RAPTOR MAPS™

Guide to Solar PV Inspection via Manned Aircraft

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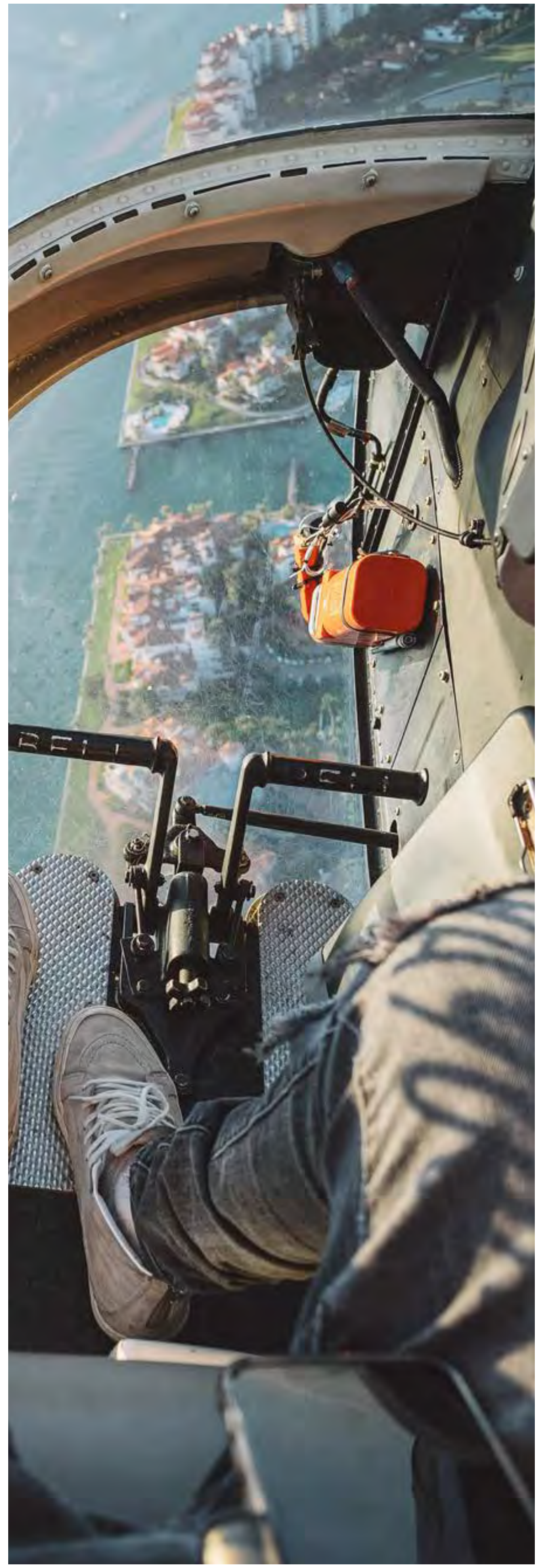


Introduction

This document is a technical guide for solar PV system inspection via manned aircraft. Inspection guidance for unmanned aerial systems (i.e., drones) is available here. Inspection contract specifications for PV system owners and operators are also available here.

Raptor Maps Banner on manned aircraft after a successful mission.

Why Inspect Solar Systems with Manned Aircraft

Manned aircraft can serve as a viable option for inspecting solar PV systems under certain circumstances. Mobilization costs may be minimized using manned aircraft when inspecting solar farms in close proximity of each other. Large solar farms, where drone pilots are unable to maintain visual line of site (VLOS) of their drone, are a suitable use-case for manned aircraft. They are good when solar systems are located in areas where airspace restrictions prohibit drone operations. Certain environmental conditions such as high winds or high temperatures can also necessitate the use of manned aircraft as they are more equipped than drones to handle environmental extremes.

Example of solar array mounted on dual-axis trackers shown in greyscale infrared.

Fixed or single-axis ground mount and roof mounted solar arrays are ideal for manned aircraft solar inspection. This is largely due to the consistent angle at which an entire solar array is oriented, making it easy to adjust the gimbal pitch to avoid glare.

⚠ Conversely, manned aircraft solar inspections are not compatible with solar arrays mounted on dual-axis trackers. Dual axis trackers are able to rotate to better track the sun throughout the day on its X-axis (East to West) as well as on it's Y-axis (North to South). The variation of tracker angles when inspecting this type of array make it difficult to identify whether elevated heat signatures are caused by electrical defects or increased glare.

Where to Find Aircrafts & Operators

It's common practice for manned aircraft solutions providers in the solar industry to use rented aircraft and contract pilots. Charter or inspection companies are a great way to find pilots and aircraft. Certified flight instructors (CFIs) at flight schools are also good resources. CFIs are already experienced in the aircraft and flight schools have posted rates for students and others who have "soloed" and are eligible to rent the aircraft. Charter companies, inspection companies and flight schools are located nationwide, so it's only necessary to move people (such as the data capture specialist) and equipment (such as the FLIR camera). A directory of flight schools can be found on the FAA website.

Flight schools can also provide connections through flying clubs where members pool resources to share one or more aircraft. As solar PV system inspection is a commercial activity, ensure that the pilot holds a commercial certificate under FAA FAR Part 61. A directory of flying clubs can be found on the AOPA website. When renting an aircraft, ensure that you are asking for the "wet" rate, which includes all operating costs, including fuel. Aircraft rentals may require a minimum rental of 4-8 hours.

Before Your Flight

Airspace Research

Prior to adding a PV system waypoint, the airspace should have been thoroughly researched by the vendor or the vendor's pilot. This includes identifying military airspace, restricted airspace, special use airspace and controlled airspace checks and authorizations. On the day of the inspection, temporary flight restrictions (TFRs) must be checked again.

The pilot must also account for terrain considerations and weather. The data collection specialist is responsible for coordinating with the customer to ensure that the PV system is fully energized and is free from soiling or other physical obstructions that can affect the analysis.

Flight Pattern Planning

In the northern hemisphere, fixed-tilt PV systems are angled towards the south (rows run east-west), while variable tilt PV systems (i.e., tilt tracker systems) follow the sun east to west (rows run north-south). The ideal flight pattern is along the rows, which means east-west passes for fixed-tilt and north-south passes for variable tilt. This is the same guidance as drone operations or an unmodified aircraft or non-gimbaled setup, the camera is generally facing out the left or right window, so unless it it close to solar noon, the camera will be facing the rear of the panels and usable data cannot be collected on the return pass.

Minimum Altitudes

Above ground level or AGL refers to an aircraft's altitude relative to the ground below. Mean Sea level or MSL refers to an aircraft's altitude above the average sea level, which makes it a constant value no matter what kind of terrain is below. Drones and manned aircraft that are operating at low heights or landing will use AGL.

⚠ For solar farm inspections, it is recommended to communicate altitude to the pilot in both AGL and MSL so you know exactly how high over the solar farm you are flying, which is a critical element of capturing good data.

Manned aircraft altimeters work off of pressure altitude which corrects for atmospheric conditions to maintain a given altitude. Small aircraft do not have radar altimeters that tell them how high they are above the ground. Because of this, the best way to ensure that the pilot flies at the correct altitude for each site is to:

1. Find the elevation of the site above sea level (Google Earth works well for this).
2. Add the inspection altitude required (AGL) to the site elevation above.
3. The resulting altitude is in MSL. Provide the pilot with this altitude to fly, which will be accurate as long as the pilot has the correct pressure setting for the area in the altimeter.

⚠ A manned, fixed-wing aircraft must maintain an altitude of at least 500 feet above ground level (AGL) when performing maneuvers (such as performing turns). Higher altitudes allow for a greater margin of safety. Below 500 feet AGL, an aerobatics license is required.

Swarms & Manned Aircraft

⚠ While it is common to "swarm" drones, with up to four operating simultaneously, this is not recommended for manned aircraft due to safety concerns. Multiple manned aircraft should not be used simultaneously for solar inspections.

Land & Asset Owner Permission

Manned aircraft do not require landowner or asset owner permission to collect thermal or color imagery. Some vendors even choose to gather intelligence on competitor solar systems, with the goals of increasing sales and providing customers with data and intelligence.

Plane of Array Irradiance

The plane of array (POA) irradiance from on-site sensors should be used the ground truth to confirm minimum irradiance levels during aerial inspection. Intermittent clouds may require a change in the flight plan because it's not economical or environmentally-friendly for an aircraft to remain in a holding pattern. For overview level inspections, failure to verify irradiance means that a majority or all of the data may have been captured under substandard conditions.

Raptor Maps' mobile app displays real-time plane-of-array irradiance fused with their solar data model.

Helicopters

A manned (piloted) helicopter is an acceptable choice for inspection. Although utilities are increasingly utilizing UAS for transmission line inspections, helicopters have traditionally been the the backbone of the fleet. Helicopters may be operated in doors-open or doors-off configurations, which is great as infrared waves cannot travel through window glass. With a helicopter, it is possible to hover and descend over a PV system to obtain high quality, high resolution sample data. However, when dozens of PV systems are scheduled in a single day, quality can degrade. Ensure that your vendor contract requires original data to prevent degradation in quality at scale.

⚠ High winds need to be considered when conducting manned operations While helicopters have omnidirectional flight capabilities, slower and controlled flight (including hovers) with a significant tailwind (above 15 knots) add additional risk factors. These include loss of tail rotor effectiveness, yaw stability, longitudinal stability issues due to wind getting under (or over) large stabilizer surfaces and potential compressor stall issues in turbine machines.

⚠ In high tailwinds the helicopter vertical tail (and fuselage) may align try to align with the wind, resulting in uncommanded yaw. If not corrected with proper pedal input, this may lead to loss of control. Clear communication between the pilot and camera operator is recommended to deconflict any wind-induced data capturing blockers.

⚠ Safety during helicopter operations is also paramount. Any equipment present within the helicopter cabin during a doors-open or doors-off flight must be secured and/or be fastened to a stable mount to minimize the risk of loss of items and flying debris. Loose items pose safety and equipment damage risk and items caught in the tail rotor can require emergency landing.

Helicopter Models

Example helicopters that can be used for solar PV site inspections (a partial list) include:

Robinson R44

The most common helicopter for solar system inspection is the Robinson R44, the world's best-selling helicopter. It has a range of 300 nautical miles and seats four, so there is adequate room for a pilot and data capture specialist. Operating costs to contract with an R44 pilot and aircraft can be $500–900 per hour. Weight Limit Per Seat - 300lb.

Robinson R22

When an overview-level inspection is needed for fewer than five small C&I PV systems, the Robinson R22 is a good choice. It is a smaller, two seat variant of the R44, and has a range of 200 nautical miles. In this configuration, a data capture specialist uses a handheld camera setup, such as the FLIR T1020 and Fluke TiX580. Operating costs to contract with an R22 pilot and aircraft can be $300–700 per hour. The R22 is not recommended for large portfolios and large solar systems. Weight Limit Per Seat - 240lb.

Bell 206 - JetRanger

If there are no Robinson R44s near the solar site, the Bell 206 JetRanger is a good option. The price point is typically more expensive at $1200-$1500 per hour, however when factoring in mobilization fees for a wvdistant R44, the JetRanger can become economically viable. Weight Limit Per Seat - None.

Fixed-Wing Aircraft

Fixed-Wing Aircraft Models

Example fixed-wing aircraft that can be used for solar PV site inspections (a partial list) include:

Cessna 172 Skyhawk

The Cessna 172 Skyhawk is the most common aircraft in the world. Most pilots have trained on this easy-to-operate, four-seater aircraft. The high-wing design of the 172 means that operators sit underneath the wing and have a superior view. For a data capture specialist, this means that a camera pointed downwards from within the cabin will have a relatively clear field of view. The two main obstructions to the field of view in a 172 are the wing spar (diagonal support) and the non-retractable wheel.

Cessna 182 Skylane

The Cessna 182 Skylane is a larger, faster variant of the 172. The increased cabin area means that interior modification of the aircraft is not necessary, and the data capture specialist can be more comfortable. The 182 is also more likely to have upgraded cockpit instrumentation, resulting in a better flying experience.

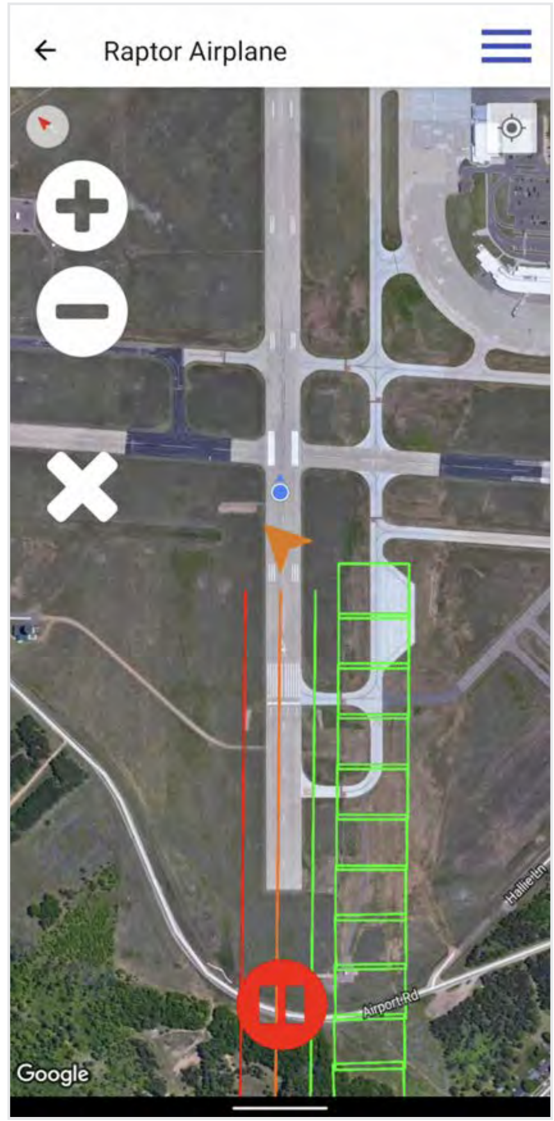
Equipment Considerations

Guidance Systems

For solar PV system inspection, two types of guidance systems are necessary for manned aircraft. The first is a general aviation app, such as ForeFlight Mobile or Garmin Pilot. In addition to guiding the aircraft to the correct PV system, the apps provide critical information to pilots such as weather, airport-specific information and communication frequencies.

⚠ The app may not ingest latitude and longitude data required to pinpoint the PV system. Five decimal places are needed e.g., (42.35930, -71.09356), but this may be truncated by the guidance app. In areas with a high density of PV systems, pilots cannot solely rely on ForeFlight or Garmin, as the risk of inspecting the wrong PV system is high.

The second type of guidance system ensures that data has been captured for the entire PV system and there are no gaps in coverage. This can be accomplished with commercially-available control systems such as those used for crop dusting, skywriting and search-and-rescue. Vendors may also develop mobile applications that incorporate telemetry data from the aircraft, imaging system and/or tablet computer to both illustrate coverage and direct pilots.



Raptor Maps coverage application for manned aircraft. Green boxes indicate coverage, blue arrow indicates aircraft direction, orange chevron indicates north.

Strafing

Strafing is the ability to move the camera independent of the aircraft in order to capture multiple sweeps without performing multiple aerial passes.

⚠ When strafing, each camera pass will result in a more "extreme" angle, and the relative distance from the modules to the aircraft will increase, resulting in a lower resolution. If strafing occurs near solar noon on a tilt tracker system, the camera angle can exceed the manufacturer-recommended angle of incidence on rows that are farther away. For fixed-tilt PV systems or tilt tracker systems operating in the early morning or late afternoon, ensure that the rows being strafed are not obscured by rows closer to the aircraft.

Drone-mounted gimbal.

Gimbals

With fixed-wing inspections, strafing is accomplished by use of a gimbal. A gimbal system requires tight integration with aircraft positional sensors to ensure that it is pointed at the correct target at all times. Nearly all drones have gimbaled sensors as this data is already being processed onboard in order for a drone to function.

A gimbal that maintains a fixed field of view regardless is not strafing. In order to strafe, a gimbal must be programmed with the appropriate pattern to capture to the area of interest. For utility-scale systems, metadata from the gimbal must be associated with each radiometric image in order to ensure accurate coverage and facilitate analysis.

With helicopter inspections, strafing can be accomplished by manual effort from the data collection specialist. If the imaging system is mounted to a tripod, the human can pan the camera back and forth to strafe the area of interest.

Wing-mounted gimbal on Cessna. Source: soloy.com

Example of a helicopter with nose-mounted camera gimbal. Source: orbicair.com

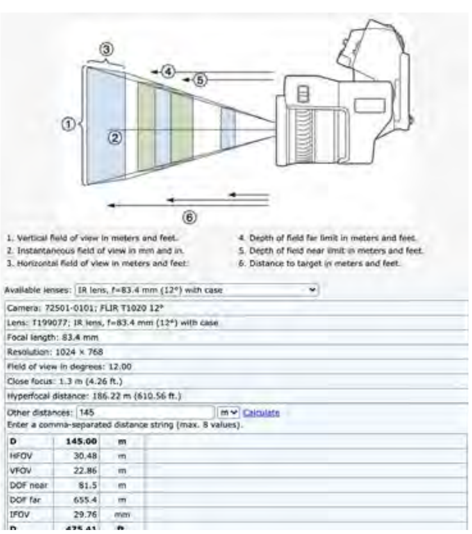
Handheld Cameras

⚠ Handheld cameras are not recommended for utility-scale PV systems, as the the lack of distinctive landmarks will result in gaps in coverage and make automated analysis difficult. Handheld cameras are also not recommended for fixed-wing aircraft, as motion blur will occur, and the minimum required flight speed does not provide sufficient time for a human to focus and trigger the shutter.

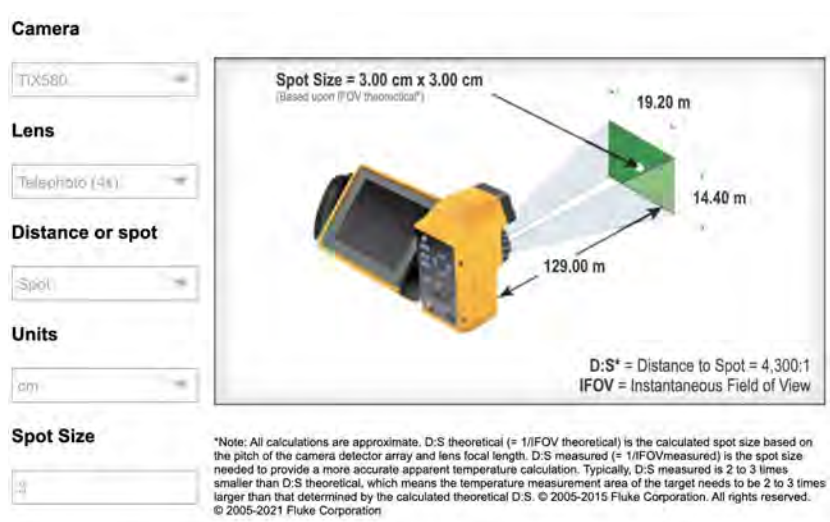
Handheld Camera Models

Despite drawbacks with handheld cameras, two recommended handheld thermal cameras are the FLIR T1020 and the Fluke TiX580. Both cameras are in the long-wave infrared (LWIR) spectral range, and inspections can be done to IEC TS 62446-3:2017 compliance with a tight data capture protocol.

Specification	FLIR T1020	Fluke TiX580
Spectrum	7.5–14 µm (long-wave IR)	7.5–14 µm (long-wave IR)
Lens Configuration	12° (83.4 mm lens)	4x telephoto
Radiometric Thermal Resolution	1024 × 768	640 × 480
Artificial Resolution Enhancement	1024 × 768	1280 × 960 SuperResolution
Helicopter Max Altitude for IEC Compliance	145 m (476 ft)	129 m (423 ft)



Configuration for a FLIR T1020 to achieve IEC-compliant 3.0 cm/pixel. Source: flir.com



Configuration for a Fluke TiX580 to achieve IEC-compliant 3.0 cm per pixel. Source: fluke.com

Aircraft-Mounted Cameras

Historical Use of MWIR

Mid-wave infrared (MWIR) thermal cameras have historically been utilized for manned aircraft inspections of solar PV systems. Defects can be visualized, however these thermal cameras are not IEC compliant. Per the IEC, “Cameras operating in wavelength range of 2 μm to 5 μm shall only be used for thermography of electrical BOS components, e.g. fuses. Due to the transparency of glass in the range of 3 μm the use of that range on PV modules can lead to measurement errors.” As seen in the table below, the most popular models for PV system inspection fall within this spectral range.

Comparison to Drone Cameras

MWIR thermal cameras have historically been used due to low integration times. By relaxing the standards on the type of light that can enter the camera, more light can be collected in a shorter amount of time, which prevents the image from blurring. Manned fixed-wing aircraft are required to maintain significant margin above the stall speed — the speed at which there is significant loss of lift. In contrast, drone-based cameras have a 46% longer integration time, but fly much slower over the PV system. Integration times that are too short relative to the amount of light suffer from image degradation (e.g., a grainy photograph taken at night).

Considerations for Uncooled Cameras

In order to achieve these lower integration times, the MWIR sensors must be cooled, which contributes to the size, weight and power (SWaP) needed, resulting in a larger camera system. Although increased sensitivity can be an advantage of a cooled system, there are several reasons why uncooled thermal cameras can be advantageous:

- Far distance to target. A drone is extremely close to the PV module target, while a manned aircraft is much farther away. The distortion due to the atmosphere outweighs the benefits of cryocooling. Cryocooling is advantageous for tightly controlled benchtop scenarios (e.g., thermal imaging of microchips).

- Lack of correction factors. Aerial thermography using manned aircraft does not typically make use of instantaneous, on-site plane of array (POA) measurements or correct for ambient temperature and humidity. The sensitivity to these correction factors is several orders of magnitude higher than the effect of cooled vs. uncooled sensors.
- Exceeds warranty requirements by 3 orders of magnitude. The stated sensitivity of the most popular drone-based LWIR cameras is ≤50 mK, while the cooled MWIR sensor sensitivities are ≤30 mK and ≤45 mK, respectively. This is a difference 0.005 °C, which is negligible when compared to typical module manufacturer warranty thresholds of 20-40 °C temperature delta, depending on the defect modality.

Aircraft-Mounted Camera Models

FLIR, one of the large thermal imaging companies, recently released a new line of Strained Layer Superlattice (SLS) cameras. The SLS cameras combine long-wave infrared (LWIR) imaging, one of the requirements for IEC-compliant inspections, with long lenses (50–200 mm focal length), which enables sensors to be farther away from solar PV modules (i.e., a safe altitude for aircraft). It's recommended that customers require access to the original data, including metadata, to verify the data capture setup used.

Common camera sensors for manned aircraft are summarized in the table below. Other sensors may be acceptable but must meet resolution, metadata and image type requirements including radiometric thermal images.

Common Thermal Camera Sensors

	A6780 MWIR	A8580 MWIR	A6780 SLS (LWIR)	A8580 SLS (LWIR)
IEC-Compliant	No	No	Yes	Yes
Recommended Variant	A6783	A8583	A6783	A8581
Sensor Resolution	640 × 512	1280 × 1024	640 × 512	1280 × 1024
Recommended Lens Options	100 mm, 200 mm	100 mm, 200 mm	50 mm, 100 mm, 200 mm	50 mm, 100 mm, 200 mm
Spectral Response	≤20 mK	≤30 mK	≤45 mK	≤45 mK
Integration Time	0.48–8.00 ms	0.48–22.73 ms	0.48–22.73 ms	0.48–22.73 ms
Cooling	Closed-cycle rotary	Linear Sterling cooler	Closed-cycle rotary	Linear Sterling

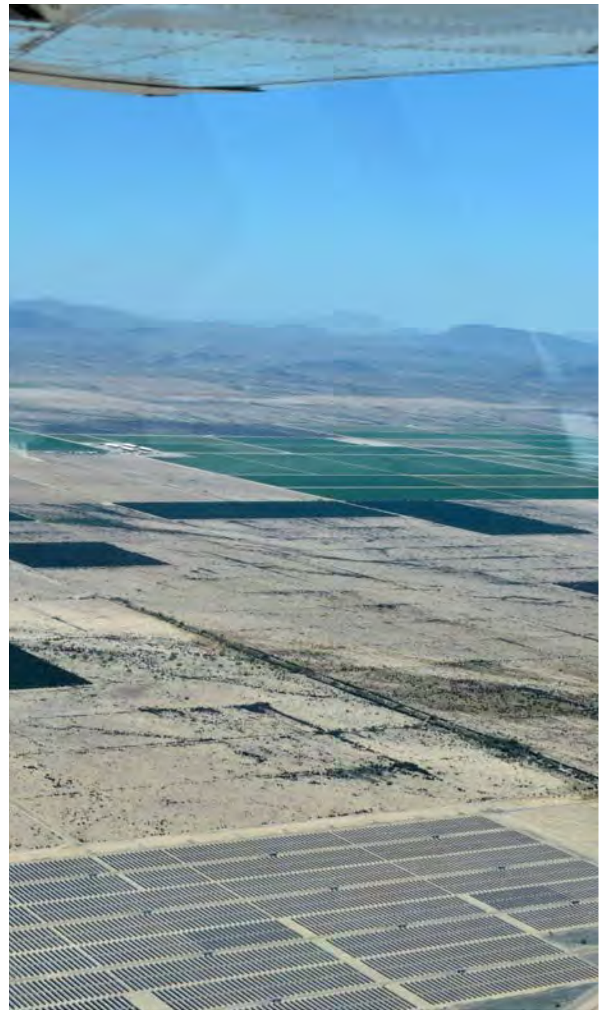
Comparing the A6000 & A8000 Series

The A6000 series has a resolution of 640 × 512, which is equivalent to most thermal imaging systems in drones. However, because manned aircraft are necessarily 5–20 times farther away from solar sites than drones, an "equivalent" resolution on a manned aircraft is less useful in practice. This economical imaging system is only recommended for helicopter-based C&I inspections and utility-scale overview inspections to detect offline strings and larger issues.

⚠ The A8000 series has a resolution of 1280 × 1024 and is the preferred thermal imaging system. The field of view is twice as wide as the A6000 series for an equivalent focal length, requiring fewer passes to capture a complete dataset.

The longest focal length lens available for these cameras is 200 mm. The 200 mm lens enables an aircraft to be maximally distant from the target, but the shorter integration time and wider field of view afforded by a 100 mm lens may be preferable to the user. Both are supported but the 100 mm lens is recommended as it offers a good balance between safe distance from the target and easy communication of coverage and flight plan between pilot and data collection specialist.

⚠ Longer focal length results in a zoomed in image and narrows the field of view. This is a necessary tradeoff for manned aircraft, as the sensor (camera on the airplane) is 500–2,000 feet away from the target (PV module). A 50 mm is acceptable for helicopter-based C&I inspections and overview inspections but will necessitate closer proximity to the site which may be distracting for individuals on the ground.



PV system visibility underneath a high-wing, such as the Cessna 172 and 182.

Camera Setup

External vs. Internal Attachment

⚠ Any external attachment of a camera is considered a modification or alteration of the aircraft and must be reviewed by an airframe and/or powerplant (A&P) mechanic. If the weight, balance, structural strength, performance, power plant operation or flight characteristics are unaffected, the A&P mechanic can sign off on the logbook.

The camera setups used for manned aircraft inspection of solar PV systems are bulky and heavy when compared to small action-cameras (e.g., GoPro). These modifications require FAA approval via FAA form 337 “Major Repair and Alteration.” For this reason, temporary setups, such as internal mounting are most commonly used. Although vendors that own and operate their own aircraft often improve the mounting system and file form 337.

FLIR infrared camera mounted to tripod in cabin. Must be secured by multiple ratchet straps of equivalent.

Mounting in Fixed-Wing Aircraft

Cessna 172 Skyhawk

In a Cessna 172, the camera should be pointed downward, out the window, and angled between the wing spar and the wheel. The camera should be vertical (nadir) as possible. The angle of the camera relative to nadir should be carefully measured. This can be accomplished by placing a pattern of known size in the center of the field of view, and measuring the distance to the midline of the aircraft. Other methods, such as utilization of an inclinometer, are also acceptable.

Cessna 182 Skylane Considerations

In a Cessna 182, the front right seat does not require removal. It can instead be slid up to accommodate the camera.

Need for Professional-Grade Tripod

A mounted camera can weigh up to five pounds. It will attach to a standard tripod shoe with 1/4-20 threads, but a sturdy, professional-grade tripod must be used. The camera is heavier than a typical SLR camera and the aircraft maneuvering will generate forces in all directions.

Open window on Cessna 172 with thermal camera pointing downward.

Imaging Through Windows & Glass

LWIR and MWIR frequencies cannot penetrate windows in aircraft. So windows must be open for proper PV system imaging. It is at the discretion of the pilot and data capture specialist whether to open the window at each PV system or leave the window open for the duration of the flight. This is not an issue for externally-mounted gimbals, which have a Germanium lens cover that is transparent to LWIR and MWIR. Owners of manned aircraft may consider installing a port through the bottom of the aircraft which could be opened for PV system inspections.

Power Sources

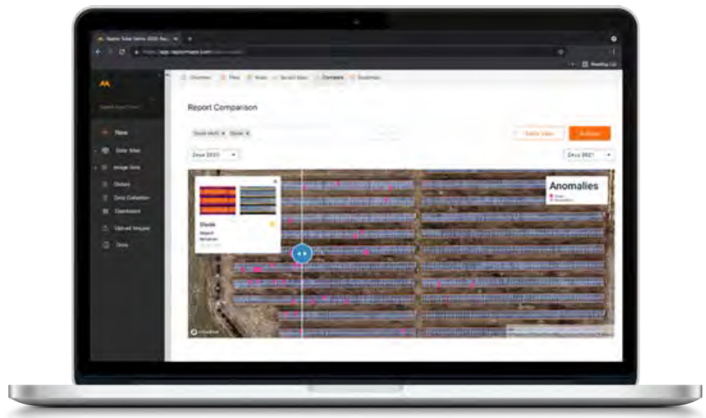
Most cameras have an inverter block, which converts AC current from a wall outlet to DC current. Aircraft batteries and external batteries that can power your setup are already DC. However, it is not recommended to bypass the AC/DC inverter and directly connect DC current from a battery to your imaging setup. The equipment is sensitive to small fluctuations in voltage, and “clean” power is required. The efficiency gains from eliminating two conversions (DC to AC, and AC back to DC) do not outweigh the risk to the equipment. It is recommended instead that you carry extra battery capacity.

⚠ Ensure that you are following FAA guidelines with regards to battery power. Some vendors have unfortunately tried using lead acid car and marine batteries in the cockpit to power imaging setups.
The preferred alternative, if you own or lease the aircraft, is to power your setup directly from the aircraft. Make sure you are utilizing a qualified aviation electrician.

Terminology

- **Manned aircraft** are those operated by an onboard, human pilot. Airplanes and helicopters are examples, but this designation also includes gliders and balloons. Inclusive terminology, such as “piloted” has not seen widespread adoption in the industry. This term can also be confusing as UAS are also piloted. Therefore, we adhere to the term “manned aircraft” in this document.
- **Fixed-wing aircraft** are propeller or jet-driven and have wings.
- **Rotary aircraft** are lifted by rotating blades. In this document, we use rotary aircraft and helicopter interchangeably.
- **Unmanned aerial systems (UAS)** refers to the entire system of an aircraft (or multiple aircraft), onboard flight controllers, the ground station to send commands and operators. The terms sUAS is used to designate “small” UAS, under 55 lb.
- **Drone** is the common term for unmanned aerial systems (UAS). In this document, we adhere to the term drone.
- **CFIs** are Certified flight instructors.
- **Data collection specialist** refers to the non-pilot member of the crew. he data collection specialist is responsible for ensuring a complete dataset captured according to the correct specifications.
- **Camera setup** describes the thermal imaging system, mounting system, power distribution, camera control system and data storage.
- **Sensor** specifically refers to the thermal camera detector, excluding the optical elements (e.g., lenses) and other parts of the camera.
- **Infrared** is the portion of the spectrum with a wavelength beyond red. Mid-wave infrared (MWIR) is 3–8 μm wavelength, while long-wave infrared (LWIR) 8–15 μm, also known as the “thermal imaging” region.
- **Thermal** is used interchangeably with infrared.
- **Radiometric** is used to distinguish the physical properties of the thermal detector, as opposed to post-processing enhancements.
- **Strafing** is the ability to move a camera independent of an aircraft.
- **Above ground level (AGL)** refers to an aircraft’s altitude relative to the ground directly below.
- **Mean Sea level (MSL)** refers to an aircraft’s altitude above the average sea level, which makes it a constant value.

About Raptor Maps



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