Observing fast mesoscale atmospheric processes with a geostationary microwave sounder

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ABSTRACT

A geostationary microwave sounder, GeoSTAR, capable of providing continuous monitoring every 15 minutes of atmospheric temperature, water vapor, clouds, precipitation, and wind in the presence of clouds and precipitation, which will add tremendously to our ability to observe rapidly evolving dynamic atmospheric phenomena, such as hurricanes and severe storms, monsoonal moisture flow, and atmospheric rivers, has been developed at the Jet Propulsion Laboratory. GeoSTAR uses aperture synthesis to overcome the difficulty of attaining adequate spatial resolution from geostationary orbit. It is made possible with new technology that has now been developed and fully tested. Low-risk mission development can start as soon as funding becomes available. The sensor can be hosted on a commercial communications satellite, which could reduce the cost substantially. Plans have been developed at JPL for such a mission, called "GeoStorm", focused on observing severe convective storms – tropical cyclones, mesoscale convective systems, and extratropical cyclones – with a goal of improving our understanding, modeling and prediction of these destructive phenomena. It can equally well be configured as an operational mission, where the goal is to collect data for immediate assimilation into regional forecast systems, provide "now-casting" as the storms unfold, and support post-disaster relief and recovery efforts. With key observables including vertical profiles of temperature, water vapor, wind and precipitation over a wide area, many focused applications are possible, particularly pertaining to aviation, transportation and marine operations, in both the civilian and defense domains.

Keywords: Atmospheric sounding, geostationary, microwave, mesoscale, severe storms

1. INTRODUCTION

It has long been recognized that a geostationary microwave sounder would be a powerful tool for weather prediction and monitoring. Microwave sounders have operated on polar-orbiting low-earth-orbit (LEO) satellites since the 1970's and have had the largest impact on weather forecast accuracy of all the satellite sensors. This is because they measure the thermodynamic state of the atmosphere even in the presence of clouds, which allows dynamic weather processes to be measured. The assimilation of data from more and more such sensors has resulted in steadily improved forecast accuracy. However, polar-orbiting LEO satellites will at best pass over a given scene only twice in 24 hours, and that means that the most rapidly evolving phenomena, such as severe storms and tropical cyclones, are poorly sampled and therefore often poorly predicted. A sensor operating in geostationary orbit would overcome that obstacle, often being capable of sampling intervals of mere minutes. There is also an urgent need for observations that can be used to improve our understanding of the underlying atmospheric processes, which will in turn lead to better prediction models.

In its "Decadal Survey" of earth science missions for NASA published in 2007 [Anthes[1]] the U.S. National Research Council (NRC) recommended that such a sensor be developed for a "Precipitation and All-weather Temperature and Humidity" (PATH) mission and recommended that it be implemented as an "array spectrometer". That was largely based on a synthetic-aperture concept then under development at the Jet Propulsion Laboratory (JPL). At the time, the required technology was not perceived as being sufficiently mature, and PATH was therefore put in the "third tier" group of missions that required further development. Under sponsorship from the NASA Earth Science Technology Office's (ESTO) Instrument Incubator Program (IIP), the key technology has now been developed and has been brought to the Technology Readiness Level (TRL) 6 required by NASA for mission implementation, thus enabling the PATH mission [Lambrigtsen[2]].

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2. GOALS, OBJECTIVES AND REQUIREMENTS

The goal of the PATH mission is to improve the understanding, modeling and prediction of severe storms and similar phenomena, including dynamic water vapor transport processes such as monsoons and atmospheric rivers. Thus, the PATH mission can be viewed as a mission to monitor the mesoscale processes and dynamic aspects of the hydrologic cycle in the atmosphere [Lambrigtsen[3]]. For NASA the main emphasis is on research, i.e. to gain a better understanding of the underlying processes, followed by model improvements. For the National Oceanic and Atmospheric Administration (NOAA) and other operational agencies the emphasis is on assimilating the observations into forecast models and generate better weather forecasts, which requires both improved models and better observations.

The fundamental requirement was for the PATH sensor to provide temperature and water vapor sounding (i.e. generate vertical profiles) continuously, with a very rapid update cycle (15-30 minutes) and under nearly all weather conditions. The spatial resolution must be sufficient to resolve key storm processes. Past research based on data from LEO sounders, such as the Advanced Microwave Sounding Unit (AMSU) [Kidder[4], Zhu[5]], suggests that this can be achieved with the capabilities of those sensors if they were available in geostationary earth orbit (GEO). Thus, the PATH sensor can be viewed as "AMSU in GEO". This requires operating in the 50- or 118-GHz band for temperature sounding and in the 183-GHz band for water vapor sounding, as noted by the NRC. It also means attaining spatial resolution of about 25 km (similar to the 15-50 km of AMSU). Such a resolution is very difficult to achieve with a microwave sensor in GEO and has prevented the development of a GEO MW system until now. For example, AMSU has an antenna aperture of about 15 cm, but scaled from LEO (830 km) to GEO (36,000 km) this becomes 6.5 m. Getting such an antenna into space while maintaining the surface precision required for sounding has been prohibitive, and scanning it across the earth disc is also a show stopper. This problem has now finally been solved with the development of the Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) design and the technology required to implement it.

3. GEOSTAR

GeoSTAR is a microwave sounder concept first proposed in 1999 [Lambrigtsen[6]] for the NASA New Millennium program. It is based on synthesizing a large antenna aperture. In essence, a large but sparse array of small antennas is used as a spatial interferometer that samples the spatial fourier spectrum of the radiometric field. This is illustrated in Figure 1. Each pair of receivers in the antenna array (upper-left) acts as an interferometer that samples a point in the 2-dimensional fourier space (upper-right), often called the uv-space. When viewing a radiometric image (lower-left), the cross-correlation between a receiver pair is a measure of the magnitude and phase of the matching fourier component of the image, and that results in a fourier image (lower-right). An inverse fourier transform then recovers the radiometric image (lower-left). This principle has been proven in radio astronomy as well as in the Soil Moisture and Ocean Salinity SMOS) space mission. The primary advantages of such a STAR system are that a large aperture can be formed with an array that can be folded during launch, is more efficient than a real-aperture system, and requires no scanning.

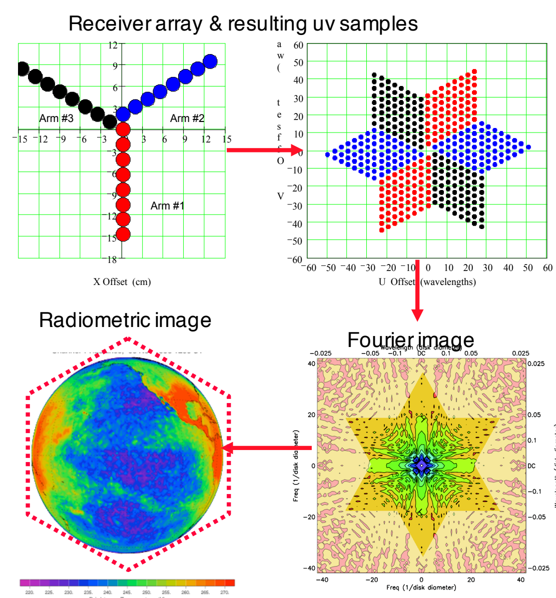

Figure 1. Basis for aperture synthesis radiometry

The GeoSTAR concept and technology were developed under three consecutive IIP efforts between 2003 and 2015. GeoSTAR-I (2003-2006), a proof-of-concept prototype operating in the 50-GHz band, was used to demonstrate the feasibility of the concept. It was established that the system can be well calibrated and is inherently extremely stable and fault tolerant. GeoSTAR-II (2008-2011) was used to develop miniature low-power 183-GHz receivers and an antenna array design that makes it possible to limit the overall field of view and greatly improve the antenna efficiency and thus the radiometric sensitivity, and to demonstrate imaging at 183 GHz. Finally, GeoSTAR-III (2011-2015) was used to develop a low-power application-specific integrated circuit (ASIC) cross-correlator. A complete end-to-end system has been built, and key components and subsystems have undergone environmental testing to validate TRL 6. Figure 2 shows a photo of the GeoSTAR-III demonstrator, a small but fully functional high-gain STAR system operating in the 183-GHz water vapor sounding band, and an example of imaging with this system.

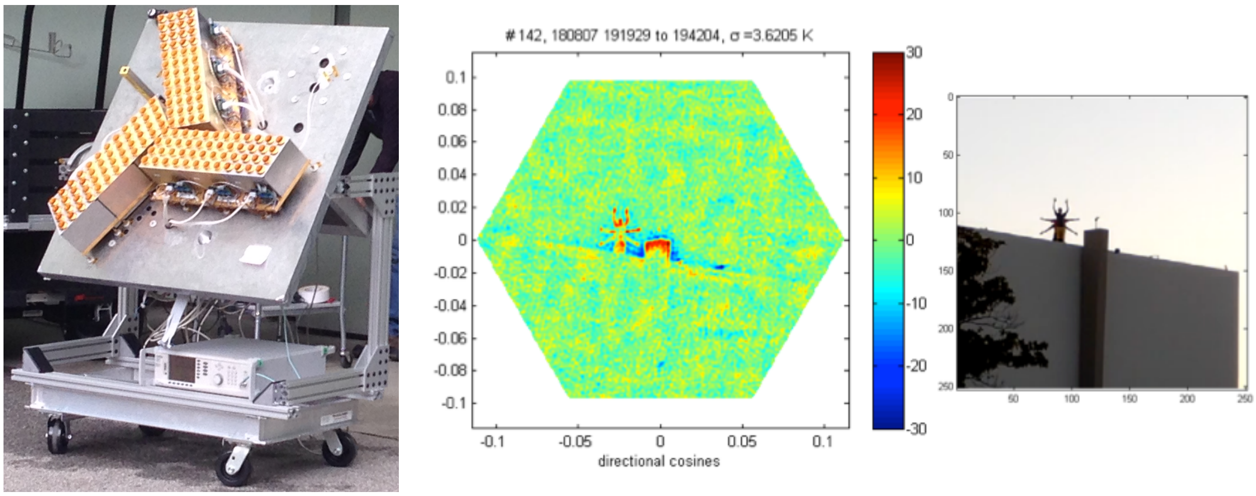

Figure 2. The GeoSTAR-III demonstrator (left); sample GeoSTAR-III image (center) of three persons on a roof (right)

GeoSTAR has functionality very similar to AMSU and similar sounders, i.e. it measures the brightness temperature in a number of spectral channels. A "retrieval system" inverts the radiative transfer equation to estimate the geophysical conditions that correspond to the observed radiation, i.e. parameters such as vertical profiles of temperature and humidity. The instrument is a "staring" imager-sounder that covers the entire observing domain without requiring mechanical scanning, and it is therefore a true "synoptic" sensor. There are no "pixels" as in conventional 2D imagers or scanning sensors; instead GeoSTAR observes a range of spatial scales, which results in a blurred but densely sampled version of the scene. Thus, "25 km resolution" does not mean "25 km pixels" but rather "spatial scales down to 25 km". In the notional implementation of GeoSTAR the spectral channels are sampled sequentially in a rapid cycle until the effective integration time yields the desired radiometric noise level (i.e. sensitivity), and all channels are therefore effectively sampled simultaneously.

4. OBSERVABLE PARAMETERS

The raw GeoSTAR measurements, which are typically downlinked from the spacecraft every minute or so, are called "visibilities" – a term coined by the radio astronomy community. They are essentially the coefficients of the spatial fourier components that GeoSTAR observes. The 2D visibility images are converted to brightness temperature images, one for each channel, through an inverse fourier transform. Each of these images is very noisy since they represent a very short integration time, but by averaging over a longer time period, the required radiometric sensitivity is achieved. Table 1 shows an example for a 15-minute averaging window, which results in noise-equivalent delta-temperature (NEDT, a commonly used measure of radiometric sensitivity in microwave sounding) of 0.3 K for the temperature sounding channels and 0.5 K for the water vapor sounding channels, which is comparable to the performance of current LEO sounders. The brightness temperatures are then used to derive a number of geophysical parameters. In NASA terminology, the visibilities are Level 1a (L1a) data products, the brightness temperatures are L1b products, and the derived parameters are L2 products. The data product precisions shown in Table 1 are based on current capabilities with LEO sounders, given these NEDTs as well as simulation studies carried out at JPL and are discussed in more detail in the following paragraphs.

The basic sounding products are vertical profiles of temperature and humidity. There are a number of algorithms that can achieve the precisions listed in Table 1, such as the Microwave Integrated Retrieval System (MIRS) used for NOAA's operational products [Boukabara[7]], and a new NASA system that produces valid results even in the presence of heavy precipitation is under development at JPL [Schreier[8]]. Estimates of column-total cloud liquid water and cloud ice are also standard products from microwave sounders. There is also a variety of algorithms that are used to derive rain rates, particularly for convective rain where scattering from the large frozen particles associated with such rain can result in very large and easily detectable signals.

Table 1. GeoSTAR measurements and precisions

Brightness temp.	0.3-0.5 K
Temp. profile	1.5-2.5 K
Hum. profile	25-40%
Wind speed profile	2 m/s
Wind dir. profile	15°
Reflectivity profile	2-4 dBZ
Rain rate	5 mm/hr
Cloud liquid	25%
Cloud ice	25%

This has been taken one step further at JPL through the development of an algorithm that converts the scattering signals into reflectivity. The basis for this was developed in connection with hurricane field campaigns where the High Altitude MMIC Sounding Radiometer (HAMSR) [Brown[9]], an aircraft-based microwave sounder developed at JPL. In particular, in the Tropical Cloud Systems and Processes (TCSP) campaign in 2005 HAMSR flew on the NASA ER-2 plane together with the ER-2 Doppler radar (EDOP), and comparisons between the data from the two instruments revealed a significant drop in HAMSR brightness temperatures when EDOP showed large reflectivity. An effort was then launched to develop a "machine learning" algorithm to derive vertical profiles of reflectivity from HAMSR, trained with EDOP profiles. This was successful, and analysis showed that HAMSR reflectivity profiles had a precision of 2-4 dBZ and a vertical resolution of 1-2 km. EDOP is an X-band radar operating at 9.6 GHz, and the HAMSR reflectivity algorithm therefore mimic an X-band radar (albeit with much lower vertical resolution). However, reflectivity changes slowly as the frequency of the radar is increased, and the HAMSR reflectivity profiles compare well also with measurements from the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP), which operates at Ka- and Ku-band. HAMSR flew together with HIWRAP on the NASA Global Hawk in the Genesis and Rapid Intensification Project (GRIP) in 2010. One flight was used to observe Hurricane Karl, a category 3 storm in the Gulf of Mexico, and Figure 3 shows a brief sequence from a pass over the eye of Karl. The HAMSR retrievals can be seen to reproduce the 2010 HIWRAP observations very well, despite the fact that the HAMSR algorithm was trained on X-band data from 2005. This algorithm has also been tested with satellite data, and the results using AMSU on the NOAA-16 satellite compares well with data from NASA's Tropical Rainfall Measurement Mission (TRMM), which carried a Ku-band radar. This is a new capability, which will make it possible to provide measurements from GEO that are otherwise not currently possible, nor is it expected to be for the foreseeable future due to the significant technical challenges in developing a radar for GEO.

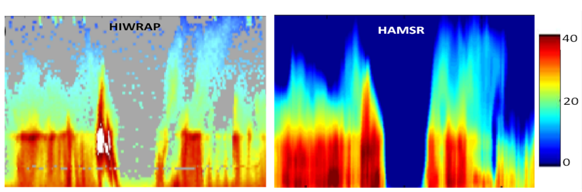

Figure 3. Nadir reflectivity of Hurricane Karl from the HIWRAP radar (left) and the HAMSR sounder (right)

Another important capability is the ability to derive vertical profiles of horizontal wind vectors by tracking the motion of water vapor features, called the atmospheric motion vector (AMV) method. This is currently done with data from visible and infrared imagers on-board geostationary satellites, but that method depends primarily on tracking clouds, which leaves large gaps in the cloud-sparse middle troposphere as well as in and below the clouds. GeoSTAR, on the other hand, will provide wind vectors everywhere and under almost all weather conditions. Figure 4 shows the results of a simulation study [Lambrigtsen[10]], which indicates that GeoSTAR can measure wind speed with a precision of ±2 m/s and direction with a precision of ±15°, which will meet the currently unmet requirements of the World Meteorological Organization (WMO). This is a borderline breakthrough capability.

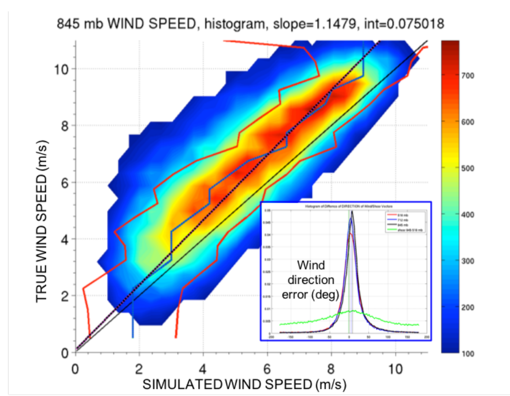

Figure 4. Histogram of simulated wind speed vs. nature run "truth" at 845 mb. Inset: Wind direction

5. MISSION CONCEPTS

GeoSTAR can be configured in a variety of ways due to a flexible design. The PATH mission is relatively large, requiring a dual-array version of GeoSTAR with several hundred receivers, so that the entire Earth disc can be observed simultaneously. The cost of such a mission was estimated by the NRC to be on the order of $450M for the payload, spacecraft and launch. A smaller and much less costly configuration was conceived to take advantage of hosted-payload opportunities that may exist for small GEO missions. There are approximately 300 communications satellites around the world in GEO, each with a typical lifetime of 15-20 years. They therefore have to be replenished at a rate of 15-20 each year. Many of them can accommodate hosted payloads, and the "GeoStorm" mission was designed to be hosted on such a satellite. The version of GeoSTAR for that mission is about half the size of the PATH version and uses an antenna innovation that was developed under the GeoSTAR-II IIP project. It achieves high antenna efficiency with a relatively narrow field of view, about 1000 km across instead of the entire Earth disc, without undue alias interference. To achieve full-disc coverage, the instrument is articulated so that it can track a storm as it evolves, or jump from target to target if there are several storms of interest at the same time. Figure 5 illustrates both mission concepts.

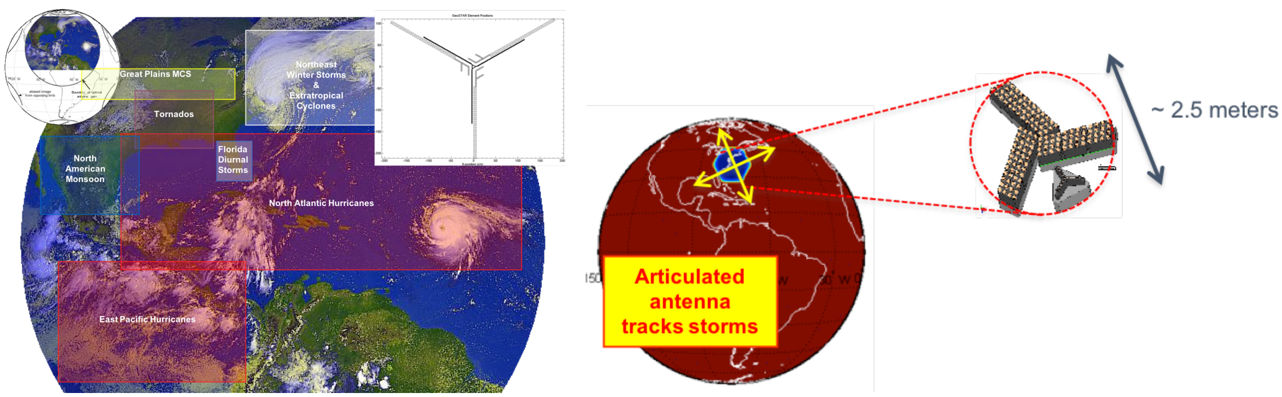

Figure 5. GeoSTAR mission concepts. Left: PATH obtains a global view; upper-left inset shows the PATH GeoSTAR configuration, with a fixed 4.5-meter dual array (one for each band) that can be folded for launch. Right: GeoStorm uses a single articulated 2.5-meter multi-row array that operates in two bands and can be pointed

6. USING GEOSTAR OBSERVATIONS

The potential usage of GeoSTAR data can be divided into three broad categories: Research, weather prediction, and applications. All revolve around rapidly evolving mesoscale phenomena, typically convective storms, where the ability to make measurements very rapidly, continuously, over a large area, and under all weather conditions (i.e. in the presence of clouds and rain) is crucial. Severe convective storms, such as tropical cyclones, mesoscale convective systems, and extratropical cyclones are particularly challenging targets. They are very large, obscured by clouds and rain, have intense wind fields, move rapidly, and it is often difficult to predict their intensity. All can cause severe damage to life and property. Atmospheric rivers, monsoons and local brief but intense rain events are also difficult to fully characterize with current observing systems and are also phenomena where GeoSTAR can contribute significantly.

NASA's focus is on research, utilizing the following sequence to improve our knowledge of the processes and environmental conditions that control the storms and similar phenomena: *technology* → *observations* → *understanding* → *model* → *prediction*. In a subsequent section we discuss an example of a focused investigation that would benefit from GeoSTAR observations.

NOAA and similar "operational" agencies around the world are largely interested in assimilating observations into numerical weather prediction models operated by, for example, the U.S. National Weather Service. The resulting "guidance" is provided along with the observations themselves to weather forecasters, including those in the private sector. There is evidence that the operational models are deficient in their ability to accurately represent storm processes (shown, for example, by the fact that only modest progress has been made in hurricane intensity forecast accuracy over many years), and it is not clear that new storm-scale observations will have much impact. Still, GeoSTAR observations can be expected to have significant impact on regional forecast accuracy because it will provide a better picture of the environment around the storm systems, which is often obscured by clouds and rain and can change rapidly and therefore is not adequately captured by existing observing systems. The GeoSTAR observations are particularly well matched to new “4D-Var” assimilation systems, which can take advantage of near-real-time (NRT) or real-time (R/T) observations. Conventional assimilation systems are tied to fixed forecast cycles and can only assimilate data that are available within narrow time windows.

Other potential users of GeoSTAR include agencies that are tasked with issuing warnings of weather hazards and impending natural disasters and respond to those afterwards – often related to precipitation and wind; the aviation sector – which needs to know about deep convection, high wind and icing conditions; agriculture – where knowledge of rain and wind is important; transportation – where it is important to know the path and intensity of severe storms that can affect road and rail conditions; the health sector – where it is useful to have a picture of storm-related conditions that are conducive to the growth and spread of mosquitos and vector borne disease. This is summarized in Table 2.

Table 2. GeoSTAR applications and the usage of data products

Focus area	Potential users	Measured parameters					
		Brightness temp	Temp, humidity	Cloud param.s	Rain rate & total	Reflectivity	Wind speed/dir
Research Storm processes, hydrologic cycle	NASA	√	√	√	√	√	√
Numerical weather prediction Assimilation of NRT data	NOAA, DoD, commercial	√				√	√
Now-casting & warnings R/T storm obs.: Intensity, path, rainfall totals	DoD, NOAA, FEMA, news org.s	√	√	√	√	√	√
Aviation R/T flight conditions: Convection, icing, wind	FAA, airlines, civil aviation		√	√			√
Agriculture Growing conditions: Rain, wind, temperatures	Farmers, insurance co.s		√	√	√		√
Transportation Storm path, flooding potential	Railways, truckers, public				√		√
Health Mosquitao conditions, air pollution events	Health care providers		√		√		√
Disaster response Water: Rainfall totals, river flow, flooding Wind: Sustained & max observed, areal averages	Resource managers, responders				√		√

Figure 6 illustrates the hierarchy of convective storms and the domain that can be informed with observations obtained with the GeoStorm mission. Here the main focus is on large convective storm systems: mesoscale convective systems (MCS), tropical cyclones (hurricanes), and extratropical cyclones (mid-latitude storms). An example investigation to be carried out with GeoStorm observations would be to determine what controls the evolution of severe thunderstorms and MCSs and in particular how the large- and meso-scale environment interacts with storm-scale processes on sub-hourly time scales. GeoSTAR will measure almost all key variables that are needed to address this: the thermodynamic state both in and around the storm, precipitation rate and type (i.e. convective vs. stratiform), vertical and horizontal structure of the convection, wind speed

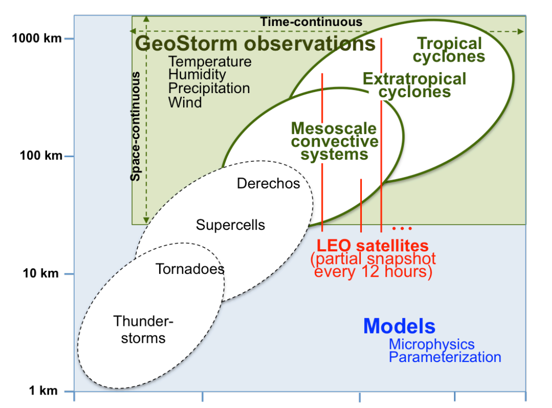

Figure 6. Hierarchy of convective storms and the GeoStorm domain

and direction at all levels of the troposphere. It will even be possible to estimate momentum transport and mass flux, which are parameters that are currently rarely known but play a key role in the dynamics of such storms. Figure 7 illustrates a simulation of an MCS. The left panel shows the humidity in the lower atmosphere at the 6-km resolution produced by the simulation model. The right panel shows the blurred view from GeoStorm. Here the dotted line outlines the area covered by clouds (which cannot be penetrated by visible or infrared sensors), white indicates areas of significant precipitation (where standard retrieval systems fail), and the inner black line outlines very heavy precipitation. GeoSTAR will observe all of this, and with the newest retrieval systems it will be possible to derive nearly all of the parameters listed in Table 1 throughout the storm. This will yield a collection of data of unprecedented scope and depth and enable significant progress in storm science.

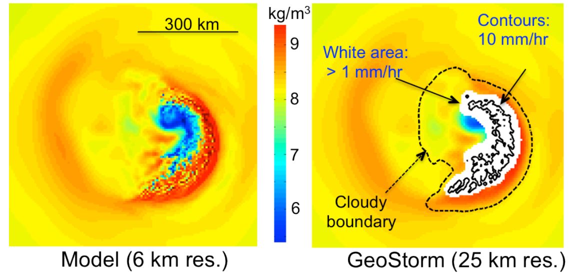

Figure 7. A simulated MCS (left) and the GeoStorm view (right)

7. SUMMARY

The development of the GeoSTAR concept and the technology required to implement it represents a major leap forward in our ability to observe severe storms and "bad weather" from space. Once it has been built and put in space, significant progress in the study of mesoscale atmospheric processes can be expected. Only funding and launch opportunities stand in the way.

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