FASTER RECOVERY, BETTER SCIENCE: METEORITE FALL EVENTS DETECTED WITH WEATHER RADARS AND SEISMOMETERS IN 2012. M.Fries,[1,2], R. Matson[1,3], J. Schaefer[1], J. Fries[1,4], M. Hankey[5]. [1] Galactic Analytics LLC, San Diego, CA 92116, [2]Planetary Science Institute, Tucson, AZ. [3]SAIC, Seal Beach, CA 90740. [4]USAF Weather Agency, 1st Weather Group, Offutt AFB, NE 68113. [5]American Meteor Society, Geneseo, NY 14454. Email: fries@psi.edu

Introduction: Analysis of meteor events that includes the use of weather radar and seismometry data has assisted in the recovery of four meteorite events in the U.S. in 2012. Two meteorite falls were detected using weather radar imagery in 2012: Sutter's Mill, CA, Battle Mountain, NV, and two events which at the time of this writing do not have names approved by the Nomenclature Committee. One of these events occurred north of San Francisco, CA, and the other in the Bankhead National Forest in Alabama. A fifth event in Texas appears briefly on radar but at the time of this writing no meteorites have been recovered there. Data are presented here that feature Doppler weather radar imagery from the U.S. NEXRAD and TDWR radars operated by the National Oceanic and Atmospheric Administration (NOAA).

Sutter's Mill, CA (22 Apr 2012 1451 UTC): *The rapid, radar-directed recovery of this meteorite yielded meteorites of unique scientific value.* This event was reported by eyewitnesses across three states and is described in considerable detail elsewhere [1]. Weather radar data features the signatures of falling meteorites in seven separate radar sweeps from the KDAX, KBBX, and KRGX radars. First appearance occurs at 14:51:57 UTC and a radar pulse centroid altitude of 17,140 m above sea level (ASL). The last appearance was at 14:58:40 UTC and an altitude of 6,520 m ASL. The fireball was recorded occurring at 14:52:12 by a privately-owned security camera near Lake Tahoe, and by the nearest seismometer at 14:51:47 UTC. Total duration of the meteorite fall, from first recorded appearance in the security camera footage to the last radar appearance, was 7 minutes 28 seconds, falling from a fireball termination altitude of 47.6±0.7 km ASL. Radar data was provided to the finders of the first two Sutter's Mill meteorites, both of whom drove to the fall site. Both individuals (Mr. Robert Ward and Dr. Petrus Jenniskens) then independently found meteorites around the parking lot where they stopped. Three Sutter's Mill meteorites were found before rains soaked the strewn field. Investigation of these pre-rain meteorites revealed the first reported detection of oldhamite (CaS) [2] in CM-type meteorites; a reactive mineral phase which is rapidly lost to ambient moisture. Rapid collection also allowed relatively low-terrestrial-contamination measurement of amino acids [1].

Battle Mountain, NV (22 Aug 2012 0619 UTC): *According to meteorite hunters who attended this meteorite recovery, this meteorite fall would not have been recovered in the absence of weather radar analysis.* The event occurred over a relatively sparsely-populated portion of the US. As a result, no video footage has been found of the fireball to date, and very few eyewitnesses came forward. Both seismometer and weather radar coverage is relatively sparse as well, but the event occurred within 40 km of one of each. Eyewitnesses include a drill rig crew collecting drill cores at the time. The crew observed the fireball passing overhead and fragmenting extensively. The crew were working under floodlights at the time, and report that the fireball was so bright that they couldn't tell the floodlights were lit. Sonic booms swept the area immediately afterwards. As they shut the drill rig down, they heard falling objects nearby that sounded like "fly rocks" thrown during blasting. Weeks later, a ~1 kg meteorite was found where the "fly rocks" were heard to fall. Signatures of falling meteorites appear in eight radar sweeps of the KLRX radar in Elko, NV. First appearance occurred at 06:19:26 UTC at an altitude of 3,450 m ASL, and the last appeared at 06:21:03 UTC and an altitude of 9,460 m ASL. The KLRX radar was running through a series of radar sweeps at ascending elevations at the time, which is why the final meteorite detection occurs at the highest altitude. A security camera in Battle Mountain recorded the fireball flash at 06:16:45 UTC for a total elapsed time of 4 minutes 18 seconds. This relatively short time was interpreted as the signature of a mechanically robust chondrite but not an iron meteorite since it lacked a late-appearing, high-reflectivity signature of ablation spherules. Approximately 5.9 kg of unbrecciated L6 meteorites were subsequently found along a ~7 km long strewn field, but eyewitnesses suggest that larger meteorites may be found further downrange. The same drill crew reported that a large object described as "like a D-8 Cat [tractor] on fire" continued along the original fireball trajectory.

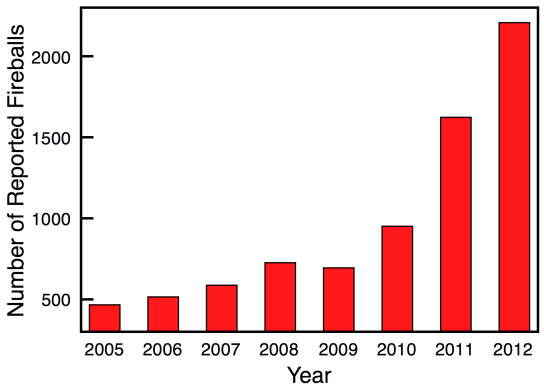
Event North of San Francisco, CA (18 Oct 2012 0245 UTC): *Radar and seismometer data assisted in the recovery of meteorites in this event.* This event generated hundreds of eyewitnesses in the San Francisco bay area as it moved inland along a southwest-to-northeast path, shedding debris along the way in a dramatic fireball. Nearby NEXRAD radars were

all in their slowest, lowest-sensitivity mode at the time, rendering it difficult to distinguish meteorite signatures from weather and other phenomena. Seismometer data proved to be very useful, with J. Schaefer generating a 3D model of the fireball path using data from over 40 seismometers. With the caveat that there is some uncertainty about which radar sweeps contain bona fide meteorite signatures, the most likely meteorite signatures appear around Novato, CA in a sequence of three radar sweeps from the KMUX radar in San Francisco. First appearance is at 02:46:49 UTC and an altitude of 6,320 m ASL. Last appearance occurs at 02:50:36 UTC and 9,880 m ASL, although additional potential signatures persist in radar sweeps to as long as 03:00:46 UTC. Potential meteorite signatures were singled out in these radar data and were used to calculate the landing sites of meteorites. Meteorite hunters report that the resulting map assisted in meteorite finds, with meteorites found within tens or hundreds of meters of the calculated fall sites. To date, six meteorites have been found of a melt-rich L-chondrite from this event, which is currently under consideration by the Nomenclature Committee.

Event in Bankhead Nat'l Forest, AL (30 Oct 2012 2236 UTC): *This event was identified, and a strewn field map generated, within 90 minutes of the event.* A southeast-to-northwest, daytime fireball was seen passing north of the Birmingham, AL area with multiple reports of sonic booms north of that city. This event occurred on a cloudless day and generated very distinct meteorite signatures in radar data from four separate radars: KOHX, KBMX, KHTX and KFFC. First appearance was at 22:36:56 UTC and 16,190 m ASL. Final appearance was at 22:43:41 UTC and 2,450 m ASL for a duration of 6 minutes and 45 seconds. The calculated strewn field for this event is almost entirely within the Bankhead National Forest in Alabama. The site was blanketed with fallen leaves at the time, making visual identification of meteorites difficult. Nonetheless, two meteorites have been reported from this locality for a total mass of less than 100 g. The intensity and persistence of radar signatures in this event indicate many more meteorites reached the ground.

Possible Event North of Houston, TX (07 Dec 2012 1243 UTC): *This event may be the detection of the smallest meteorite fall to date.* On 07 Dec, an exceptionally bright event occurred just north of Houston, TX at sunrise. The event was recorded by an all-sky meteor detection camera operated by the NASA Meteoroid Environment Office in Mayhill, NM. This site is over 1,000 km distant from the bolide. A car dashboard camera recorded the event from near Fort Worth, TX and showed that the bolide was relatively fast-moving. A potential meteorite signature appears in a single sweep of the Houston, TX KHGX radar at the time and location indicated by video and eyewitness evidence. This event also occurred about 22 km from the IAH airport's (TIAH) Terminal Doppler Weather Radar (TDWR), which is used for aviation purposes around major airports. Radar data from the TIAH radar includes a few features which may be meteorite-related. The single NEXRAD radar sweep featuring potential meteorite signatures occurs 7 minutes and 35 seconds after the bolide. This length of time requires a high fireball terminus altitude and probably indicates meteorites with low density and of a low-mass (1-10g?) range. Appearance in a single sweep would be consistent with a number of meteorites of similar size generated in a single detonation. While no meteorites have been found at the time of this writing, this event is of special interest because the relatively high-velocity bolide which appears to have produced low-density meteorites would suggest a carbonaceous body.

Discussion: The events detailed here describe a recent increase in the number of meteorite falls recovered in the U.S. The number of fireball events reported to the American Meteor Society also shows a marked increase over the past two years (Figure, below). Explanations for this include an increase in meteor flux or an increase in public awareness and participation in meteor and meteorite science. Meteor flux for small meteors has not increased appreciably over the past two years (P.Brown, pers. comm.) so the latter explanation is most likely. In either case, meteorite recovery is appreciably improved though a combination of increased public interaction and a dedicated team of experts using multiple detection techniques. The result is a broad consortium of scientists, hobbyists, and the general public, offering a tremendous opportunity for NASA planetary science outreach.



[1] Jenniskens *et al, Science* **338**, 6114 (2012) 1583-1587. [2] Zolensky *et al* 75th MetSoc (2012) # 5264.