Bands.[11-12] The only planned difference between MODIS-3U and the original MODIS instrument will be the narrower swath.

	GSD	Format	FFOV	Swath	Aperture
Band	(m)	(Pixels)	(Deg)	(Km)	(mm)
VNIR	250	2048x1024	32.6	512	25.4
SWIR	500	1024x1024	32.6	512	21.6
MWIR	500	1024x1024	32.6	512	21.6
LWIR	500	1024x780	32.6	512	31

Figure 4 MODIS-3U First Order Parameters

Technology improvements have enabled the fitting of multiple imagers into a 3U CubeSat. These include the development of High Operating Temperature MWIR FPAs, which operate with smaller and lower-power cryocoolers, and the development of high dynamic range CMOS image sensors and LWIR microbolometers. The instrument will have four cameras: High Dynamic Range VNIR, extended SWIR, MWIR, and LWIR, each with a striped filter. Next generation PbSe detectors are also being evaluated to completely eliminate the cryo-cooler.

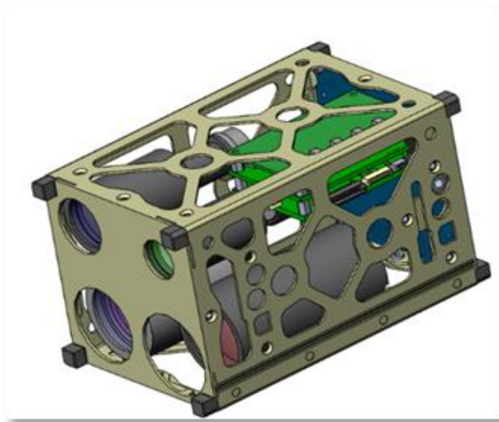

Figure 5: MODIS-3U Instrument

T-STAR™ – GPI Space Systems

T-Star is another 3U spacecraft which uses limb observations of stellar refraction to determine temperature profiles. It is based on the GATS Inc. patented method of using two celestial points to measure light bending angles as the two points are occulted. This technique is operational on the SOFIE solar occultation instrument aboard the AIM satellite, where the two points are, effectively, the top and bottom edges of the solar image.[13] The apparent vertical (i.e. perpendicular to earth surface) angular separation of the points is measured continuously, providing a direct measure of bending angle as a function of time, given orbit knowledge. A significant engineering advantage to T-Star is the implementation of well-developed centroiding algorithms and star maps developed for Star Trackers, along with stray light mitigation technology. The FPA will likely be the same as the MODIS-3U High Dynamic Range VNIR camera.

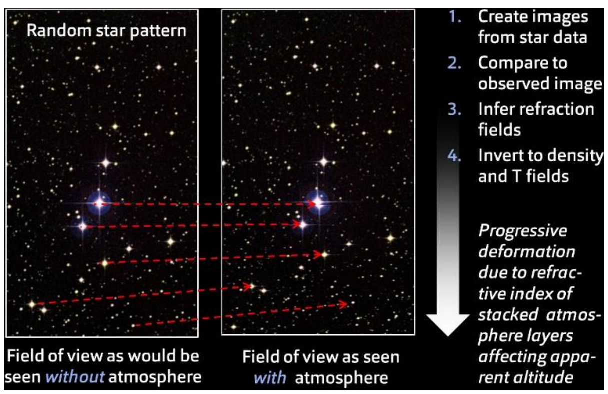

Figure 6 T-Star™ Measurement

Microwave Compact Sounder (MCS) – Boulder Environmental Science and Technologies

Microwave measurements of atmospheric constituents are large part of weather forecasting. A 2013 study by the European Centre for Medium-Range Weather Forecasts looked at the contributions of various space-borne radiometers to the improvements in weather forecasting. The report determined that microwave sounders had the greatest impact in reducing errors in forecast errors, with IR sounders being the second most important.[14] Although spatial sampling is larger than infrared, the ability to see through the cloud deck makes it a vital instrument in the MetNet™ constellation.

To include these measurements in MetNet™ we will use the Microwave CubeSat Sounder (MCS) being developed by Boulder Environmental Sciences & Technology. The MCS is a 6U form factor instrument which will measure temperature profile, water-vapor profiles, cloud liquid-water total column (droplet size < 100μm). The key technology in miniaturization is the deployable expanding microwave reflectors of 30-cm and 12-cm, which are planned to yield performance comparable or exceeding legacy microwave sounders, as shown in the accompanying figure.

The sensor will also contribute to mapping of freezing-level and melting layer depth in clouds, the cloud liquid-water profile, cloud drop effective radius profile, total ice column measurements, cloud ice effective radius profile, the precipitation profile, precipitation rates at the surface, accumulated precipitation, and downwelling longwave irradiance at the surface.

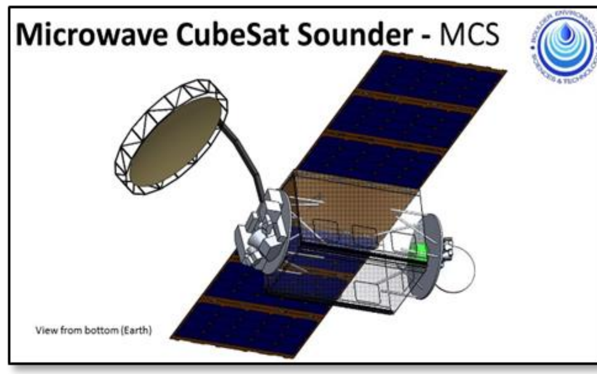

Figure 7 Microwave Compact Sounder

Aerosol Cloud Characterization Imaging Polarimeter – Brandywine Photonics

The ACCIP satellite builds on the concepts developed for the Hyper-Angle Radiometric Polarimeter (HARP) CubeSat, which focuses on meaurements of aerosols in cloud science.[15] The polarization effect induced by wide-angle nadir viewing of clouds are used to determine the distribution of aerosols in cloud formations. Our sensor will modify the design to include the Fully-depleted Backside-illuminated eXtreme performance (FBX) CMOS Image Sensors. This detector will provide additional sensitivity through high quantum efficiency from 380-980 nm, with an expected QE of >85% from 450-850 nm. Also under consideration for ACCIP is an Oxygen-A line Spatial Heterodyne Spectrometer for measurement of cloud scattering properties.

Compact Infrared Sounder (CIS) – Brandywine Photonics

The CIS builds on the instrument being developed under the NASA JPL CIRAS program, which is an imaging spectrometer to measure upwelling terrestrial infrared radiation.[16-18] The CIS design is different from CIRAS in that it will reside in the larger MicroSat bus as opposed to a 6U CubeSat, allowing us to install 3 separate pushbroom imaging spectrometers instead of a single instrument with a scanner. This improves reliability over extended lifetimes by eliminating a mechanism, and improves Signal to Noise Ratio. The spectrometer design may also be different, investigatng using a ZnSe volume phase holographic grating instead of a silicon grism grating. The detector will be either an nBn engineered bandgap material or T2SLS, depending on the final thermal budget. The CIS sensor, like the CIRAS, will focus on measuring the temperature and water content in the lower troposphere.

Doppler Wind Temperature Sounder – GPI Space Systems

One of the more innovative techniques that MetNet™ will use is the Doppler Wind and Temperature Sounder (DWTS™) for mapping of upper atmosphere temperatures and wind velocities. It will measure the wind vectors and atmospheric temperature from approximately 20 Km to 200 Km altitude, day and night.[19-20] This technology makes use of Doppler shifts of gas emission lines, to effectively scan narrow absorption spectra with complimentary gas cell spectra.. It is a simple design optically and mechanically, that uses a standard MWIR camera with band pass filters and a gas cell added to the optical path. This sensor views air masses on the earth limb to the right or left sides of the satellite orbital direction. This measurement will be coupled with a nadir-viewing sounder as a means of cross-calibration for accuracy improvements.

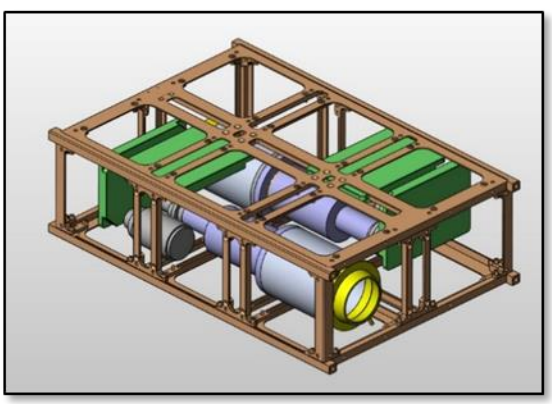

Figure 8 Double-sided, Single Band DWTS™

High Altitude Temperature Sounder – GPI Space Systems

The High Altitude Thermal Sounder (HATS™) instrument is a a sensor having the ability to do nadir thermal sounding of the atmosphere from tropospheric cloud-top to the upper mesosphere.[21] It makes nadir observations using a Doppler Modulated Gas Correlation (DMGC) approach similar to DWTS™, but in the nadir as opposed to limb. In effect, Doppler broadened lines are used to scan Doppler broadened line due to an orbit velocity induced Doppler shift. The resulting effective spectral resolution of the scan surpasses other passive spectrometers by typically a factor of 10. For example, DMGC CO_2 measurements at 15 μm can achieve an effective spectral resolution of <0.002 cm^{-1}, which can be used to generate averaging kernels from nadir observations with an unprecedented 4–12 km vertical resolution from tropospheric cloud top up to 95+ km. HATS™ can retrieve temperature profiles with a sensitivity better than 2°K over the entire altitude range. The key technology being evaluated for HATS is Type-2 Strained Layer Super Lattice (T2SLS) FPAs. Recent publications indicated much improved dark current over traditional HgCdTe detector material, thus significantly reducing the size of the cryo-cooler and radiator surfaces, enabling easily fitting on a MicroSat.

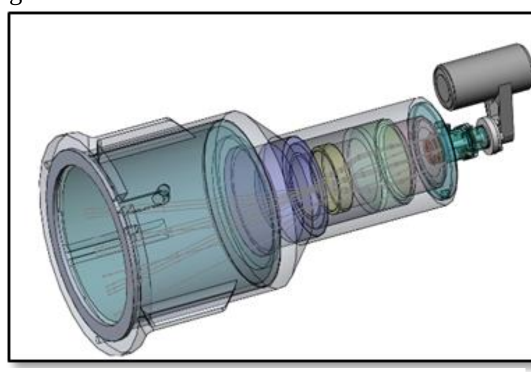

Figure 9 HATS™ Preliminary design

OTHER INSTRUMENTS

As the MicroSat (50-75 Kg) form factor may have additional spacecraft resources, the hosting of additional small payloads is being considered. Of significant interest is a small lightning imager similar to that on the ISS Lightning Imaging Sensor[22] to support storm intensity measurement. GPSRO would be a relatively straight-forward accomadation on the MicroSats, as the technology has been proven at TRL-9 and would supplement Microwave measurements with *a priori* wind measurements.[23] Lastly, a GFCR limb instrument using a subset of the Global Limb Observer channels on SOCRATES would assist in measuring mixing of trace gases in the Upper Troposphere/Lower Stratosphere as applied to weather. Using standard databus architectures (e.g. SpaceWire, SpaceFibre, etc.) will facilitate late integration of these and similar small hosted payloads.

SUMMARY

The MetNet network of small weather satellites has many of the standard advantages of a CubeSat constellation over traditional large weather satellites. These advantages include resiliency, revisit times, and cost, along with opportunities to generate new data products based on combining data from disparate sources. The combination of limb and nadir sounder data from constellations will enable a significant advance in enhancing retrieval quality and quantifying previously unobservable dynamics for improved mid-range weather forecasting, especially for extreme weather events. Next steps in the development of MetNet™ will include orbital analysis for each of the constellations, data flow and architecture analysis, and preliminary selection of a MicroSat spacecraft.The MetNet-1 satellite, a MODIS-3U instrument, will be the first satellite designed under a recently awarded US Air Force Small Business Innovative Research Grant.

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References

1. Pagano, T. “CubeSat Infrared Atmospheric Sounder (CIRAS)” American Meteorological Society “Advances in CubeSats and SmallSats to Improve Earth Science and Weather Forecasting” (2016).
2. Blackwell, William, et al. "Nanosatellites for earth environmental monitoring: The MicroMAS project." *Microwave Radiometry and Remote Sensing of the Environment (MicroRad), 2012 12th Specialist Meeting on*. IEEE, 2012.
3. Schutz, B. E., et al. "Overview of the ICESat mission." *Geophysical Research Letters* 32.21 (2005).
4. Skone, S., et al. "GNSS Radio Occultation Methods for CubeSat Missions: The University of Calgary and Spire Partnership." AGU Fall Meeting Abstracts. Vol. 1. 2014.
5. Remer, Lorraine A., et al. "Validation of MODIS aerosol retrieval over ocean." Geophysical research letters 29.12 (2002).
6. Ruf, Christopher S., et al. "The CYGNSS nanosatellite constellation hurricane mission." Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International. IEEE, 2012
7. Bevilacqua, R. et. al., “Solar Occultation Constellation for Retrieving Aerosols and Trace Element Species (SOCRATES) Mission Concept, Small Satellite Conference (2015).”Charney, Jule G., and Philip G. Drazin. "Propagation of planetary‐ scale disturbances from the lower into the upper atmosphere." *Journal of Geophysical Research* 66.1 (1961): 83-109.
8. Fuller‐ Rowell, T. J., et al. "Impact of terrestrial weather on the upper atmosphere." *Geophysical Research Letters* 35.9 (2008).
9. Barry, Roger G., and Richard J. Chorley. *Atmosphere, weather and climate*. Routledge, 2009.
10. Mailhot, Jocelyn, and Robert Benoit. "A finite-element model of the atmospheric boundary layer suitable for use with numerical weather prediction models." *Journal of the Atmospheric Sciences* 39.10 (1982): 2249-2266.
11. Schueler, Carl, and Alan Holmes. "HawkEye: CubeSat SeaWiFS update." *SPIE Optical Engineering+ Applications*. International Society for Optics and Photonics, 2016.
12. Schueler, Carl, and Alan Holmes. "SeaHawk CubeSat system engineering." *SPIE Optical Engineering+ Applications*. International Society for Optics and Photonics, 2016.
13. Gordley, Larry L. Method of Determining Atmospheric Refraction Profile Using Two Spatially Separated Light Sources. G & A Technical Software, Inc, assignee. Patent US7265820B. 04 Sept. 2007.
14. English, Stephen, et al. *Impact of satellite data*. Vol. 711. ECMWF Technical Memorandum, 2013.
15. Martins, J., et al. "Measurement of Aerosol and Cloud Particles with PACS and HARP Hyperangular Imaging Polarimeters." *AGU Fall Meeting Abstracts*. 2013.
16. Pagano, Thomas S., et al. "The CubeSat Infrared Atmospheric Sounder (CIRAS), Pathfinder for the Earth Observing Nanosatellite-Infrared (EON-IR)." (2016).
17. Pagano, T., et al. "CubeSat Infrared Atmospheric Sounder (CIRAS)." *NASA Atmospheric Infrared Sounder (AIRS) Spring Science Team Meeting, Pasadena, CA*. 2016.