The TropSat Mission: An Observatory for Mesoscale Convective System Processes in the Global Tropics

David G. Long, Ralph Milliff, Ernesto Rodriguez

***Abstract*—A satellite mission is proposed to provide frequent, high-resolution measurements of surface winds, rain, and temperature profiles to support critical observations of Mesoscale Convective Systems (MCS) over the global tropical oceans. The proposed mission includes an innovative active/passive microwave system coupled with IR cloud top measurements for multi-layer atmosphere observations.**

The TropSat system will provide frequent, high-resolution measurements of the near-surface wind vector and rain rate over the tropical oceans. The senor design is based on the proven technology of SeaWinds but includes key innovations and an integral radiometer. The main sensor will include: (1) dual-band (C- and Ku-band) and dual beam (inner/outer beams) operation (C- and Ku- band) at multiple polarizations and (2) ground-based post processing to achieve the desired high spatial resolution. Backscatter measurements over land can support vegetation and climate change studies. This paper provides a brief description of the TropSat mission, discusses various instrument and mission tradeoffs, and presents performance estimates to demonstrate the feasibility of the mission concept.

I. INTRODUCTION

SURFACE vector wind measurements made from space by scatterometers, and rain and temperature measurements from radiometers and precipitation radars have become operational at number of weather prediction agencies. Such information is vital in understanding air-sea processes. However, the temporal sampling of existing polar-orbiting systems is inadequate to study rapidly evolving processes that require more than one or two observations per day. In particular progress in understanding and forecasting large-amplitude and large-scale elements of weather and climate systems on Earth are limited now by our inability to accurately model smaller scale processes of organized convection in the tropics.

While individual convective updrafts may have spatial scales shorter than 1 km and last only tens of minutes, the vast majority of tropical rainfall occurs in aggregations of convective cells and lines with associated patches of stratiform precipitation. These are identified by the generic name Mesoscale Convective Systems (MCS). Massive kinetic and potential energy conversions and exchanges are associated with dynamical and thermodynamical processes of MCS throughout their life-cycles in the maritime tropical troposphere, see Fig. 1. These exchanges are modulated by, and modify in turn, the large-scale circulation in fundamental ways such that the aggregate effects of maritime tropical convection are essential components of the general circulation. Moreover, fluctuations and organizations of MCS drive large-amplitude perturbations of weather and climate on our planet. MCS organization underlies essential dynamics and thermo-dynamics of tropical cyclogenesis, monsoons, the Madden-Julian Oscillation (MJO) and the El Nino/Southern Oscillation (ENSO). It is therefore necessary to observe simultaneously the energetic MCS processes and their large-scale contexts, region-by-region and hour-by-hour. Only in this way can unbiased and robust regional statistical distributions for aspects of maritime tropical MCS be built for the purposes of driving and validating new process model development that will capture the essential roles of the tropical MCS processes for research and forecast purposes.

As revealed in tropical rain climatology, MCS occur primarily with in 14º of the equator [1]. Practical orbit limitations preclude continuous observations of MCS with a single satellite sensor. However, with a wide swath and proper orbit design, frequent repeat cycle observations, spaced about 1.5 hours apart can be obtained using a single sensor in an equatorial orbit. Such observations would be augmented by existing sensors in polar orbits.

Coupling the capabilities of various proven satellite sensor systems and trading off cost and performance, a set of realistic geophysical measurement requirements has been developed that would provide the measurements needed to understand MCS. These are summarized in Table 1. The goal of the mission is to collect and analyze the data necessary to parameterize MCS to improve their representation in process models and numerical weather prediction systems.

The goal of this paper is to provide a brief description of the TropSat mission concept, its sensors, and a summary of the predicted system performance based on simulation. The TropSat mission is designed to augment existing and planned scatterometer and radiometers and will benefit from them. After a short discussion on mission requirements, an integrated scatterometer/radiometer sensor system is described which can fulfill the mission requirements. Simulations are used to predict system. A short conclusion is then provided.

D.G. Long is with the Dept. of Electrical and Computer Engineering, Brigham Young University, 459 Clyde Building, Provo, UT 84602 USA (801-422-4383; long@ee.byu.edu).

R. Milliff is with NWRA, CORA Division, Boulder, CO USA (303-415-9701; milliff@cora.nwra.com)

E. Rodriguez is with the Jet Propulsion Laboratory, Pasadena, CA USA (Ernesto.Rodriguez@jpl.nasa.gov; 818-354-5668).

978-1-4244-2871-7/09/$25.00 ©2009 IEEE

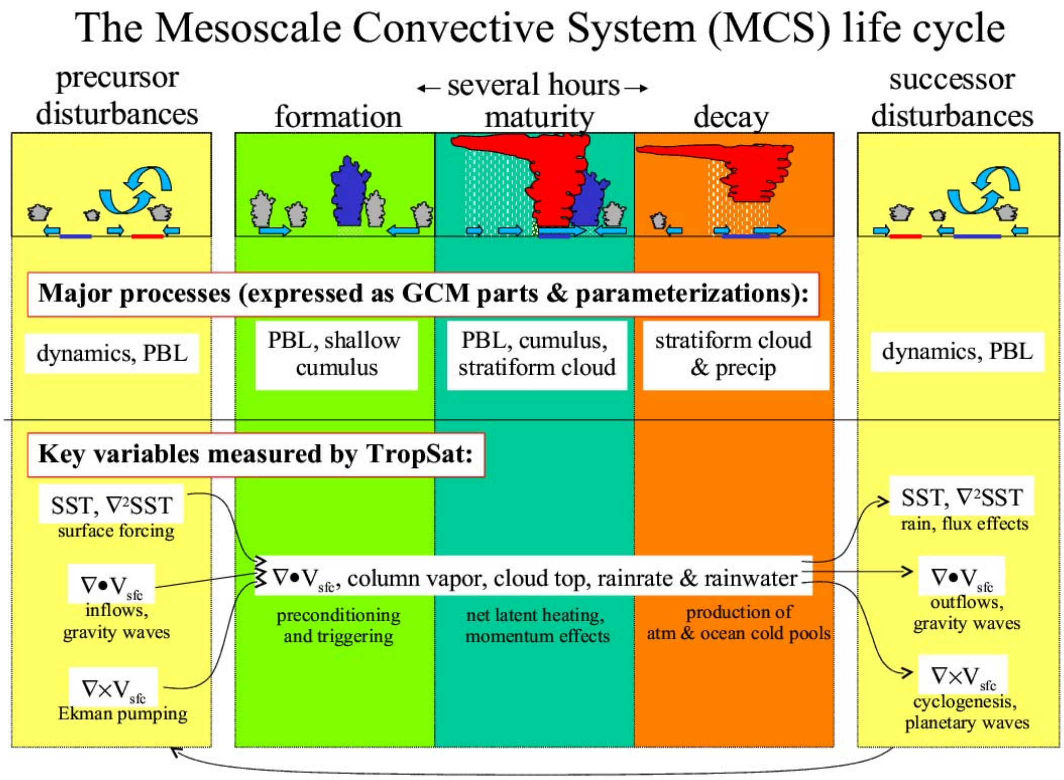

Fig. 1. Mesoscale convective system (MCS) processes and TropSat observations over the MCS life cycle.

II. Mission Requirements

TropSat sensor performance requirements are summarized in Table II. With its low inclination angle orbit, TropSat is optimized for tropical observations and is designed to augment existing planned polar orbiting sensors. To minimize mission cost a small launch vehicle is planned. This constrains the system size, power, and weight. For example, the antenna aperture is assumed to be limited to approximately 1 m. This poses a significant challenge to achieving the desired resolution, requiring an innovative approach based on ground reconstruction processing.

TABLE I
TropSat Mission Requirements

Parameter	Value
Wind speed	
Dynamic Range	1-30 m/s, 1-50 m/s goal
RMS speed accuracy	10% or 2 m/s, whichever greater
RMS direction accuracy	20º for *selected* ambiguity plus < 10º rain-induced error (larger rain-induced errors to be flagged)
Surface rain	
Dynamic range	1-100 mm/hr
RMS accuracy	2 mm/hr
Integrated water vapor	
Dynamic range	TBD
RMS accuracy	TBD
Vertical temperature profile	Two layer, 2º RMS accuracy
Spatial resolution	10 km rain & temp / 2.5 km SVW
Vertical resolution	Surface + two layer temp
Orbit	Equatorial
Altitude	750 km
Inclination angle	12-20º
Swath width	1200 km
Revisit frequency	4-6 observations in 6-10 hours at least 50% of the time

TABLE II
TropSat Mission and Instrument Parameters*

Parameter	Value
Scatterometer	Dual-freqency, dual-beam
Frequency	13.4 (Ku-band) 5.4 (C-band) GHz
Peak transmit power	100 W (each)
Pulse length	200-240 us
PRF	3-4 kHz
Duty cycle	60-80%
Transmit bandwidth	1 MHz
Noise temp	< 800 K
Receive bandwidth	(TBD) 10 MHz
Beamwidth	1.25º and 3.18º
Incidence angles	48º and 57.5º
Radiometer	4 Channels
Frequency/polarization	6.9 V/H, 22 V, 37 V GHz
Bandwidth	100 MHz
ΔT	~0.5 K
Beamwidth	~ 3º, 1º, 1º
Incidence angle	57.1º
Antenna	Single reflector
Size	1 m
Rotation rate	~15 rpm
Orbit	Equatorial
Altitude	750 km
Inclination angle	12º
Eccentricity	0.001

* Preliminary design configuration

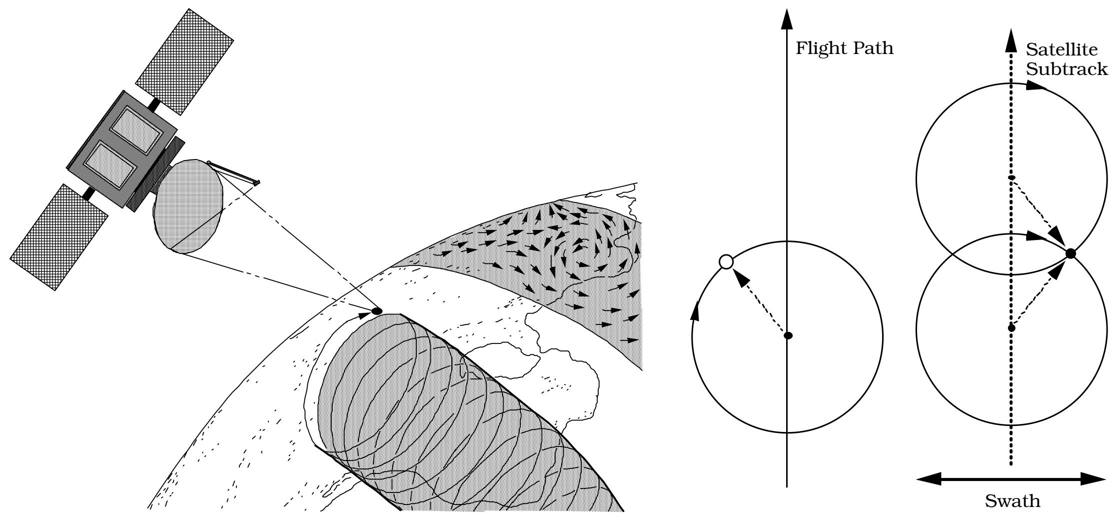

Fig. 2. Conceptual diagram of TropSat. For simplicity, only a single beam is shown. (left) Surface scan pattern. (right) Illustration of the multi-look observation scheme. As spacecraft moves along its orbit the scanning pattern traces out a helix. Each point over the swath width is first observed by a forward-looking scan, then by an aft-looking scan. With two beams at different incidence angles, each point is observed four times at different azimuth and incidence angles. Dual frequency and polarization measurements are also collected, increasing the number of backscatter measurements to 16 over most of the swath.

The key TropSat sensor is an integrated microwave radiometer/ scatterometer system coupled with an orbit optimized for observation of tropical MCS on their inherent timescales of variability. The TropSat scatterometer is based on the highly successful SeaWinds design, but with additional capability to enable robust estimation of surface winds in the presence of rain. The multiple microwave radiometer channels are supplemented by an IR temperature sensor in order to measure cloud top temperatures. The active and passive channels share the same antenna and have a common boresite to ensure simultaneous observation. The microwave sensor has significant SeaWinds scatterometer heritage but it differs from SeaWinds in a number of key areas:

1. Dual-frequency operation (C- and Ku -band) is employed.
2. To make up for the low spatial resolution at C-band afforded by the antenna, ground-based reconstruction/ resolution enhancement post-processing is used.
3. An integral multiband radiometer with a boresighted IR sensor for cloud top temperature measurement is included.

In the following discussion, we focus primarily on the active (scatterometer) system for wind and rain measurement. There are a number of areas to tradeoff performance versus complexity. Some of these tradeoff issues are considered in the following section.

III. Scatterometer System

TropSat will use a conically scanning pencil beam antenna. The rotating antenna makes it possible to simultaneously make collocated radiometer mode measurements along with the active radar measurements. Scanning is obtained by a multi-beam fixed off-nadir looking pencil-beam antenna rotating about the spacecraft nadir vector. Figure 2 illustrates the scan pattern relative to the spacecraft nadir. (Since the nadir point propagates on the earth's surface as the satellite orbits, the actual scan patterns on the surface are helices.) The antenna rotation is selected in combination with the orbit so that the antenna completes a full revolution in the time required for the satellite to move a fixed distance. For example, in a 750 km equatorial orbit, a rotation rate of 15 rpm provides 25 km along-track scan separation.

The TropSat antenna scan geometry and the measurement timing provides multiple backscatter measurements at each sample point in the swath. The diversity of azimuth angles, incidence angles, frequencies, and polarizations of the backscatter measurements enables accurate retrieval of the near surface vector wind and the integrated rain rate. A good tutorial on the fundamental theory of scatterometry can be found in [2], which describes how scatterometers measure wind from measurements of radar backscatter.

Rain plays a key role in the performance of wind scatterometers. It is well known that SeaWinds wind measurements can be adversely affected by rain. However, this sensitivity can be exploited to enable estimation of rain from SeaWinds rain measurements [3]. While conventional wisdom has believed that C-band is only minimally affected by rain, this is not the case – there, in fact, an observable rain signature in winds retrieved from ERS-1/2 backscatter measurements than can be used to retrieve rain rate [4]. At the operating incidence angles of TropSat, the impact of rain can be significant for rain rates over a 1-2 km-mm/hr at C-band, though the impact is lessened at high wind speeds [4].

Contrasting C- and Ku-bands, we note that rain has a smaller effect at C-band than at Ku-band; however, wind measurement accuracy at low wind speeds using C-band is much less accurate that when Ku-band is used. By combining C and Ku bands, TropSat scatterometer can exploit the advantages of both. The radiometer measurements provide

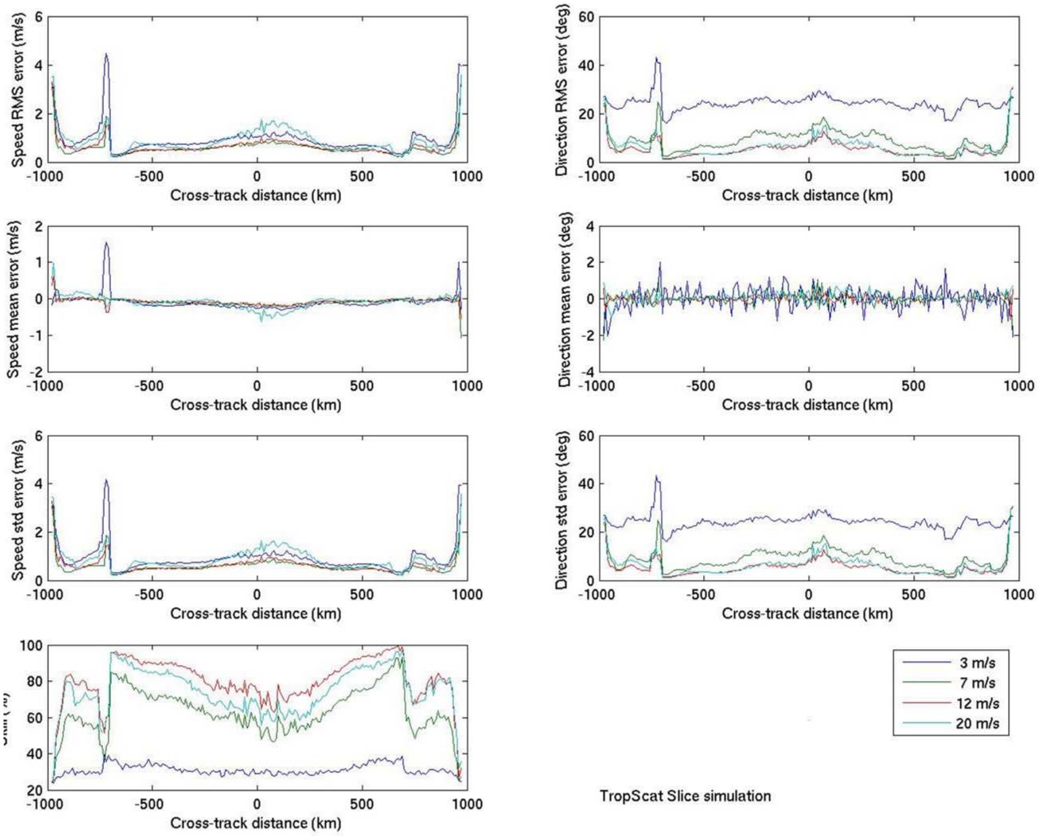

Fig. 3. Compass simulation estimates of wind measurement performance at 10 km resolution w/o rain. The wind-only swath corresponds to the full coverage patter while rain retrieval is restricted to the inner swath is wider than rain measurement swath.

additional information for rain estimation and temperature profiles.

Both near-surface vector winds and rain rate can be estimated from scatterometer measurements over the inner swath using simultaneous wind/rain retrieval (SWR), a technique that has been successfully demonstrated at Ku-band with SeaWinds [3] and at C-band for ERS-2 [5]. Combining the two frequencies improves both the wind and rain estimate accuracy over either band alone.

To compensate for the relatively large scatterometer footprint, particularly at C-band, range-Doppler filtering is used to resolve the antenna illumination footprint into cross-scan "slices". This also facilitates processing to match up the effective resolution of the Ku-band and C-band observations. As has been demonstrated with SeaWinds data, reconstruction/resolution enhancement processing enables high-resolution wind and rain retrieval from the backscatter measurements [6]-[8]. By designing the instrument with this processing in mind, we can optimize the reconstruction resolution enhancement [9].

IV. Performance Evaluation

Following in the long scatterometry tradition, to evaluate the wind and rain performance, Monte Carlo simulation is employed. The TropSat observation geometry is used to generate synthetic backscatter measurements using Ku-band and C-band wind and rain model functions. Monte Carlo noise is added based on the predicted *Kp* value. In "compass simulation", this is repeated for each wind speed and direction "around the compass". A combined Ku/C-band simultaneous wind/rain retrieval algorithm is used to estimate wind and rain. The results presented below are averaged over all directions for each swath location. In these results, the number of realizations of the noise is limited so the performance curves are noisy. We note that it is expected that tuning of the retrieval algorithm will improve the results. In the compass simulations results presented below, the closest ambiguity (in RMS wind speed difference) to the true wind is used as the selected ambiguity.

Fig. 3 shows the baseline wind estimate performance at 10 km resolution versus swath location at the equator for zero true rain. Since the rain is set to zero for this simulation, conventional wind-only retrieval can be used. This case is provided for comparison to SWR results later. Note that performance varies over the swath and is somewhat poorer in the near-nadir region, similar to SeaWinds. General performance meets requirements for all but the lowest wind speeds where the unfavorable SNR results in poor wind direction retrieval. Note that these results are obtained using reconstruction processing at 10 km resolution.

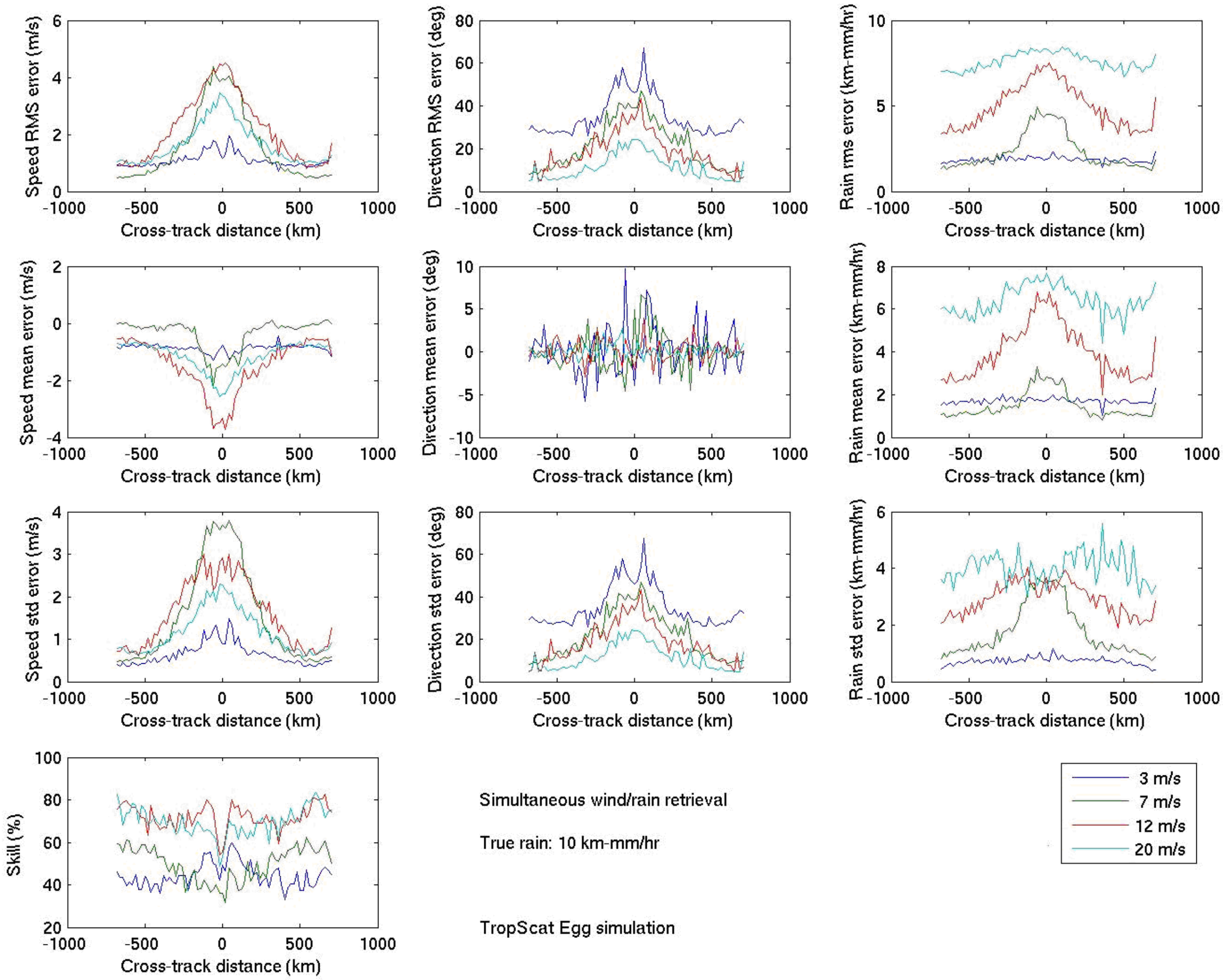

Fig. 4. Compass simulation estimates of TropSat SWR wind and rain measurement performance at 20 km resolution. For this analysis SWR is performed only over the inner, four-azimuth backscatter observation portion of the swath.

In Fig. 4, the performance of simultaneous wind and rain retrieval is estimated. In this case the true rain rate is 10 km-mm/hr, which is fairly high. (Fewer simulation realizations were used in generating this figure compared to Fig. 3, which results in plots with greater variability.) Note that simultaneous wind/rain retrieval can only be performed over the inner swath region where there is sufficient diversity of azimuth observations. In this example, SWR retrieval is done at 20 km resolution.

Preliminary TropSat simulation results suggest that even using SWR, overall wind measurement performance is degraded in the presence of rain as expected. However, wind and rain performance is generally acceptable except over the near-nadir region.

We note that the rain retrieval accuracy is wind speed dependent and degrades with increasing wind speed. As the rain rate increases, the wind speed accuracy degrades. At a geometry-dependent threshold, the rain component of the observed backscatter tends to dominate the wind signature and wind retrieval is not possible [3]. While the desired accuracy requirements are not met in all regions of parameter space over the full swath, further tradeoffs and optimization of the design parameters are expected to improve the results. Further, improvement is expected by combining the active and passive measurements in wind/rain retrieval, particularly in the nadir region of the swath.

V. Conclusion

The low cost TropSat mission concept is designed to augment existing and planned sensors to provide a vital set of measurements to better understand MCS. Such measurements will enable new understanding of fundamental processes in air-sea interactions and improved weather prediction.

References

[1] P.P Xie and P.A. Arkin, "Analyses of global monthly precipitation using gauge observations, satellite estimates, and numerical model predictions," *J. Clim.*, Vol. 9, pp. 840-858, 1996.

[2] F. Naderi, M.H. Freilich, and D.G. Long, "Spaceborne Radar Measurement of Wind Velocity Over the Ocean--An Overview of the NSCAT Scatterometer System," *Proc. IEEE*, pp. 850-866, Vol. 79, No. 6, June 1991.

[3] D.W. Draper and D.G. Long, "Simultaneous Wind and Rain Retrieval Using SeaWinds Data," *IEEE Trans. Geosci. Remote Sens.,* Vol. 42, No. 7, pp. 1411-1423, 2004.

[4] C. Nie and D.G. Long, "A C-band Wind/Rain Backscatter Model," *IEEE Trans. Geosci. Remote Sens.,* Vol. 45, No. 3, pp. 621-631, 2007.

[5] C. Nie and D.G. Long, "A C-band Scatterometer Simultaneous Wind/Rain Retrieval Method," *IEEE Trans. Geosci. Remote Sens.*,Vol. 46, No. 11, pp. 3618-3632, 2008.

[6] D.G. Long, "Ultra High Resolution Rain Retrieval from QuikSCAT Data," *Proc. IGARSS*, pp. 4113-4116, 2006.

[7] D.G. Long, "High Resolution Wind Retrieval from SeaWinds," Proc. IGARSS, pp. 751-753 , 2002.

[8] B.A. Williams and D.G. Long, "Estimation of Hurricane Winds from SeaWinds at Ultra High Resolution," *IEEE Trans. Geosci. Remote Sens*., Vol. 46, No. 10, pp. 2924-2935, 2008.

[9] D.G. Long, M.W. Spencer, and E.G. Njoku, "Spatial Resolution and Processing Tradeoffs for HYDROS: Application of Reconstruction and Resolution Enhancement Techniques," *IEEE Trans. Geosci. Remote Sens*, Vol. 43, No. 1, pp. 3-12, 2005.