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Lorenzo Bruzzone
Jon Atli Benediktsson
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Remote sensing at the NASA Kennedy Space Center and the Eastern Range: a perspective from the ground up

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ABSTRACT

This paper provides an overview of ground based operational remote sensing activities that enable a broad range of missions at the Eastern Range (ER), which includes the National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC) and U.S. Air Force Cape Canaveral Air Force Station (CCAFS).

Many types of sensors are in use by KSC and across the ER. We examine remote sensors for winds, lightning and electric fields, precipitation and storm hazards. These sensors provide data that are used in real-time to evaluate launch commit criteria during space launches, major ground processing operations in preparation for space launches, issuing weather warnings/watches/advisories to protect over 25,000 people and facilities worth over $20 billion, and routine weather forecasts. The data from these sensors are archived to focus NASA launch vehicle design studies, to develop forecast techniques, and for incident investigation. The wind sensors include the 50-MHz and 915-MHz Doppler Radar Wind Profilers (DRWP) and the Doppler capability of the weather surveillance radars. The atmospheric electricity sensors include lightning aloft detectors, cloud-to-ground lightning detectors, and surface electric field mills. The precipitation and storm hazards sensors include weather surveillance radars.

Next, we discuss a new type of remote sensor that may lead to better tracking of near-Earth asteroids versus current capabilities. The Ka Band Objects Observation and Monitoring (KaBOOM) is a phased array of three 12 meter (m) antennas being built as a technology demonstration for a future radar system that could be used to track deep-space objects such as asteroids. Transmissions in the Ka band allow for wider bandwidth than at lower frequencies, but the signals are also far more susceptible to de-correlation from turbulence in the troposphere, as well as attenuation due to water vapor, which is plentiful in the Central Florida atmosphere. If successful, KaBOOM will have served as the pathfinder for a larger and more capable instrument that will enable tracking 15 m asteroids up to 72 million kilometers (km) away, about half the distance to the Sun and five times further than we can track today.

Finally, we explore the use of Site Test Interferometers (STI) as atmospheric sensors. The STI antennas continually observe signals emitted by geostationary satellites and produce measurements of the phase difference between the received signals. STIs are usually located near existing or candidate antenna array sites to statistically characterize atmospheric phase delay fluctuation effects for the site. An STI measures the fluctuations in the difference of atmospheric delay from an extraterrestrial source to two or more points on the Earth. There is a three-element STI located at the KaBOOM site at KSC.

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Keywords: Remote sensing, Eastern Range (ER), Kennedy Space Center (KSC), Cape Canaveral Air Force Station (CCAFS) weather, radar, lightning sensors, Doppler Radar Wind Profilers (DRWPs), antenna arrays, atmospheric fluctuations, coherent uplink, phased arrays, adaptive optics, site test interferometers (STIs)

1. INTRODUCTION

Remote sensing has become a common term in atmospheric and environmental discussions. The vast majority of the references deal with data produced by space based or "satellite remote sensing" instruments. There is however a broad range of remote sensing applications that are ground based. A number of these applications are currently in use at the Eastern Range (ER, Appendix A contains an acronym list) which includes Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) in Florida (FL) to support a broad range of National Aeronautics and Space Administration (NASA), United States Air Force (USAF) and commercial space launch missions. This paper describes the vital role that ground based remote sensing plays in launch operations, personnel safety, resource protection, and historical databases for mission planning and forecast improvement; in deep space investigations; and in research to measure the effects of turbulence in the atmosphere on space communication, navigation and radar signals.

2. WEATHER AND LAUNCH OPERATIONS

Comprehensive weather services to the United States of America's space program at the ER is provided by the USAF's 45th Weather Squadron (45WS)[1]. To provide these services, the ER and 45WS use extensive networks of ground-based instrumentation to ensure successful launch operations and to aid in vehicle design. These networks comprise the most unique and dense suite of weather sensors found in operational meteorology today. Lightning detection systems, specifically the Launch Pad Lightning Warning System (LPLWS), the Four Dimensional Lightning Surveillance System (4DLSS), and the National Lightning Detection Network (NLDN), are used to detect lightning and assess the Lightning Launch Commit Criteria (LCC). The C-Band Weather Radar assists in applications that include high precision lightning forecasting, evaluating lightning LCC, stringent convective wind prediction, severe weather warnings, hail detection, heavy rain advisories, and warning of local tropical system threats. The Doppler Radar Wind Profiler (DRWP) system provides wind profiles used to evaluate loads on both day-of-launch and during vehicle design assessments.

Weather is the leading cause for launch scrubs and delays and has a large impact on many aspects of space launch activities. These include active launch operations, ground processing operations in preparation for launch, post-launch operations, various special missions, routine 24/7 weather watch and warning responsibilities for personnel safety, resource protection and mission planning. During launch countdowns, the 45WS forecasts and evaluates the Lightning LCC, Range LCC, and User LCC[2]. [2] The Lightning LCC are a set of complex rules used to avoid natural and rocket triggered lightning[3,4,5]. The Range LCC include boundary layer profiles of wind, temperature and moisture that are primarily used for predicting transport and dispersion of atmospheric constituents. This is especially important in the event of an explosion or other major malfunction where toxic chemicals are released into the atmosphere. Many atmospheric phenomena generate and/or store electrical charge that is insufficient to cause natural lightning. However, when a large rocket flies near those areas of electric charge, the long conductive exhaust plume and length of the metal rocket can amplify the associated electric fields by a factor of over 100. If the amplified electric field exceeds the breakdown voltage of the air, a rocket triggered lightning occurs. While the lightning can damage the rocket itself, or more likely the onboard electronics, the greatest concern is the lightning may damage the flight termination system. This would stop the ability of the flight controllers from being able to destroy the rocket if it goes too far off course. The User LCC are limits for various weather categories such as near surface winds so the rocket can safely clear the launch tower, temperature for mechanical integrity of the rocket, and precipitation to avoid damaging the rocket while in-flight. Requirements also exist for upper level winds to avoid over stressing the space launch vehicle as it counter-steers through the actual winds versus the planned winds to stay on the correct trajectory and achieve the desired orbit. The User LCC varies between launch vehicle programs and different configurations of vehicles in the same program[6].

The 45WS is responsible for the weather safety of over 25,000 personnel and resource protection for over $20 billion of facilities, not including the payloads and space launch vehicles. Each year, the remote sensing capabilities at KSC facilitate the issuance of over 2,500 weather warnings, watches, and advisories. These include warnings for tornadoes, large hail, strong winds, and imminent or occurring lightning; watches for convective winds, steady state winds, developing lightning, and heavy rain; and advisories for temperature. Over 5,000 ground processing operations are

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performed annually in preparation for space launches[7]. Major ground processing operations include vehicle rollouts to the launch pads, stacking and destacking rocket segments, transporting and mounting and demounting payloads, and large crane operations. Crane lifts can be very wind sensitive, especially when lifting fueled solid rocket boosters, multi-billion dollar payloads, or multi-million dollar rocket segments. Minor operations can be as simple as performing corrosion maintenance on the launch pads. Many of these processing operations are conducted outside and must be curtailed under certain weather conditions. Some processing operations have restrictive weather limits that can result in weeks of delay[6].

The hazards of lightning, both natural and triggered, are well known and include direct and indirect effects. Direct effects include heating, pitting or melt-through of conducting materials, puncturing or splintering of nonmetallic surfaces, burning holes in the skin, the welding or fusing of hinges and bearings; damage to antennas and/or lights; and, rarely, explosions due to the ignition of fuel vapors[8]. Indirect effects include any momentary upsets or permanent damage caused by the transient voltages and currents that are induced by direct or nearby discharges[8]. For most spacecraft, the penalties in added cost and weight of hardening against these hazards are too great, so the only option is avoidance[9]. Lightning is also a significant weather safety hazard, being the third leading source of storm deaths in the United States[10].[10] Lightning advisories are issued for 10 areas, consisting of circles with a 9.26 kilometer (km, 5 nautical mile (NM)) or 11.11 km (6 NM) radii safety buffer centered on operationally significant sites: seven areas with considerable overlap on CCAFS/KSC, one with little overlap on KSC, one at Patrick Air Force Base (AFB), and one for a satellite processing facility at Titusville (Figure 1). A Phase-1 Lightning Watch is issued for one or more of these areas if lightning is expected with a desired lead-time of 30 min. A Phase-II Lightning Warning is issued when lightning is imminent or occurring in one or more of these areas. One of the greatest challenges is the ability to reliably cancel these lightning advisories more quickly to allow outdoor work to resume, while still maintaining safety[6]. As one might expect with all the thunderstorm activity, convective wind warnings are also important, with an average of over 175 warnings each year. The convective wind warnings have unusually precise requirements and large desired lead-times[6].

In addition to those items already discussed, four other aspects of launch are evaluated for weather concerns. The first launch aspect is 'LOADS', which refers to the aerodynamic loading on the rocket as it counter-steers against the upper-level winds to stay on the desired trajectory. If the actual winds differ too much from the assessed winds, the rocket could destroy itself. The LOADS community of aeronautical engineers continually analyzes the observed winds and assesses their impact to the vehicle to prevent this from happening. There is an extensive archive of vertically complete wind profiles generated by the Marshall Space Flight Center (MSFC) Natural Environments (NE) group using the DRWP network at the ER. This archive is used to mitigate the multiple shortcomings of utilizing balloon-based measurements for space vehicle loads and trajectory assessments. Launching vehicles into space requires accurately characterizing the wind environment that the vehicle will experience through ascent. Specific effects of the ascent winds on launch vehicles depend on the characteristics of the vehicle components and the magnitude of the wind acting on those components[11]. Range Safety evaluates the second, third, and fourth aspects of launch: 'Toxic Dispersion', 'BLAST', and 'Debris'[12]. Toxic dispersion from nominal and catastrophic launches is analyzed to ensure that they will not exceed allowable toxic exposure limits for the on-base and nearby civilian populations. 'BLAST' analyzes the likelihood of windows in nearby towns being broken and causing a safety hazard if a rocket explodes[13]. The 'Debris' program considers if parts of the rocket from a nominal or catastrophic launch would fall outside of the allowed impact areas[6].

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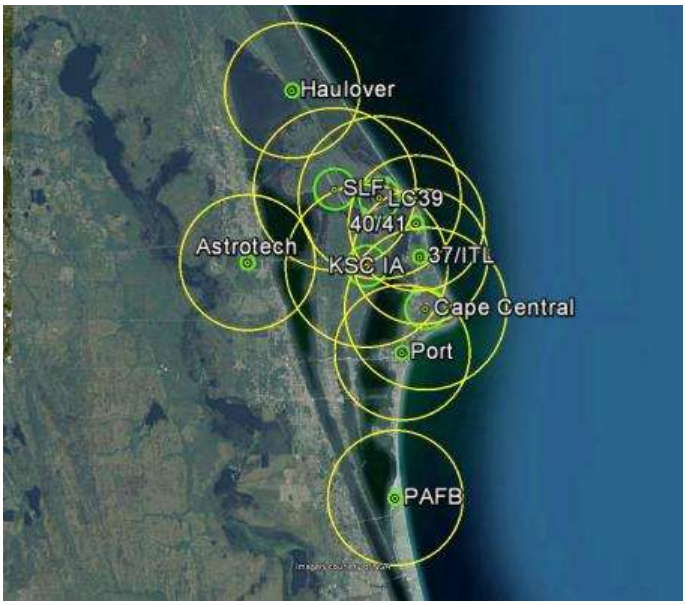

Figure 1. The 10 lightning warning circles used by 45 WS.

2.1 Eastern Range Weather Systems

The ER possesses one of the world's most dense operational networks of weather instrumentation[14]. This instrumentation is used to minimize the impact of weather while ensuring the safe processing and launching of space vehicles. Some, but not all, of these weather instruments use remote sensing. For example, the ER uses a network of 28 weather towers that measures wind, temperature, and moisture in the first few hundred feet of the atmosphere. However, this paper will focus only on the ER weather instruments that use ground-based remote sensing. These include lightning detection systems, the DRWPs, and the weather radar. The ground-based remote sensing weather sensors and the data they provide are listed in Table 1.

Table 1. Ground-based remote sensing weather sensors at the Eastern Range

Sensor	Data Provided	Main Operational Applications
Four Dimensional Lightning Surveillance System (4DLSS)	• Cloud-to-Ground Lightning - return strokes (not flashes) - latitude, longitude - date, time - peak current, polarity • Lightning aloft - step leaders - latitude, longitude, height - date, time	• Assess risk of induced current damage, Lightning warnings (approaching storms), Evaluate Lightning LCC • Lightning warnings Evaluate Lightning LCC
Launch Pad Lightning Warning System (LPLWS)	• Surface electric field	• Evaluate Lightning LCC
Weather Radar	• Reflectivity • Doppler velocity • Spectral width • Differential reflectivity	• Lightning prediction, Lightning LCC evaluation, severe weather warnings, precipitation detection, general weather support • Severe weather warnings • None • Possibly lightning onset and hydrometeor identification for lightning cessation, hail

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Sensor	Data Provided	Main Operational Applications
	• Phase differential • Correlation coefficient	warnings, tornado detection, etc. • Possibly hydrometeor identification for lightning cessation, hail, tornado, etc. • Possibly hydrometeor identification for lightning cessation, hail, tornado, etc.
50-MHz Doppler Radar Wind Profiler (50DRWP)	• Vertical wind profiles - wind speed/direction vs. height (base-top)	• Evaluate LOADS
915-MHz Doppler Radar Wind Profiler (915DRWP)	• Vertical wind profiles - wind speed/direction vs. height (base-top)	• Evaluate toxic dispersion, BLAST, and Debris

2.2 Lightning Detection Systems

The ER is well instrumented with respect to lightning detection sensors. These sensors exist not only because lightning can adversely affect the vehicle and corresponding operations, but also because central Florida is the area of highest lightning activity in the United States (U.S.)[15] The ER utilizes the Launch Pad Lightning Warning System (LPLWS), the Four Dimensional Lightning Surveillance System (4DLSS), and the National Lightning Detection Network (NLDN) to detect lightning.

The LPLWS consists of a network of 31 field mills distributed in and around the launch and operations areas of CCAFS and KSC. The location of the 31 mills is shown in Figure 2 and picture of one of the field mills is shown in Figure 3 The network measures the electric field at the surface, which is used to infer electric fields aloft - a key to evaluating the danger of triggered lightning during launch operations[14]. In the Lightning LCC, field mills can be used to either avoid launch under hazardous conditions, or to allow safe launch that otherwise would have been falsely identified as hazardous. The one-minute average of the electric field mill network may not exceed -1 or +1 kilovolts per meter (kV/m) within 9.26 km (5 NM) of the launch pad or the lightning flash at any time within 15 minutes prior to launch. This field mill criteria becomes -1.5 or +1.5 kV/m if there are no clouds within 18.52 km (10 NM) of the flight path except those that are transparent[3,4,5].

The 4DLSS detects both cloud-to-ground return strokes and lightning aloft[16,17].[16] The 4DLSS was a major upgrade to the previous Lightning Detection and Ranging (LDAR) system that detected lightning aloft and the Cloud to Ground Lightning Surveillance System (CGLSS)[16,17]. The cloud-to-ground lightning part of the network consists of a network of six low frequency (LF) magnetic direction-finding and time-of-arrival (IMPACT) sensors located in and around the launch and operations areas of CCAFS and KSC (Figure 4). A picture of one of these sensors is shown in Figure 5. They are deployed on relatively short baselines and operate at low gain to ensure the requirements for high location accuracy and detection efficiency of cloud-to-ground strikes are satisfied[14]. This part of 4DLSS provides the latitude, longitude, time, peak current, and polarity for each return stroke within a lightning flash. The lightning aloft part of 4DLSS consists of a network of nine receiver sites which detect inter-cloud, intra-cloud and cloud-to-ground lightning. Lightning aloft is geolocated using VHF time-of-arrival between multiple pairs of sensors[14]. The locations of the sensors is shown in Figure 6 with an example of one of the sensors is at Figure 7. The time-of-arrival differences between multiple pairs of sensors is used to locate the three dimensional (3-D) structure of the lightning. The 4DLSS is being replaced with a new system to overcome sustainment problems of the old sensors and take advantage of improvements in lightning detection technology. The new system is the Mesoscale Eastern Range Lightning Network (MERLiN).

The 45WS also has a direct link to the NLDN, which is a network of about 130 cloud-to-ground sensors across the contiguous U.S[18]. The NLDN is also has a relatively new low detection efficiency capability for detecting lightning aloft. This NLDN link is used as a back-up to the cloud-to-ground portion of 4DLSS, for cloud-to-ground lightning detection capability for occasional missions beyond the range of 4DLSS, and as supplemental quality control of 4DLSS cloud-to-ground lightning.

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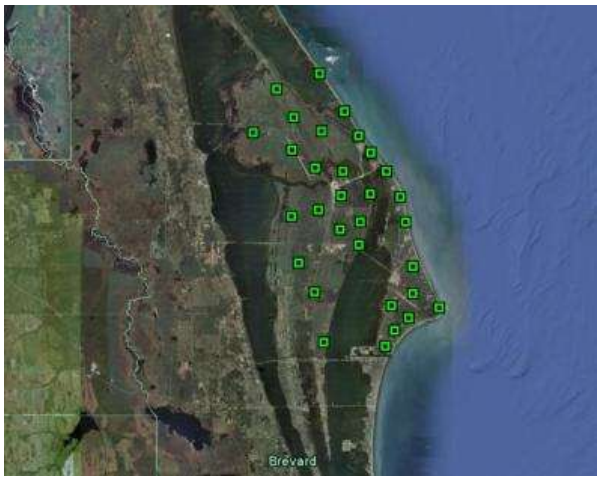

Figure 2. Field mill sensor locations.

Figure 3. A field mill sensor.

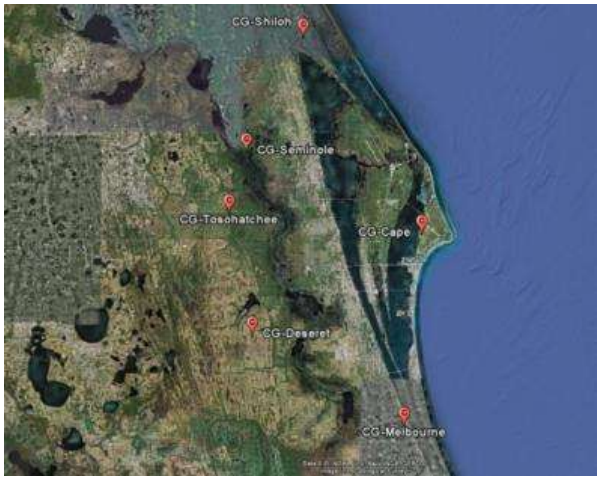

Figure 4. CGLSS sensor locations**.**

Figure 5. A CGLSS sensor.

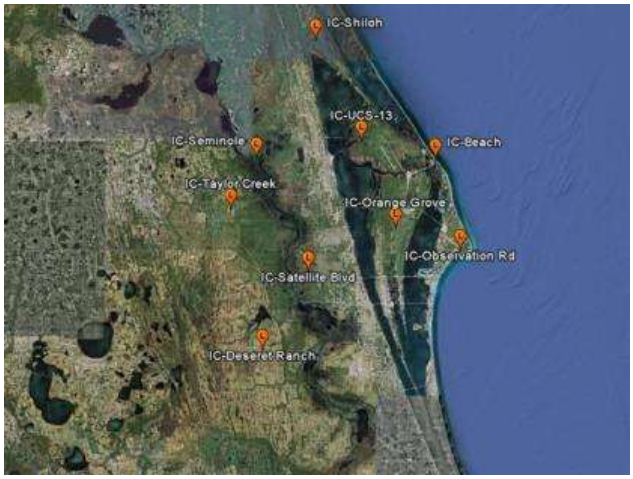

Figure 6. An LDAR-II sensor.

Figure 7. LDAR-II sensor locations.

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2.3 Weather Radar

One of the most important weather sensors is the C-band (5 cm) Radtec Titan Doppler Radar with 4.3 m diameter antenna and 250 kW average transmitted power (TDR 43-250) manufactured by Radtec Engineering, Inc[19]. The space program on the ER makes use of several atypical applications of weather radar[20]. These applications include high precision lightning forecasting, evaluating lightning LCC, stringent convective wind prediction, severe weather warnings, hail detection, heavy rain advisories, and warning of local tropical system threats[20]. The location of the 45WS radar and a picture of the radar are shown in Figure 8 and

Figure 9, respectively.

The TDR 43-250 radar is a dual polarization Doppler weather surveillance radar that detects reflectivity, Doppler velocity, spectral width, differential reflectivity, phase differential, and correlation coefficient. Reflectivity indicates the intensity of precipitation, and the shape and motion of thunderstorms that can imply the type and intensity of hazard they may produce. Reflectivity is especially useful in forecasting the onset of lightning in locally developing thunderstorms[21,22] and in evaluating Lightning LCC. Doppler velocity can detect storm rotation that can indicate severe weather, especially tornadoes. Differential reflectivity, phase differential, and correlation are new dual polarization capabilities that should have many new capabilities including lightning formation[21,22], lightning cessation, hail detection, tornado detection[23], and eventually Lightning LCC evaluation.

The 45WS also has a direct feed from the Weather Surveillance Radar – 1988 Doppler (WSR-88D radar) at Melbourne, FL. This radar is part of the Next Generation Weather Radar (NEXRAD) network shared by the Department of Defense (DoD), National Weather Service (NWS), and the Federal Aviation Administration (FAA). This radar is an S-band (10 cm) dual polarization Doppler weather surveillance radar. This radar serves as a back-up to the Radtec radar and provides dual wavelength capability in combination with the 45WS radar.

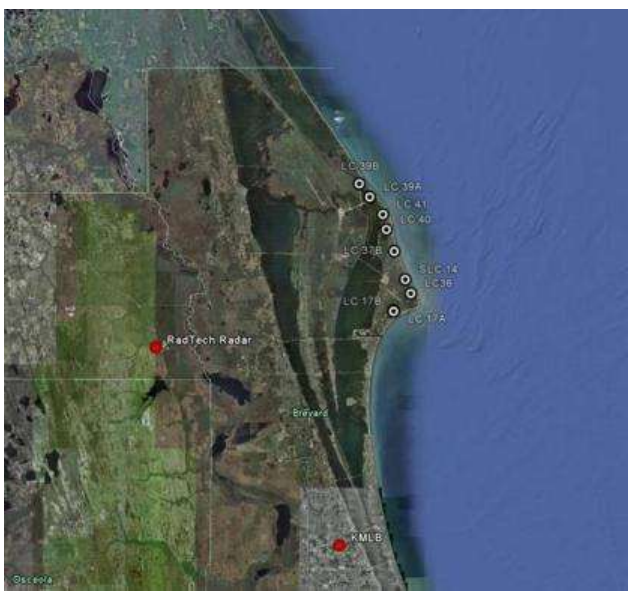

Figure 8. Locations of radars used by 45WS.

Figure 9. 45WS C-band weather radar.

2.4 Doppler Radar Wind Profilers

A Doppler Radar Wind Profiler (DRWP) is a radar system designed to detect the Doppler shift of clear-air turbulence in order to measure vertical profiles of wind. DRWPs work by transmitting radio pulses along two or more beams and using the Doppler shift of the returned signals from the two vectors to calculate the wind vector, and use different frequencies and different transmission powers depending on maximum height of wind required. DRWP systems are remote sensors and the maximum height probed varies with atmospheric conditions and especially latitude[24]. The MSFC NE group generates an extensive archive of vertically complete wind profiles using the DRWP network at the ER to

mitigate the shortcomings of utilizing balloon-based measurements for space vehicle loads and trajectory assessments. Launching vehicles into space requires accurately characterizing the wind environment the vehicle will experience during ascent. Specific effects of the ascent winds on launch vehicles depend on the characteristics of the vehicle components and the magnitude of the wind acting on those components[12]. The shortfall of balloon measurements of winds are long sensing time (over 1.5 hours to measure winds from surface to ~30,000 m), downwind drift of the balloon (up to 280 km downwind or more at ~30,000 m), and pendulum motion of the sensor at the end of the 30 m string attached to the balloon.

2.4.1 50-MHz DRWP

Every launch passes through the atmosphere. Winds below altitudes of 18 - 20 km (60 - 65 kft) are a major concern for safety and mission assurance, guidance and steering, and aerodynamic loads. The 50-MHz DRWP is located just east of the Shuttle Landing Facility at KSC (Figure 10). The former 50-MHz DRWP consisted of an irregular octagon-shaped antenna field, which spanned 15,600 square meters (m) and consisted of coaxial-collinear elements set 1.5 m above the ground plane made of copper wire. These elements sent electronic pulses at 49.25 MHz through three beams. One beam pointed vertically, and two oblique beams pointed 15° off zenith at azimuths of 45° and 135° East from due North (Figure 11). To measure wind velocities, the 50-MHz DRWP sent radio pulses in the three beam directions sequentially and measured the return signals that were reflected by temperature and humidity fluctuations in the atmosphere. Bragg Scattering designates this process, where changes in temperature and humidity with length scales of about half of the DRWP's wavelength, (~3 m for the 50-MHz DRWP), produce the return signal. A Fast Fourier Transform converted the signal in the time-domain to the frequency domain (Doppler power spectra) over 256 frequency bins at each range gate. There were 111 range gates from 2,666-18,616 m every 145 m and profiles were generated every three minutes[12].

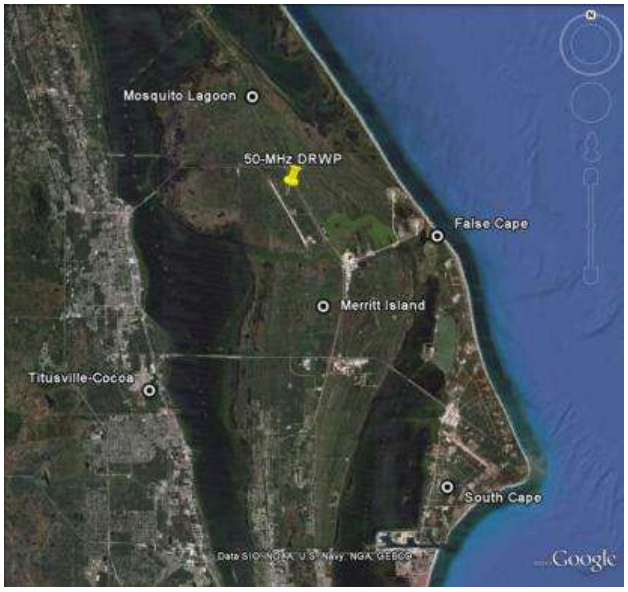

Figure 10. 50-MHz DRWP location at the ER.

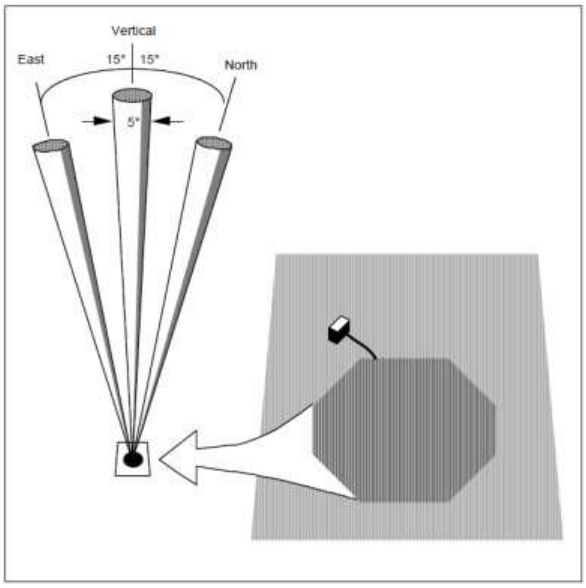

Figure 11. A schematic of the DRWP's beam configuration[12].

Currently this system is being replaced by a new 50-MHz DRWP manufactured by DeTect, Inc. The antenna of the new system will have a full beam steering (FBS) capability. (NASA will use specific pointing directions, however.) It is of a scalable design and is primarily soft-fail. The new antenna is comprised of 640 Yagi elements arranged in a thinned pattern. Each Yagi element transmits at the same power level and the antenna amplitude taper minimizes sidelobes.

This new 50-MHz DRWP, which is based on the NOAA National Profiler Network[24] contains a solid state 250 kW transmitter, solid state programmable phase switching, and permits additional operating modes such as 4-beam and Velocity Azimuth Display (VAD) modes without modification.

2.4.2 915-MHz Boundary Layer DRWP Network

A network of five 915-MHz DRWPs is arranged in a diamond-shaped pattern around the periphery of the ER (Figure 12). The 915-MHz DRWP is smaller than the 50-MHz DRWP due to its antenna structure, and thus one can use more of them in a given region. Figure 13 shows a picture of one of the 915-MHz DRWPs in the region. The network's configuration allows for each 915-MHz DRWP to potentially sample a different atmospheric boundary layer regime, especially in a dynamic environment[12]. This network was installed to fill the gap from the top of the wind towers to the lowest gate of the 50-MHz DRWP. Vertical profiles are generated from 120-5,000 m every 100 m and profiles are generated every fourteen minutes. The system's primary mission objectives are: (1) to collect wind profiles for use by the Launch Weather Officer to monitor rapidly changing weather conditions, help ensure that launch constraints are satisfied, and to provide Range Users with timely guidance during the countdown and launch pad operations; (2) to monitor rapidly changing weather conditions that could affect ground and launch operations by Range Safety and as an input to the Range Safety models used to predict the transport and diffusion of airborne contaminants released from ground level spills; and (3) to provide forecasters with a continuous description of the intermediate levels of the atmosphere for routine weather forecasting and the early detection of hazardous conditions[25].

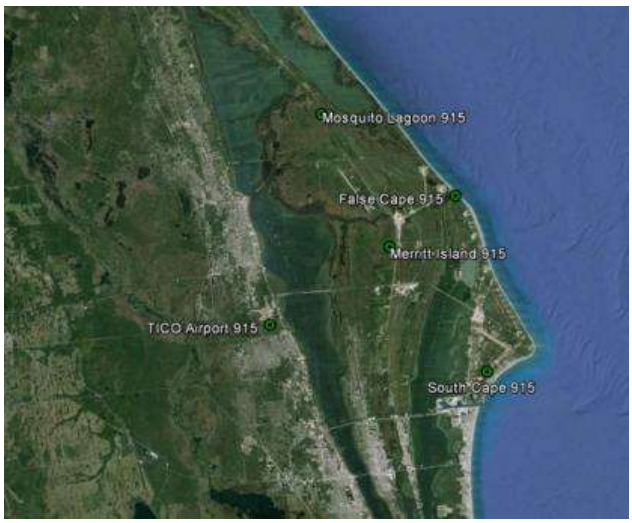

Figure 12. 915-MHz DRWP locations at the ER.

Figure 13. A 915-MHz DRWP at the ER.

3. KA BAND OBJECT OBSERVATION AND MONITORING

3.1 KaBOOM

The weather sensing technologies for processing and launching rockets will be of little use if a piece of orbital debris destroys a spacecraft in orbit or if a potentially hazardous asteroid or comet is on a collision course with the Earth. Therefore, NASA has embarked on a path to implement a high power, high resolution radar system to better track and characterize near-Earth objects (NEOs) and orbital debris. KaBOOM is a phased array of three 12 meter (m) diameter antennas at KSC. NASA is exploring the use of small diameter antennas as a phased radar array that is both scalable and extensible to achieve high power, high resolution, high reliability, simultaneous multiple direction operations, low life cycle cost, and elimination of power density restrictions. Applying this technique of coherent uplink arraying would produce a more reliable, available, scalable, extensible radar with a lower life cycle cost[26].

3.2 Potentially Hazardous Asteroids (PHA's)

If an object is verified to be on an Earth colliding trajectory, it seems likely that this collision possibility will be known several years prior to the actual event[27]. With this lead time, existing technology could be used to mitigate the threat to the Earth. In the short term, the probability of an Earth impact is low, however, over longer periods of time, the probability of Earth impact is not negligible. One can view the probability of potential Earth impact events based on

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currently available observations in the Jet Propulsion Laboratory (JPL) Near-Earth Object (NEO) Program Sentry Risk Table at http://neo.jpl.nasa.gov/risk/.

Potentially Hazardous Asteroids (PHAs) are defined based on the asteroid's potential to make threatening close approaches to the Earth. Specifically, all asteroids with an Earth Minimum Orbit Intersection Distance (MOID) of 0.05 AU (4,650,000 miles) or less, and asteroids smaller than about 150 m (500 ft) in diameter are not considered PHAs. There are currently 1487 known PHAs[27].

This "potential" to make close Earth approaches does not mean a PHA will impact the Earth. It only means there is a possibility for such a threat. By monitoring these PHAs using phased array antennas such as those being demonstrated by KaBOOM, and updating their orbits, we will be able to better predict the close-approach statistics and their Earth-impact threat[27].

Besides 24/7 availability for planetary protection (NEO tracking and characterization), NASA has several other uses for uplink arraying: improved detection and tracking of small (≤ 1 - 10 cm) orbital debris particles; rapidly available high power emergency uplink capability for spacecraft emergencies; radio science experiments (tomography of planetary atmospheres, general relativity tests, mass determinations, occultations, surface scattering, etc.); and beam sailing propulsion capability[26].

3.3 The Demonstration Project

The KaBOOM demonstration consists of a phased array of three 12 m diameter antennas, shown in Figure 14 below. It is intended to extend prior experiments to higher frequencies, and will eventually operate near 30 GHz. Its main features are the ability (a) to produce phase-aligned signals at a distant target without external calibration, and (b) to use a downlink signal (if one is simultaneously present) to measure the effects of tropospheric turbulence along the signal paths and apply real-time corrections to the uplink signal. The effects of tropospheric turbulence increase in proportion to signal frequency, as do the effects of errors in the instrumentation[28,29], making the KaBOOM demonstration particularly challenging.

In 2008, uplink arraying demonstrations were carried out by two different groups at JPL, one using two and three of the Goldstone Deep Space Network (DSN) site's 34 m at 7.2 GHz[30] and another using five 1.2 m antennas at 14 GHz[31]. Both demonstrations were successful. The systems were stable and the expected change in power at the target with number of active antennas was observed. (For identical antennas and transmitters, the received power for an N-antenna array is N^2 times that of one antenna.) There was no correction for atmospheric turbulence in either case.

In 2010, NASA funded an uplink array demonstration at 8 GHz using three 12 m antennas in Melbourne, FL. That experiment seemed to show that phase-aligned signals at the target can be achieved without external calibration by using internal phase-transfer electronics and correcting for measured mechanical differences among the antennas[29,32]. Furthermore, it was demonstrated that real-time compensation for tropospheric turbulence may be possible when there is a strong reference source in the antenna beams, such as a beacon on the target satellite. The atmosphere compensation was demonstrated not only in clear, relatively dry air, but also during Tropical Depression 16/Tropical Storm Nicole (Figure 15)[32]. The present KaBOOM demonstration is using the very same 12 m antennas and some of the electronics that were used in the Melbourne experiment, although completely new electronics and more precise mechanical measurements will be needed at 30 GHz.

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Figure 14. KaBOOM antennas at KSC.

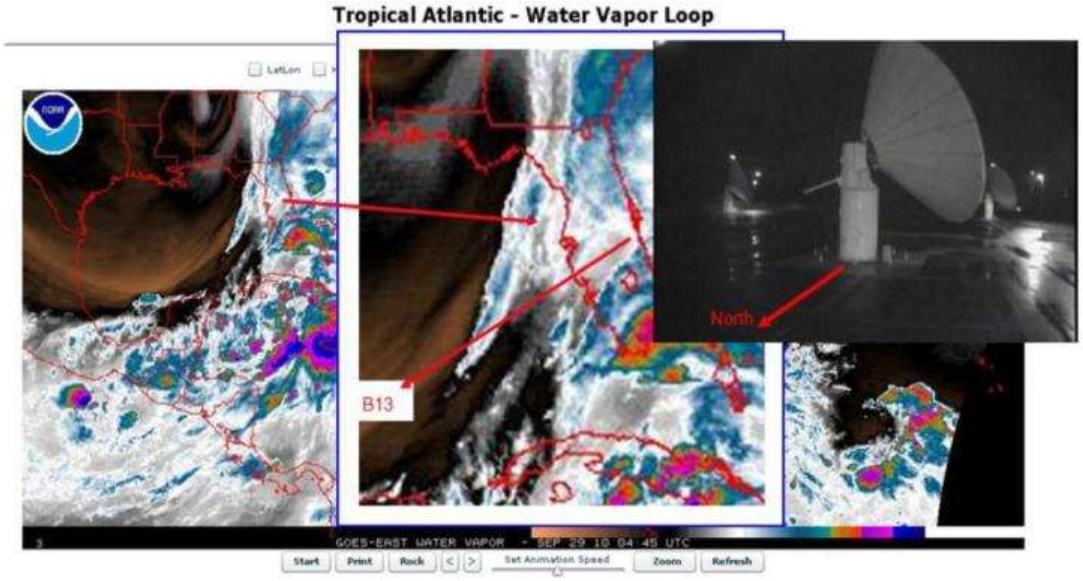

Figure 15. Tropical Atlantic water vapor loop showing environmental conditions during testing of the real-time atmospheric fluctuation compensation test in September 2010. Tropical Depression 16, September 29, 2010, 04:45 UTC. Light rain and substantial irregular water vapor content along pathway.

4. SITE TEST INTERFEROMETERS

4.1 Transition to Higher Frequencies

As NASA progresses into the 21st century, its communications network systems (e.g., Deep Space and Near Earth Networks) are expected to transition frequencies above 30 GHz. These systems will be required to provide services with a system availability of higher than 99% (versus the current 90% availability) and gigabit data rates (versus current ~ megabit data rates). However, the atmospheric phase stability (time delay fluctuations) and attenuation of a particular site must be well characterized.

A Site Test Interferometer (STI) measures the difference in signal delay from a celestial source (typically a geostationary satellite) to two or more points on the Earth. Variations in that delay difference are primarily due to turbulence in the troposphere, which creates a difference in the mean refractive indices along the paths[33].

An STI constructed by the JPL and based on a design provided by the Harvard Smithsonian Center for Astrophysics (CfA) has been installed at KSC. Nearly identical instruments have been deployed by JPL at five additional sites around the world, and other STIs have been in operation at radio observatories for many years. The KSC STI uses three small (0.8 m) antennas in a triangular configuration with spacings of 135 to 289 m to receive and process signals from a commercial geostationary satellite (NIMIQ 5, azimuth 163.8° and elevation 55.6°). The observed turbulence varies with weather and season, but its effect over ~200 m distance scales is not measurable by ordinary meteorological instruments, hence the need for a specialized instrument. While the STI is designed to provide a long-term statistical characterization of the site, it will also help KaBOOM to determine how much its signals are being disrupted by the atmosphere in near-real-time, and thus provide a measure of how well KaBOOM's atmosphere compensation process is working[34].

4.2 Operational Sites

Two STIs have been operating at the NASA DSN site in Goldstone, California for several years[33]. These instruments have two and three antennas, respectively, with element separations of ~200 m. Three-element STIs have also been installed at the Canberra and Madrid DSN sites. The antennas continuously observe signals emitted by geostationary satellites, and the phase difference of the received signals is measured. During post-processing, long period trends due to satellite motion and instrumental drift are removed. Fluctuations in the resulting phase delay residuals are dominated by the troposphere on timescales ranging from <<1 s to several hundred seconds[33].

Although an STI and a nearby communication array or radio telescope are expected to see the same short- and long term statistical delay fluctuations, the instantaneous delay measured by the STI is generally not useful for correcting delay errors in the array because their targets are in different directions and their signals pass through different parts of the turbulent distribution. However, the statistics acquired over long periods are useful for characterizing the site.

The statistics vary among sites due to climate and altitude and at any one site diurnally, seasonally, and with passage of weather systems. The long-term statistics can be used to determine the suitability of a site for hosting an array, or they can be used in communication link budgets of current or proposed missions using an array at the site. Short-term (intraday) statistics can be used to assist in scheduling communication links so that the best conditions are used for links with small margins, and conversely[33].

We intend to operate the STI several years in order to obtain sufficient data for reliable statistical characterization of our KaBOOM site. The KaBOOM/STI location is shown in Figure 16 and a picture of one of the STI elements is shown in Figure 17. Figure 18 displays the zenith delay root mean square (RMS) for all three KSC STI baselines for the month of September 2013. One can clearly see a diurnal variation, where the delay RMS peaks within a few hours of local noon. Figure 19 displays the cumulative distribution of the delay RMS for several months since the instrument started operations in August 2013. One can clearly see a seasonal trend where the zenith delay RMS is higher during summer than during the winter for a given CD value.

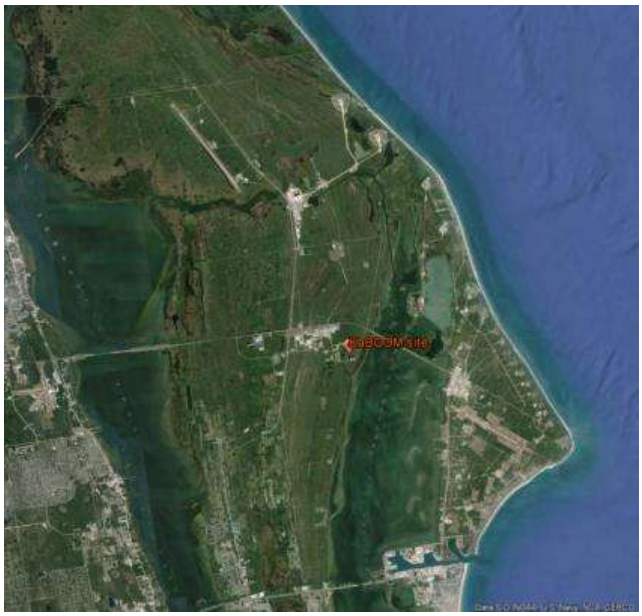

Figure 16. Location of the KaBOOM antennas and STI instrument at KSC.

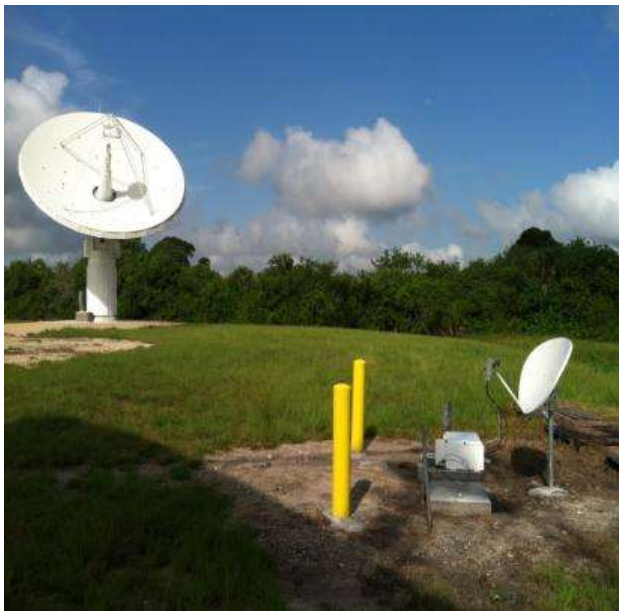

Figure 17. Foreground: one of three small antennas that make up the STI instrument. Background: one of the larger antennas of the KaBOOM demonstration.

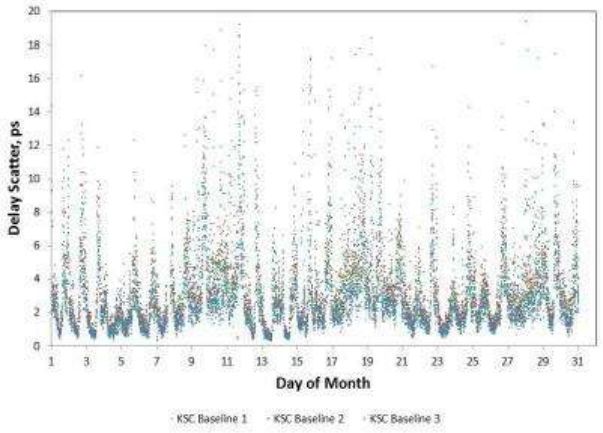

Figure 18. Delay RMS in 600-s blocks referenced to zenith for the KSC STI (all three baselines).

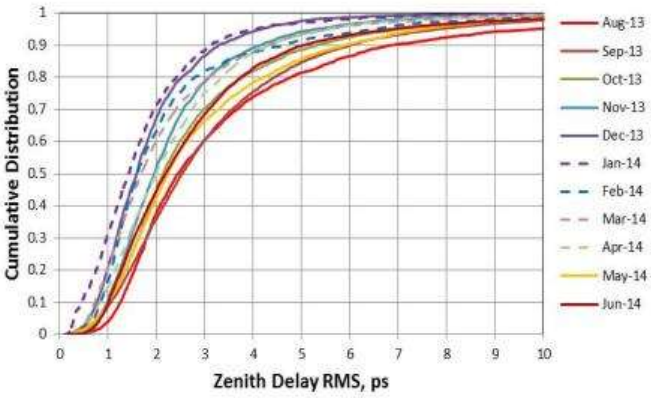

Figure 19. Monthly cumulative distribution curves of zenith delay RMS for the KSC STI (warmer months shown in reddish curves, winter months in bluish/purplish curves.

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5. CONCLUSION

Remote sensing in meteorology is normally thought of as being done from satellites. However, ground-based remote sensing is also important in operational meteorology. As is described, ground-based remote sensing is critical to the success of America's space program at NASA's Kennedy Space Center and Cape Canaveral Air Force Station in Florida. In addition, the Ka Band Object Observation and Monitoring project, which is a unique application of remote sensing being developed to improve capability for tracking space debris and near Earth asteroids will become more important as future satellites are deployed and greater use is made of Low Earth Orbit (LEO). Site Test Interferometers, which will allow for scheduling observations to minimize atmospheric degradation on the project's operations is an example of the emerging ground based technology that will support and enhance future remote sensing capabilities.

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APPENDIX A – LIST OF ACRONYMS

3-D	three dimensional
45WS	45th Weather Squadron
4DLSS	Four Dimensional Lightning Surveillance System
AFB	Air Force Base
CCAFS	Cape Canaveral Air Force Station
CfA	Center for Astrophysics
CGLSS	Cloud-to-Ground Lightning Surveillance System
cm	centimeter
DoD	Department of Defense
DRWP	Doppler Radar Wind Profiler
DSN	Deep Space Network
ER	Eastern Range
FAA	Federal Aviation Administration
GHz	gigahertz
HQ	Headquarters
IF	intermediate frequency
JPL	Jet Propulsion Laboratory
KaBOOM	Ka band Objects Observation and Monitoring
kft	kilofeet
km	kilometer
KSC	Kennedy Space Center
kV/m	kilovolts per meter
kW	kilowatt
LEO	Low Earth Orbit
LCC	Launch Commit Criteria
LDAR	Lightning Detection and Ranging
LO	local oscillator
LPLWS	Launch Pad Lightning Warning System
m	meter
MERLiN	Mesoscale Eastern Range Lightning Network
MHz	megahertz
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NE	Natural Environments
NEO	Near-Earth Object
NEXRAD	Next Generation Weather Radar
NLDN	National Lightning Detection Network
NM	nautical mile
NWS	National Weather Service
ps	picosecond
RMS	root mean square
s	second
STI	Site Test Interferometer
U.S.	United States
USAF	United States Air Force
VAD	Velocity Azimuth Display
VHF	very high frequency
WSR-88D	Weather Surveillance Radar 1988 Doppler