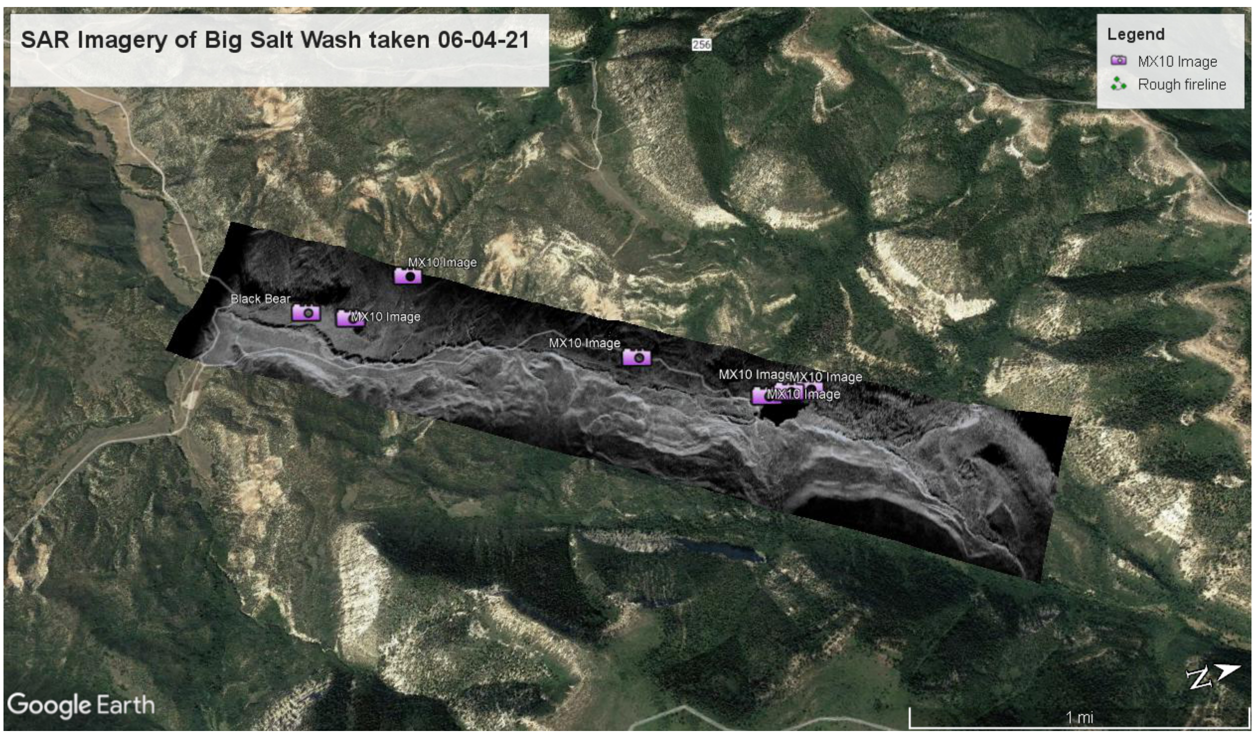
COLORADO
Center of Excellence for Advanced Technology Aerial Firefighting
Division of Fire Prevention & Control

Use of Synthetic Aperture Radar for Wildfire Monitoring



CoE-22-002.1

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Purpose

In June and July 2021, the Center of Excellence for Advanced Technology Aerial Firefighting (CoE) conducted an evaluation of an IMSAR (imsar.com) NSP-7 Synthetic Aperture Radar (SAR) for post-wildfire monitoring. The IMSAR NSP-7 SAR was evaluated to determine the ability of SAR to detect post-fire erosion, soil movement, and well-defined burn boundaries following a high-intensity wildfire in northwest Colorado. Flights were conducted in the Big Salt Wash area within the Pine Gulch fire scar[1]. IMSAR's Aerial Imaging Team conducted 4 sorties for a total of 10 hours and collected approximately 18,500 acres of SAR at 1 meter (3.3 feet) and .1 meter (4 inches) resolutions. CoE staff analyzed the equipment, collection process, and data products.

> The CoE is the research and development section within the Division of Fire Prevention and Control (DFPC), whose mission is to protect the citizens, land, and resources in Colorado.

Executive Summary

During the Pine Gulch Synthetic Aperture Radar project, the CoE evaluated the use of an airborne synthetic aperture radar (SAR) to detect post-wildfire changes in vegetation and ground surface resulting from erosion and depositional responses of the burned watershed in the Big Salt Wash area. Burn area boundary detection was also evaluated. This effort was undertaken to look at how a SAR might be used in support of wildland fire monitoring and for other applications such as detecting subsidence and landslides, flood events, forest health, and degradation among others. Changes between flights were detected using Coherence Change Detection (CCD) imagery.

The data collected did not indicate any significant changes in the surveyed area between a "base-map" flight conducted on June 4th, 2021, and the "revisit" flight done on July 29th, 2021. It should be noted that no significant weather occurred during that time. IMSAR was able to map large areas where there is evidence on SAR imagery depicting the difference between healthy and dead/burned vegetation. Coherence Change Detection (CCD) did indicate a significant change in the water level at Echo Lake.

The SAR proved effective in distinguishing between bare surfaces or burned trees and unburned forest for the Pine Gulch wildfire. The addition of high-resolution optical imagery from the MX-10 camera ball expands the monitoring capability beyond just SAR. Whether as a standalone sensor or used in conjunction with EO/IR sensors, the analysis of SAR products can greatly increase firefighter capabilities and assist in wildfire containment.

After initial research into available options for an airborne SAR instrument, the CoE chose to test the NSP-7 SAR system produced by IMSAR of Springville, Utah.

The primary components of this SAR are a small, lightweight transceiver, antenna, and down-link and LISA-3D image processing systems.

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1) On August 27, 2020 the Pine Gulch Fire temporarily became the largest wildfire in Colorado State history, surpassing the Hayman Fire that burned near Lake George, CO in the summer of 2002.

Figure 1: IMSAR's Cessna 206 below. NSP-7 Radar attached to the wing pylon (CoE Photo)

Figure 2: SAR Operator workstation on board the Cessna 206 aircraft. (CoE Photo)

Background

The use of optical imagery from aircraft such as Colorado's Multi-Mission Aircraft (MMA) or Unmanned Aerial Vehicles to monitor and map wildfires is becoming more common and important in wildland fire response. However, optical images collected by the Colorado Division of Fire Prevention & Control's, Multi-Mission Aircraft (MMA) are sometimes unavailable, even at critical times due to cloud or smoke cover over many areas. Optical sensors are passive and rely on sunlight reflecting from the earth's surface. This can be blocked by clouds or smoke, and are ineffective when there is insufficient ambient light. Infrared (IR) imagery detected by these systems can see through smoke, but not through clouds. SAR is an active sensing technology. Instead of relying on reflected light or emitted IR SAR, uses its antenna to transmit a radio signal to the terrain and then interprets the signal reflected by the terrain to create an image. SAR imagery requires a different way of thinking in that the signal is based on surface characteristics like structure and moisture. Optical imaging is similar to taking a picture of the Earth, whereas SAR imaging is more similar to measuring the topography of the Earth.

SAR's signal is capable of penetrating clouds and smoke, as well as imaging during day or night. Whether as a standalone sensor or used in conjunction with EO/IR sensors, the analysis of SAR products may greatly increase firefighter capabilities and assist in wildfire containment.

SAR may be a valuable addition to EO/IR cameras used on some current fire mapping and monitoring aircraft, such as the MMA.

The data collected during this effort is available for future use. One point that is crucial to this effort is to determine the SAR sensor's utility for Colorado's Multi-Mission Aircraft, as this sensor does provide an all-weather, day/night real-time imaging capability. The data collected during these two flights highlights just one of the use-cases where SAR could be of use in providing critical situational awareness data to fire managers. Other examples of how SAR is being used to respond to natural disasters include:

- Agriculture. Differences in surface roughness are indicative of field plowing, soil tillage, and crop harvesting.
- Floods. Differences in surface reflection can help distinguish heavy flooding, light flooding, urban areas, and permanent bodies of water.
- Land subsidence. Differences in measurements over time can reveal displacements of land motion over time from the first to the second image.
- Snow cover. Differences in surface reflection can help forecast snow melt by distinguishing wet snow, dry snow, and snow-free areas.
- Wildfires. Penetration through thick smoke can provide more accurate and timely information about the extent of a forest fire and can help quantify vegetation loss.
- Wetlands. Penetration through wetland areas can reveal flooded vegetation where land is covered by shallow water.

Despite the many use cases and potential advantages of SAR, it's still an underused technology compared to traditional optical imagery.

Objectives

1. Use the SAR and CCD techniques to detect if post-fire changes to surface vegetation, soil, and water resources are evident?
2. Determine if SAR data is useful and adds value when compared to existing systems such as EO/ IR sensors.
3. Collect necessary imagery to show CCD on Pine Gulch burn scar.
4. Document results of using SAR to inform fire and resource managers and determine possible next steps.

Project Design

As part of our ongoing efforts to evaluate new technologies in firefighting, the CoE discussed using SAR to detect changes to surface vegetation and to determine whether the post-fire effects pose a threat to life or property or will cause degradation to natural or cultural resources. Recent wildfires in the area such as the Pine Gulch fire in 2020 presented compelling possibilities for SAR watershed monitoring of post-fire effects.

Because SAR emits radio waves at relatively high power, a Federal Communications Commission (FCC) approval must be obtained before SAR is used during flights in any area. This approval can take 45-90 days and must be for a defined location and time frame. For that reason, flying on an emerging wildland fire in an unknown area is not practical. Therefore, the CoE determined mapping a burn scar rather than an active burn was the best approach. The CoE contacted the Bureau of Land Management (BLM) and worked with the local BLM Hydrologist Kevin Hyatt. The BLM identified the areas of highest priority in the Pine Gulch burn scar for the collection area and the approximate dates of collection were determined. The BLM hydrologist provided ArcGIS files to the CoE and these were used by IMSAR to develop their flight plans and FCC approval for the missions.

> The CoE is currently pursuing an authorization with the FCC to conduct SAR over much of Colorado. This would allow SAR Data collection flights on active fires in the State on short notice.

During this time the CoE's Aviation Projects Manager, Dave Toelle, coordinated with IMSAR to identify and confirm the areas to be imaged. IMSAR secured an FCC clearance for the collection area valid for both the initial and re-visit flights.

The Study Area—Pine Gulch Burn Scar

The BLM identified the Big Salt Wash area within the Pine Gulch wildfire burn scar as an area of high concern and high risk for post-fire erosion and soil movement. This area was being monitored closely by the BLM for adverse post-fire effects.

Wildfires often have a domino effect. Wildfire increases the risk of flooding because the fire burns almost everything in its path including anything that would slow the pace of water, which then increases surface erosion and sedimentation, debris flow, and reduces water quality. The effects are naturally most marked on steep slopes where runoff and soil erosion tend to increase after high-intensity wildfires.

The Pine Gulch Fire was a wildfire that burned in Mesa County and Garfield County, Colorado. The fire was started by a lightning strike and was first reported on July 31, 2020, and quickly grew and eventually burned 139,000 acres (InciWeb 2021).

Data Collection Flights

The first data collection flight was conducted by IMSAR on June 4, 2021, flying within the gridded areas shown in the photo below using their Special Missions Cessna T206H aircraft equipped with an NSP7 Radar, MX10 Camera Ball, and ZM3 Airborne Processing Server. This flight collected the ‘base map’ to be used by CCD to identify changes in subsequent flights.

IMSAR conducted a second “revisit” data collection flight on July 29, 2021, using the same equipment, a similar flight plan, and geometry. In two flights, IMSAR flew 10 hours, generating SAR imagery of approximately 18,500 acres at 1 meter (3.3 feet) and .1 meter (4 inches) resolution.

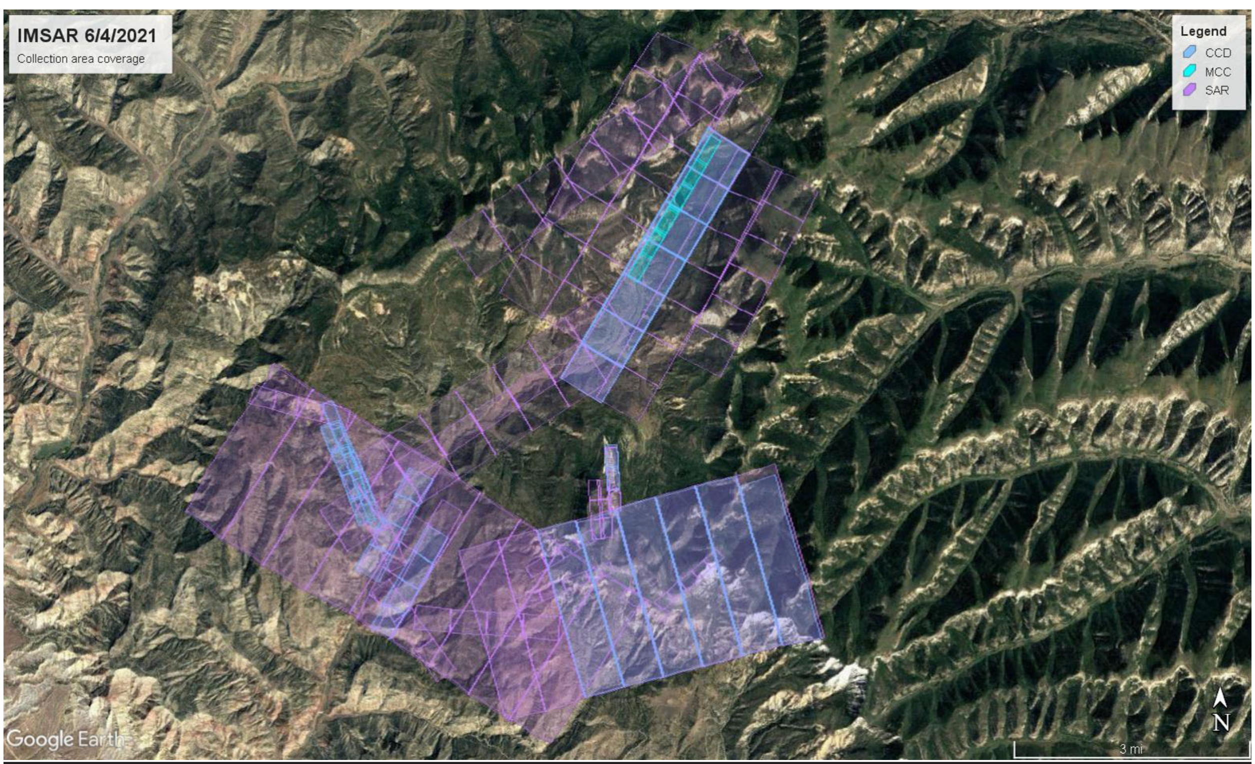


Figure 3: Flight plan developed by IMSAR on Big Salt Wash (IMSAR photo)

Coherence Change Detection

Coherence Change Detection (CCD) with SAR involves comparing pairs of images of the same area, collected using the same system settings and geometry conditions but at different times. To identify changes, CCD software compares two different attributes of the two images: phase and amplitude. Change is quantified in SAR images by measuring the difference pixel by pixel between two registered images, a change is identified by a decrease in coherence (consistency) which is highlighted by the change detection (CD) process. The SAR image areas containing change can then be superimposed onto optical imagery for geographical context. Since SAR data contains amplitude and phase information, both parameters can be used as indicators of change.

- Amplitude information of SAR data captured at different times is used to understand surface changes. Since SAR data is minimally influenced by the atmosphere, analyzing change is immediate and very efficient.
- Amplitude can be used to pick up physical information on the surface and is commonly used for agriculture, forestry, and feature monitoring.
- Analyzing phase change provides the ability to see minuscule surface changes that are impossible to see otherwise. This approach makes it possible to analyze deformation that affects both extended and localized structures related to natural or human-induced phenomena.
- Applications include analyzing volcanic or seismic activity, landslides, land subsidence, and building failures.

CCD is widely used to enhance the detection of the motion of objects and surface change and to detect subtle scene changes that may occur in the time interval between the initial and repeat pass data collection. Small perturbations caused by the compaction or displacement of soil (e.g. from vehicle traffic), vegetation, or rock (e.g. from excavation or erosion) will induce a measurable change.

Figures 4 and 5 are SAR and Coherence Change Detection (CCD) images from Big Salt Wash. The SAR images show the outlines of Echo Lake. These images depict the difference revealed by CCD when using a revisit time of approximately 5 minutes, versus a revisit time of 55 days.

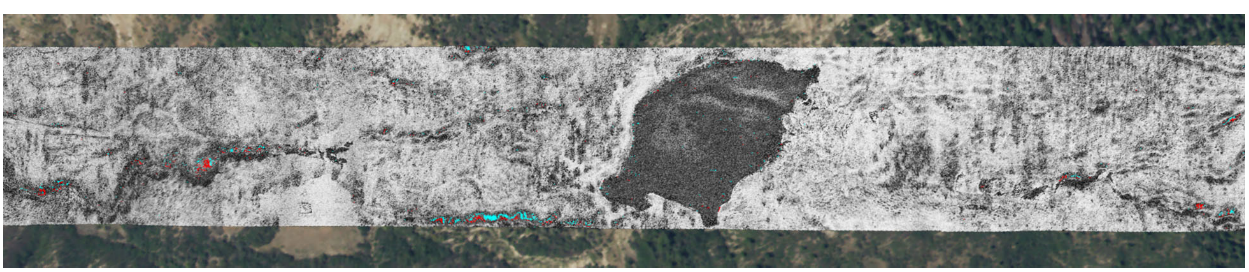


Figure 4: SAR Image of Echo Lake taken June 4, 2021 (5 minute revisit time). Water tends to scatter comparatively little radiation back to an imaging sensor (called back-scatter), which makes it distinct compared to land.

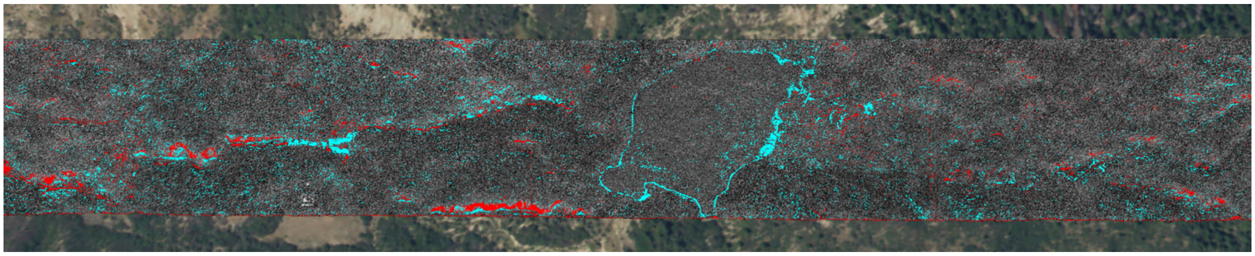


Figure 5: CCD Image taken of Echo Lake July 29, 2021 (55 days revisit time). Blue color depicts a brighter return in imagery compared to the baseline image, indicating the water line has receded.

Results

The data collected did not indicate any significant changes due to erosion or extreme weather activity during the time between June 4th, 2021, and July 29th, 2021. IMSAR was able to map large areas where there is clear evidence on SAR imagery depicting the difference between healthy and dead/burned vegetation. IMSAR also noted a significant change in the water level at Echo Lake, as evidenced by CCD imagery as seen in Figure 6. The CoE also learned we need to use shorter revisit cycles to obtain better quality CCD images for our use case.

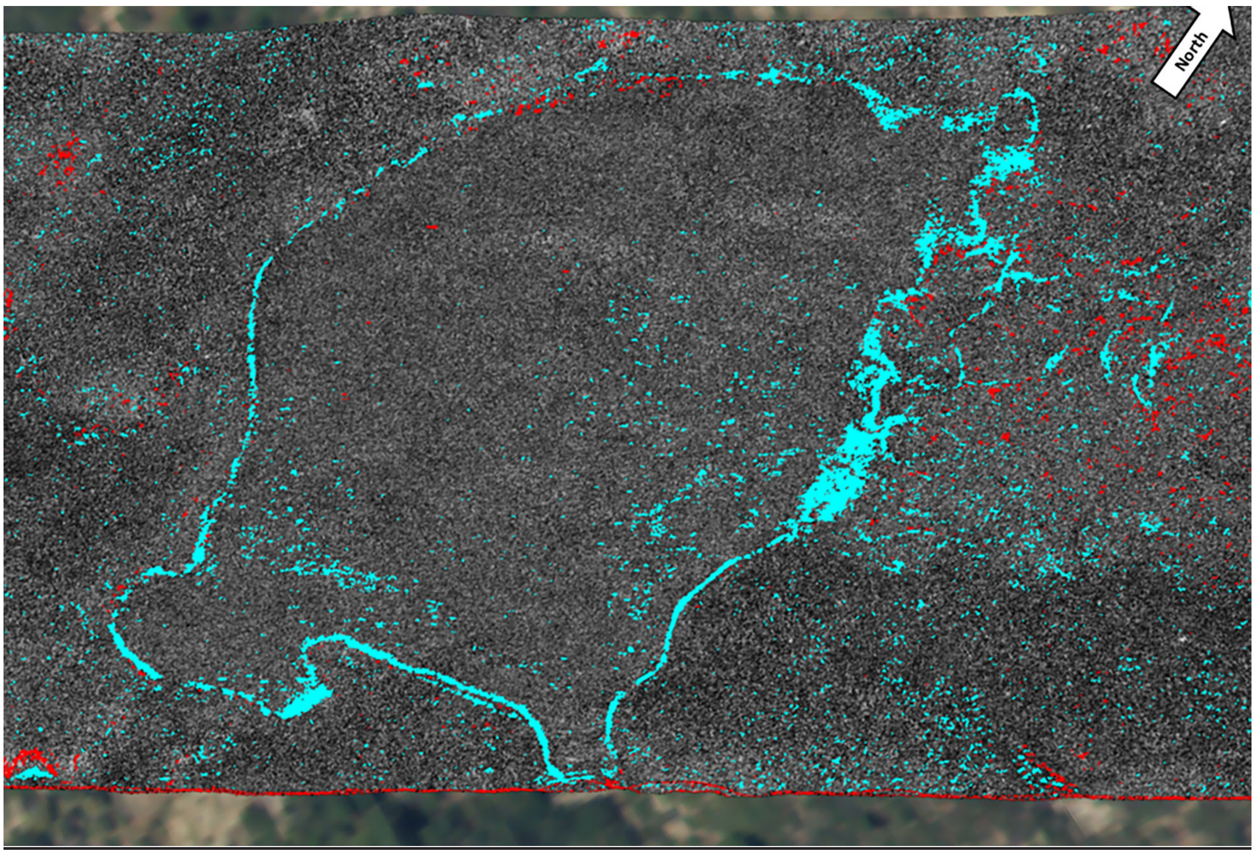


Figure 6: The CCD image taken July 29, 2021 shows blue false-coloring along the shorelines of the lake, which indicates a significant change in magnitude received from those areas. (IMSAR Photo)

For wildland fire events, IMSAR recommends that a revisit flight happen within one day to be effective when using SAR for reporting and measuring fire growth. For larger-scale terrain changes due to flooding, landslides, lake levels, vegetation clearing, or rehabilitation, IMSAR recommends weekly revisits at a minimum to ensure the best CCD quality (IMSAR 2021).

Interpreting SAR

While optical imagery is similar to interpreting a photograph, SAR imagery requires a different way of thinking because the signal is based on how radio waves (RADAR) are reflected by surface characteristics like structure and moisture. While the result can be presented as a pseudo image, see Figure 6, that image does not represent changes that could be seen by the eye. Therefore some interpretation of the SAR results is required.

While SAR imagery may not be simple to interpret, it does offer advantages when scanning large areas by automating the detection of changes that have taken place and highlighting those changes. SAR may indicate the points of interest for a more thorough examination by EO/IR sensors that can be used for comparison.

Electro-optical (EO) imagery uses light from the sun as illumination, like the main camera on an iPhone, which makes it easy to gather. Another key advantage is that it is intuitive to analyze, since EO sensors measure light in the visible spectrum, resulting in images that have familiar characteristics to the human eye. However, EO imaging does not directly indicate changes like CCD on SAR images does.

As an example, Figure 7 is a color EO image of Echo Lake and the burned area surrounding it but does not indicate the changes in water level shown by CCD (Compare to Figure 6).

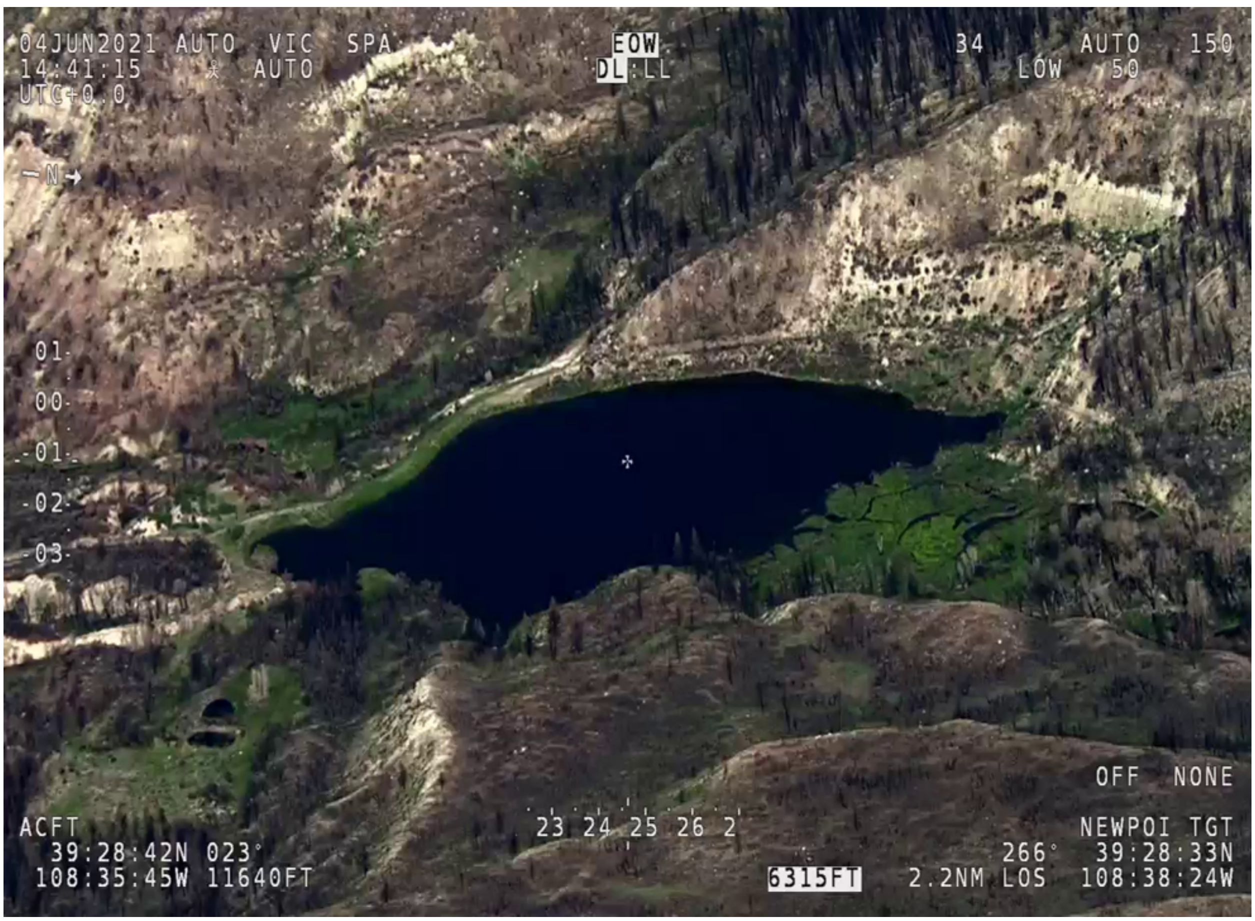


Figure 7: Color EO image of Echo Lake taken from MX-10 camera ball on June 4, 2021. The lake is shown, but water level changes are not indicated. (IMSAR Photo)

SAR on Active Wildland Fire

Due to FCC and scheduling limitations, the CoE and IMSAR were unable to fly active fires. However, it is expected that by using SAR with CCD, the SAR images would quickly and effectively highlight changes in the burn perimeter between flights, much like the water level on Echo Lake was highlighted. The CoE has applied for FCC approval to fly over much of Colorado in anticipation of flying SAR on active wildland fires to test this hypothesis.

What is Synthetic Aperture Radar (SAR)

SAR is an emerging technology in remote sensing and is a type of active data collection where a sensor produces energy and then records the amount of that energy reflected after interacting with the Earth. It uses the motion of the aircraft to synthetically (simulate) create an Aperture (antenna) for RADAR. The aperture of an antenna is essentially the “size” of the antenna. SAR uses the motion of the aircraft to create a very large aperture. It is ‘synthetic’ because it is not a physical structure. RADAR (RAdio Detection and Ranging), transmits pulsed radio signals at targets and records reflected signals from the target, land, in this case, to generate a picture or rendering of the terrain shown in Figure 8.

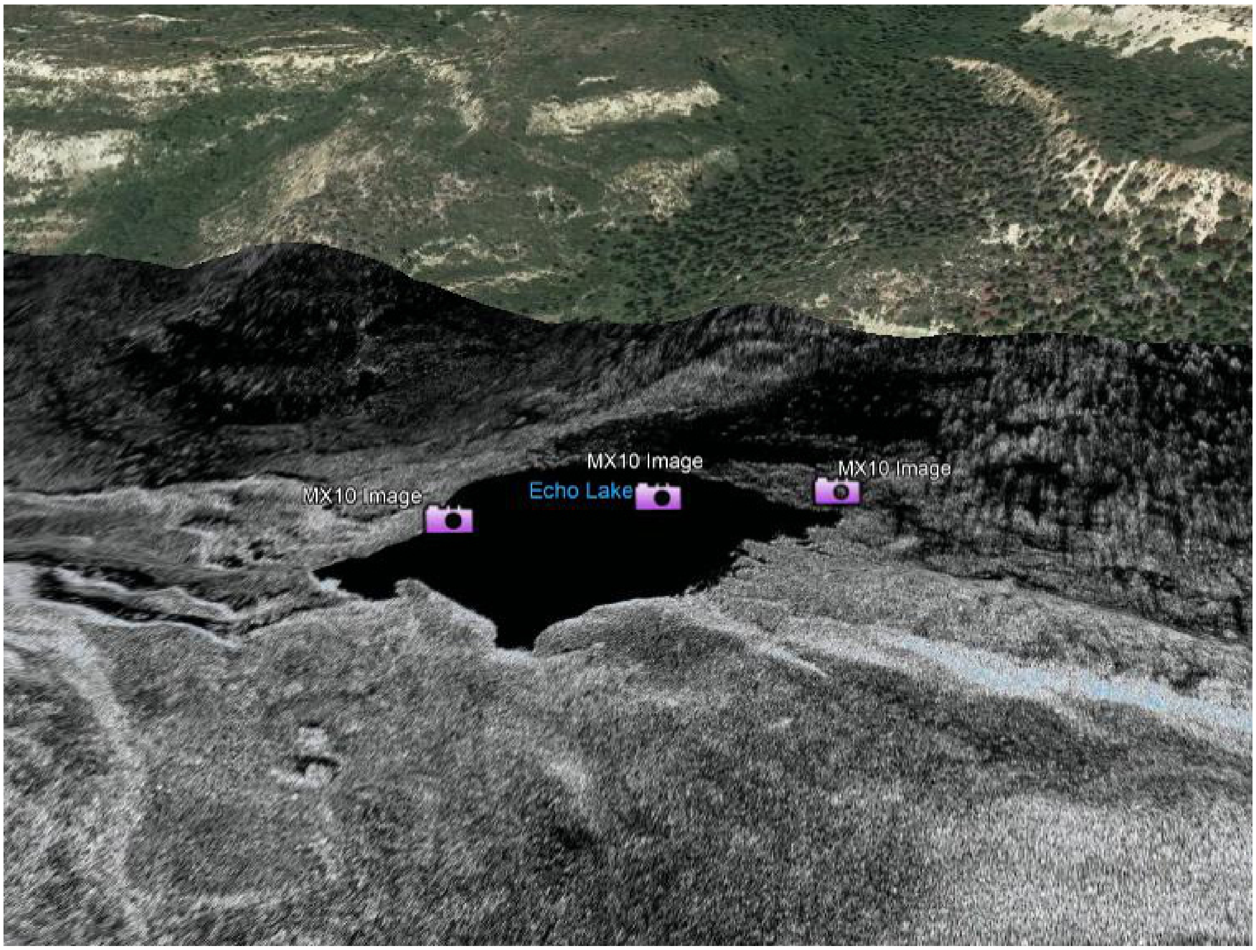


Figure 8: SAR image of Echo Lake taken June 4, 2021. (IMSAR Photo)

An aircraft SAR like the one used in our study operates by transmitting Radio Frequency (RF) pulses from a side-looking antenna (i.e. looking in the direction perpendicular to the direction of flight and downward approximately 45º from the horizontal) as the aircraft flies along a straight flight path. Generally, SAR is side-looking. This means it does not look straight down (Nadir), but at an angle. Each point in the ground swath scatters a small portion of the incident pulse back toward the SAR where it is captured, creating a small signal contribution with a unique amplitude and phase. Back-scatter signals from many points are combined coherently to produce a single signal magnitude for each pixel in the SAR image.

Echoes from ground targets are received and processed continuously. As the aircraft travels along the flight path (azimuth direction) the radar synthesizes a long effective antenna aperture by tracking and processing Doppler frequency shifts from received echoes produced by the relative motion between the aircraft and the ground. As the radar moves along its path, it sweeps the antenna's footprint across the ground while continuously transmitting pulses – short signal bursts separated by time – and receiving the echoes of the returned pulses.

SAR is a completely different way to generate a picture by actively illuminating the ground rather than utilizing the light from the sun as with optical images. The image above shows how very different SAR images look from optical images. These differences present challenges but also create new capabilities and potential benefits.

Benefits of SAR

SAR has the ability to see in the dark and through degraded visual environments, such as smoke, clouds, and fog. With this advantage, SAR systems complement and work with other platform sensors, such as EO/IR cameras, for a true all-weather solution (IMSAR 2020).

Since SAR data is minimally influenced by the atmosphere, analyzing change is immediate and very efficient. SAR can be used to pick up physical information on the surface and is commonly used for agriculture, forest biomass monitoring, and many other data products.

Challenges of SAR

One of the limitations of working with SAR data has been the somewhat tedious preprocessing steps that lower-level SAR data requires.

Special software is required to process SAR data. For this project, IMSAR provided their Lisa 3D software which is a fully integrated, operationally tested software program for mission planning, sensor Command and Control (C2), and Processing, Exploitation, and Dissemination (PED) of data from multiple sensors simultaneously (IMSAR 2021).

While the data created by SAR can be rendered into a synthetic image, there are important differences between optical imagery and SAR imagery. SAR imagery is considered a non-literal imagery type because it does not look like an optical image which is generally intuitive to humans. These aspects must be understood for the image to be interpreted accurately. With a SAR image, we are not looking at a photograph of Big Salt Wash. What appears as a black and white optical satellite image is, in reality, a visual representation of the radar data — the reflectance of radio waves against the Earth's surface and man-made objects.

Future Plans

The CoE's goal is to fly the SAR on an active wildfire or prescribed fire to evaluate how effective SAR is for fire mapping/progression. However, SAR requires a permit from the Federal Communications Commission (FCC). This process typically takes up to 45 days to complete and is only valid for specified locations and dates. This limits the use of SAR for wildfire data collection since wildfires are real-time events. To address this:

- In the short term, the CoE has applied for an FCC Experimental License which would allow SAR usage over significant portions of Colorado
- Longer term, if testing validates the use of SAR on Wildland fires, CoE will work with the FCC to see if an emergency response process could be developed for wildland or public safety emergencies.

IMSAR recommends using shorter revisit cycles to obtain better quality CCD images of a target area. For wildland fire events, a same-day revisit cycle may be most effective when using SAR for reporting and measuring fire growth. For larger-scale terrain changes due to flooding, landslides, lake levels, vegetation clearing, or rehabilitation, weekly revisits at a minimum to ensure the best CCD quality are recommended (IMSAR 2021).

We hope to learn more from our planned use of SAR on active wildfires, and further evaluate if SAR adds value to our current wildland fire detection and monitoring capabilities used by DFPC MMA aircraft

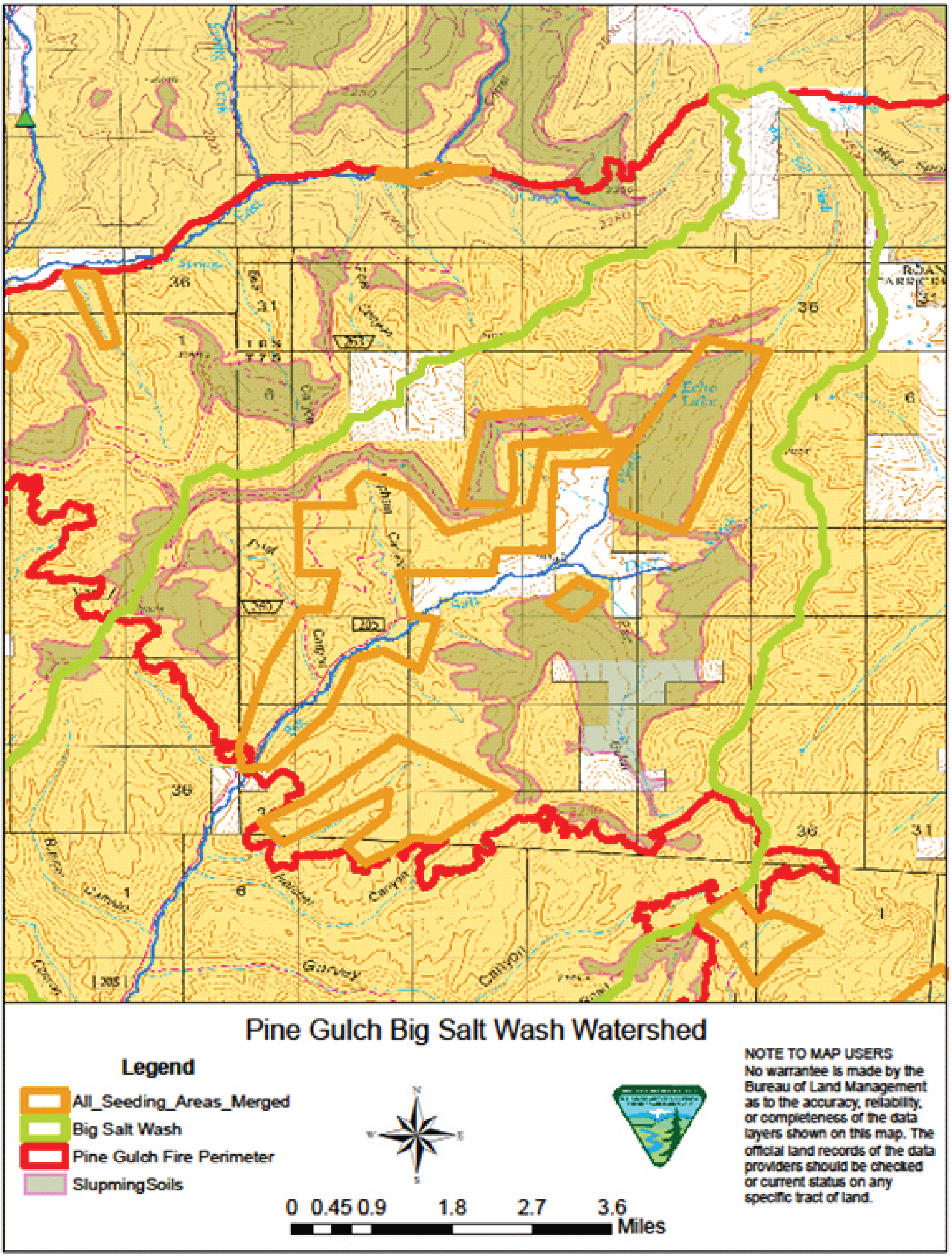
Appendix A: Frequency and Wavelengths (Bands used in SAR)

The table below notes the band with associated frequency, wavelength, and the application typical for that Frequency band.

Wavelength is an important feature to consider when working with SAR, as it determines how the radar signal interacts with the surface and how far a signal can penetrate a medium. For example, an X-band radar, which operates at a wavelength of about 3 cm, has very little capability to penetrate broad-leaf forest, and thus mostly interacts with leaves at the top of the tree canopy. An L-band signal, on the other hand, has a wavelength of about 23 cm, achieving greater penetration into a forest and allowing for more interaction between the radar signal and large branches and tree trunks. Wavelength doesn't just impact the penetration depth into forests, but also into other land cover types such as soil and ice.

Band	Frequency	Wave Length	Application
Ka	27-40 GHz	1.1-0.8 cm	Rarely used for SAR (airport surveillance)
K	18-27 GHz	1.7-1.1 cm	rarely used (H2O absorption)
Ku	12.5-18 GHz	2.4-1.7 cm	Ku- and Ka-band tend to be used for surface, canopy, or high resolution target applications.
X	8-12.5 GHz	3.8-2.4 cm	High resolution SAR (urban monitoring,; ice and snow, little penetration into vegetation cover; fast coherence decay in vegetated areas)
C	4-8 GHz	2.5-3.8 cm	SAR Workhorse (global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence); ice, ocean maritime navigation
S	2-4 GHz	15-7.5 cm	Little but increasing use for SAR-based Earth observation; agriculture monitoring (NISAR will carry an S-band channel; expends C-band applications to higher vegetation density)
L	1-2 GHZ	30-15 cm	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)
P	0.3-1 GHZ	100-30 cm	Biomass. First p-band space-borne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR

Appendix B: Map of the Big Salt Wash Study Area



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