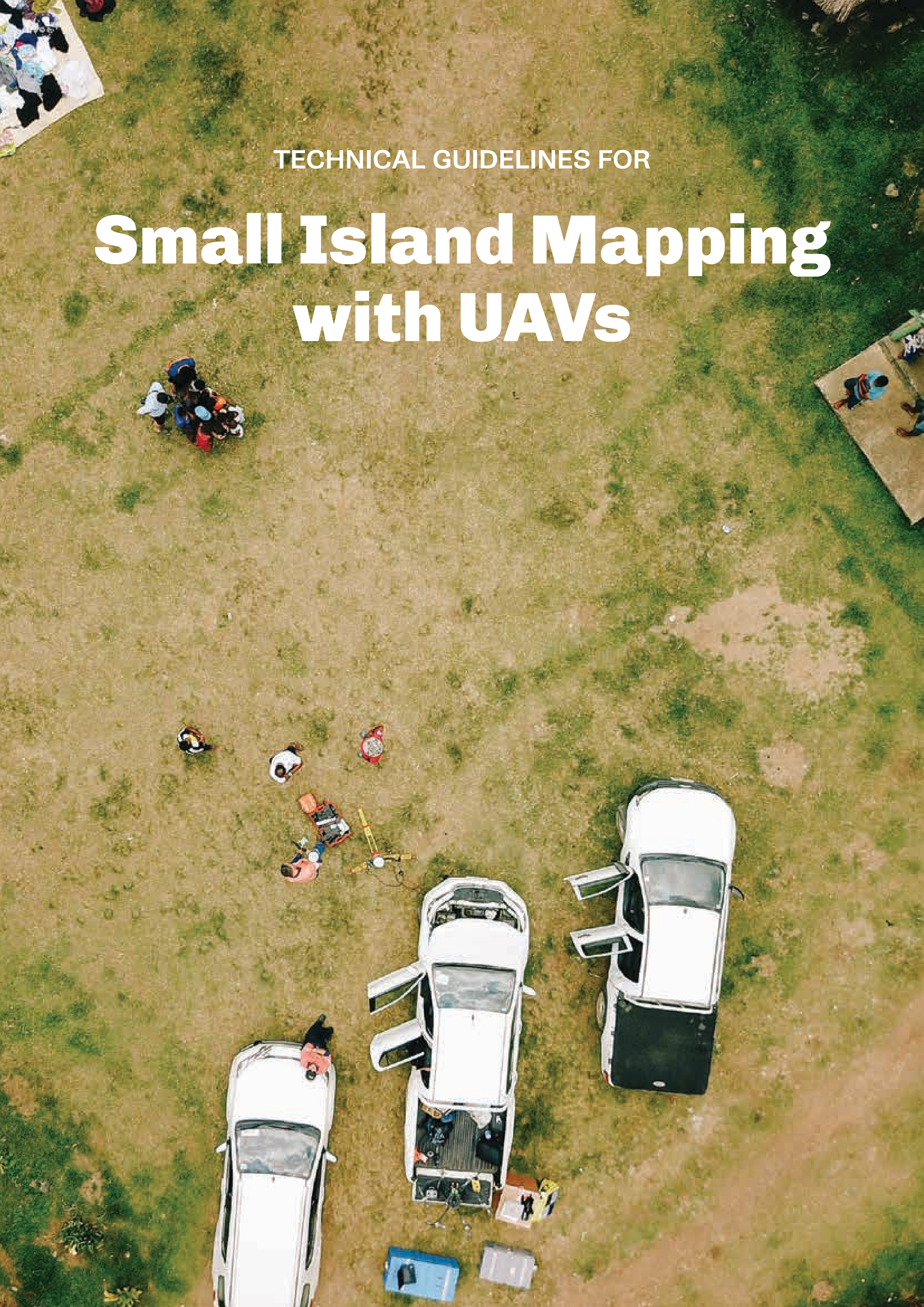
TECHNICAL GUIDELINES FOR

Small Island Mapping with UAVs



WORLD BANK GROUP

Open Data for Resilience Initiative

Humanitarian OpenStreetMap Team

ACP-EU Natural Disaster Risk Reduction Program

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ABBREVIATIONS

2D	two-dimensional
ADS-B	Automatic Dependent Surveillance–Broadcast
AGL	above ground level
AOI	area of interest
AT	automatic triangulation
ATC	air traffic control
CAA	Civil Aviation Authority
CV	computer vision
DSLR	digital single-lens reflex
DSM	digital surface model
DTM	digital terrain model
EXIF	exchangeable image file format
GCP	ground control point
GeoTIFF	Georeferenced Tagged Image File Format
GIS	geographic information system
GPS	Global Positioning System
GPU	graphics processing unit
HOT	Humanitarian OpenStreetMap Team
IMU	inertial measurement unit
LiDAR	Light Detection and Ranging
LiPo	lithium polymer
NIR	near infrared
NOTAM	Notice to Airmen
OAM	OpenAerialMap
OSM	OpenStreetMap
PacDID	Pacific Drone Imagery Dashboard
PIC	Pacific Island Country
PPK	Post-Processed Kinematic
RGB	red-green-blue
RTK	Real-Time Kinematic
SfM	Structure from Motion
SIDS	Small Island Developing States
SSD	solid-state drive
UAV	unmanned aerial vehicle
UAViators	Humanitarian UAV Network

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Executive Summary

Image acquisition and surveying using unmanned aerial vehicles (UAVs) is a very promising technology for Small Island Developing States (SIDS). UAVs can be a relatively low-cost data collection tool at the surveying scales often needed in small island contexts. Further, UAVs can capture thousands of images in a single flight and provide greater detail than satellites or even manned aircraft. The World Bank and Humanitarian OpenStreetMap Team (HOT) compiled this guidance note to document experience and best practices in the use and operation of UAVs for economic development in SIDS. Many of the lessons presented in this guidance note stem from the UAV4Resilience organized by the World Bank (World Bank 2017b) and from experiences with Pacific Drone Imagery Dashboard (PacDID) deployments in the Pacific islands (HOT 2016). This report is intended for local technological agencies of island nations that work to operationalize UAVs as a standard data collection tool.

The report offers the following key messages:

- UAVs can be used to collect information for disaster risk reduction and response. For both these tasks, it is vitally important that high-quality baseline data be collected and made available before a disaster strikes as part of preparedness and capacity-building work (page 57).
- Platforms that are suitable for the mapping needs and local conditions in small island states should be selected, if the budget permits, several platforms can be used for various specialized tasks (page 28).
- Flying the UAV is only a very small portion of the time needed. Most of the time required is taken up by planning, obtaining permission to fly, and post-processing of the data captured (page 36).
- To ensure safety during flying operations, regulations and air traffic control procedures need to be clear and understood and must be rehearsed before emergency conditions arise (page 15).
- To expedite licensing and regulatory processes and reduce costs, it helps to use local service providers that specialize in the mapping areas of interest within the country. Capacity building of in-country actors ensures that needed skill sets are available on short notice (page 54).
- Power and battery management for UAVs and for ground control stations can be a challenge in the field if not planned thoroughly in advance of activities (page 53).

1. Objective of this guidance note

The objective of this guidance note is to establish key principles for end use of unmanned aerial vehicles (UAVs) in a Pacific Island Country (PIC) context. The document addresses how, when, and for what applications UAVs should be used. For pilots who are new to UAV mapping, it also provides instructions and recommendations to ensure that imagery of high quality is generated for accurate integration with other geospatial layers.

The ultimate goal is to establish UAVs as the principal data collection and survey mapping instrument for Small Island Developing States in the Pacific region and beyond. As the principles and best practices described in this document are applicable globally, the plan is for this document to continue to evolve and for its online version (https://docs.openaerialmap.org/uav-guidelines) to reflect the latest in UAV technology.

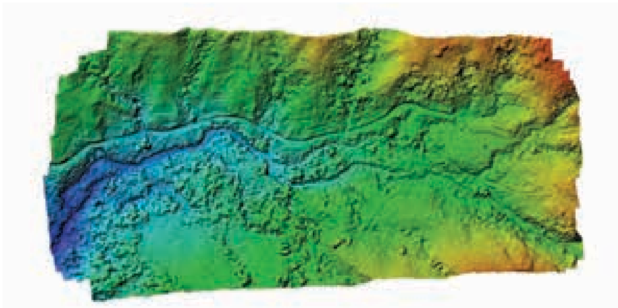
To take stock of the current operating conditions in the Pacific region, field tests were conducted in Tonga and Fiji in October 2017. Five survey mapping challenges were carried out to generate five types of typical geospatial data products that are high in demand (shown in table 1).[1]

Lessons learned and best practices derived from these exercises are offered throughout this note to help the reader better understand how most effectively to use UAVs for survey mapping. Other applications of UAVs, such as for cargo delivery, are beyond the scope of this note.

Flight itself constitutes only a small portion of the entire UAV operation (as explained in chapter 7). Post-flight data processing and data sharing with end users represent a much larger share of the operation, and they present huge challenges given the sheer volume of data that needs to be processed;[2] challenges are even greater if time is limited. Important lessons on data sharing, learned from the Pacific Drone Imagery Dashboard (PacDID) project,[3] have been integrated in this guidance note. Efficient access to imagery can lead to improved mapping work flows for disaster risk management and other applications.

1. Details on the field tests carried out to generate the five types of data products are in Table1.
2. The data size often runs into hundreds of gigabytes.
3. PacDID is a platform that leverages the OpenAerialMap (OAM) concept, making open imagery collected by satellites and UAVs easily available and accessible, particularly for the target audience in Pacific Island Countries. More information is available at Pacific Humanitarian Challenge (n.d.).

TABLE 1. Summary of Disaster Effects by Sector (T$ millions)

SURVEY TYPE/ UAV PLATFORM	AREA	OUTPUT/FILE TYPE	OUTPUT EXAMPLE	OUTPUT USE/APPLICATION
Small area (Challenge 1) Fixed-wing	10 km^2	2D orthorectified mosaic RGB and RGB+ NIR (GeoTIFF)		General mapping, including delineating building footprints and road networks; location and geometric features of bridges and other key infrastructure, such as electricity/telephone poles, power lines; river embankments, bridges and land use and land cover. If an NIR channel is available, classification of vegetated areas, identification of permanent and temporary water bodies, etc. are possible.
Medium area (Challenge 2) Fixed-wing with RGB camera	50 km^2	2D orthorectified mosaic RGB (GeoTIFF)		Same as Challenge 1.
Elevation (Challenge 3) Multirotor with LiDAR sensor	0.5 km^2	Surface model Point cloud (GeoTIFF)		Inputs for flood modeling, drainage design, transportation design, coastal engineering, landslide modeling (susceptibility), and erosion monitoring for slope stability studies.

Real-time, beyond line of sight (Challenge 4) Delta wing fixed-wing	0.5 km^2 (10 km from take off location)	Video, photos, orthomosaic (MP4, JPEG GeoTIFF)		Near-real-time information collected by flying the UAV beyond line of sight for post-disaster reconnaissance, situational awareness, damage assessment, post-disaster mapping, etc.
Bathymetry (Challenge 5) Multirotor	0.5 km^2	Point cloud and DEM (GeoTIFF)		Tsunami and storm surge modeling, coastal inundation/erosion modeling, reef monitoring, etc.

Source: UAV4Resilience 2017

Note: RGB = red-green-blue; NIR = near infrared; DEM = digital elevation model. The field tests used various types of UAVs. All orthomosaic outputs are available from OpenAerialMap.org.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2. UAVs as a game changer for PICs

The Pacific region is one of the most disaster-prone regions of the world. It is subject to a variety of natural hazards, including floods, tropical cyclones, earthquakes, tsunamis, droughts, and volcanic eruptions. Geospatial data can play a key role in monitoring hazard conditions on the ground, but unique data collection challenges exist for PICs. Because these counties consist of multiple small islands or atolls that are often very remote from one another, it difficult to collect geospatial data at the appropriate scale for analysis.

In most countries, mapping is conducted using satellite, aerial, or ground-captured data, or a combination of these. However, in an island country context, satellite images do not have the necessary spatial resolution (pixel size) to show details, as the islands are so small relative to the pixel size.

Given islands' sparse distribution, moreover, PICs may not be captured by satellite imagery unless operators specifically prioritize them. Thus PICs must employ alternative means for capturing very high-resolution imagery data.

UAVs may solve this issue for PICs. Unlike aerial surveys using manned aircrafts, UAVs can be flown at very low cost by qualified personnel and have the flexibility to handle PICs' various requirements. Now a mature technology, UAVs are potentially a game changer that will allow high-resolution images of these remote islands to be regularly and affordably captured by local experts.

3. Securing UAV flight authorization and permits in the Pacific

Flying UAVs requires a thorough understanding of local and national civil aviation regulations. Many governments now provide specific provisions for UAV operations, including permits and licenses that must be obtained before even entering the country. To learn about countries' specific requirements and rules for flying UAVs, the Global Drone Regulations Database is a good starting point.[4]

New Zealand regulations are the most prevalent in the Pacific. Many countries in the region base their regulations on the New Zealand Civil Aviation Authority (CAA) UAV regulatory framework (see Box 1) and modify them for local contexts. Some Pacific countries, such as Fiji, take a hybrid approach and reference aspects of Australian regulations along with New Zealand's. In general, familiarity with New Zealand or Australian regulations will be beneficial for UAV pilots planning to fly in the Pacific region.

The Airshare website[5] offers an excellent entry point to learn about regulations in New Zealand's controlled airspace. In addition to an online learning module, Airshare also provides a decision tree (Figure 1) that allows UAV pilots to navigate through the different conditions under which the UAV flight is being planned and thus identify the approvals required to fly under those conditions.

In many countries, flight authorizations are granted relatively easily if flights are conducted within the visual line of sight in uncontrolled airspace where there are least restrictions, and below 400 ft (or 120 m). For the simple flight authorization, UAVs should weigh less than 15 kg; should stay clear of all manned aircraft, persons, and property; and should remain outside of airspace restricted areas and the 4 km radius of any aerodrome – flying under these conditions makes the flight qualify under the Part 101 rules under New Zealand regulations. In Tonga, pilots operating under these conditions can fly once the UAV is registered with the Tongan CAA without requesting authorizations for each flight.

4. Global Drone Regulations Database, https://www.droneregulations.info.

5. Airshare, https://www.airshare.co.nz.

If a flight goes beyond the Part 101 rules (e.g. fly above 400 ft), the pilot and their organization must apply for Part 102 exposition. For the field testing in Tonga, a Part 102 exposition was obtained to fly above 400 ft and in controlled airspace. Details on how to obtain Part 102 expositions can be found on Airways website[6].

To supplement these official regulations, the Humanitarian UAV Network (UAViators), a global volunteer organization of humanitarian UAV pilots, developed a code of conduct and a set of UAV mission best practices (uavcode.org) that should be incorporated when planning UAV mapping activities, particularly in the context of humanitarian projects.[9]

The permit application process in Fiji is described in annex 1.

6. https://www.caa.govt.nz/unmanned-aircraft/intro-to-part-102/
7. See Airshare, "4 Things You Need to Know about Flying Near an Aerodrome," https://www.airshare.co.nz/must-know/things-to-know-flying-near-an-aerodrome.
8. See Airshare, "My Flights," https://www.airshare.co.nz/my-flights/plan-a-flight.
9. See UAViators (n.d.) for the code of conduct and UAViators (2015) for a guide to best practices.

BOX 1.

NEW ZEALAND CAA PART 101 RULES FOR PERSONS OPERATING GYRO GLIDERS AND PARASAILS, UNMANNED AIRCRAFT, KITES, AND ROCKETS

1. They may not operate an aircraft that is 25 kg or larger, and they must ensure that it is safe to operate.
2. They must at all times take all practicable steps to minimize hazards to persons, property, and other aircraft.
3. They may fly only in daylight.
4. They must give way to all crewed aircraft.
5. They must be able to see the UAV with their own eyes (i.e., not through binoculars, a monitor, or smartphone) to ensure separation from other aircraft (or they may use an observer to do this in certain cases).
6. They must not fly their aircraft higher than 120 m (400 ft) AGL (unless certain conditions are met).
7. They must have knowledge of airspace restrictions that apply in the area in which they will operate.
8. They may not fly closer than 4 km to any aerodrome[7] (unless certain conditions are met).
9. When flying in controlled airspace, they must obtain an air traffic control (ATC) clearance issued by Airways (via Airshare[8]).
10. They may not fly in special-use airspace (e.g., military operating areas or restricted areas) without the permission of the area's controlling authority.
11. They must have consent from anyone they wish to fly above.
12. They must have the consent of the property owner or person in charge of the area they wish to fly above.

Disclaimer: *This diagram is provided for information purposes only and is not to be relied on as a substitute for a comprehensive knowledge of the relevant rules and regulations that apply to the operation of UAVs. It is the UAV operator's responsibility to read, understand and operate any UAVs in accordance with the Civil Aviation Rules.*

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DATA
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4. Determining whether the UAV is the right mapping tool

UAVs may not always be the best mapping tool for a project. Before deciding whether to use a UAV, a satellite, or other tool, the project's data needs, budget, and time frame must be understood. Table 2 lists some key factors to consider when deciding on the tool to use.

When selecting a survey method, the scale and extent of the area of interest must be considered, along with the technical constraints of the project, availability of surveying equipment (to establish GCPs), and the method's cost-effectiveness. For instance, to acquire baseline imagery of large areas at a resolution of 50 cm/pixel with a capture window of one year, satellites are most practical.

On the other hand, a UAV is preferable for mapping a small footprint (e.g., small pockets of high-flood-risk areas, or a small and remote island community). More often than not, a single method is not used exclusively; rather, the various survey methods are used in complement to one another. For example, a group of small islands can be surveyed using a satellite or full-size plane every five years, complemented with local UAV survey updates every six months. The important thing is to establish a strategy that best captures the necessary data in the most cost-effective way.

Figure 2. **Launching the Goshawk III Surveyor UAV by V-TOL Aerospace in Tonga.**

Credit: UAV4Resilience 2017

TABLE 2. Comparison of Survey Mapping Methods

	SATELLITE	AIRPLANE	UAV
Approximate area covered in a day	10,000 km^2	750 km^2	10–25 km^2 (for a UAV equivalent to an eBee)[a]
Detail level	30–50 cm/pixel	> 6–30 cm/pixel	3–10 cm/pixel
Cost per 10 km^2	$$	$$$	$
Cost per 1 million km^2	$	$$	$$$$
Time to deploy	24 hours–1 week	3 days	24 hours (provided flight permits have been granted)
Ease of deployment	Easy (once the satellite is in orbit)	Medium	Easy
Blocked by clouds	Yes	Depends on altitude	No (though may be blocked by fog and rain)
Blocked by wind	No	Yes	Yes
Regulatory burden	Low	Medium–high	High

Note: The number of $ denote relative costs: least costly ($) to most costly ($$$$)

a. The use of a high-end UAV will allow a larger area to be captured. In Tonga, after Cyclone Gita in February 2018, approximately 40 km^2 was captured per day using a Goshawk by V-TOL Aerospace Australia; see Figure 2.


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5. Choosing the Right UAV Platform

If a UAV is the right tool, the next decision concerns which platform to use. There are multiple factors to consider in making this choice: the purpose of the data capture, the weight of platform allowed by local regulations under the conditions of the intended survey location, the need for weatherproofing, and the project's technical requirements (e.g., the type of sensor/camera needed for the survey).

The choice of platform has a number of consequences:

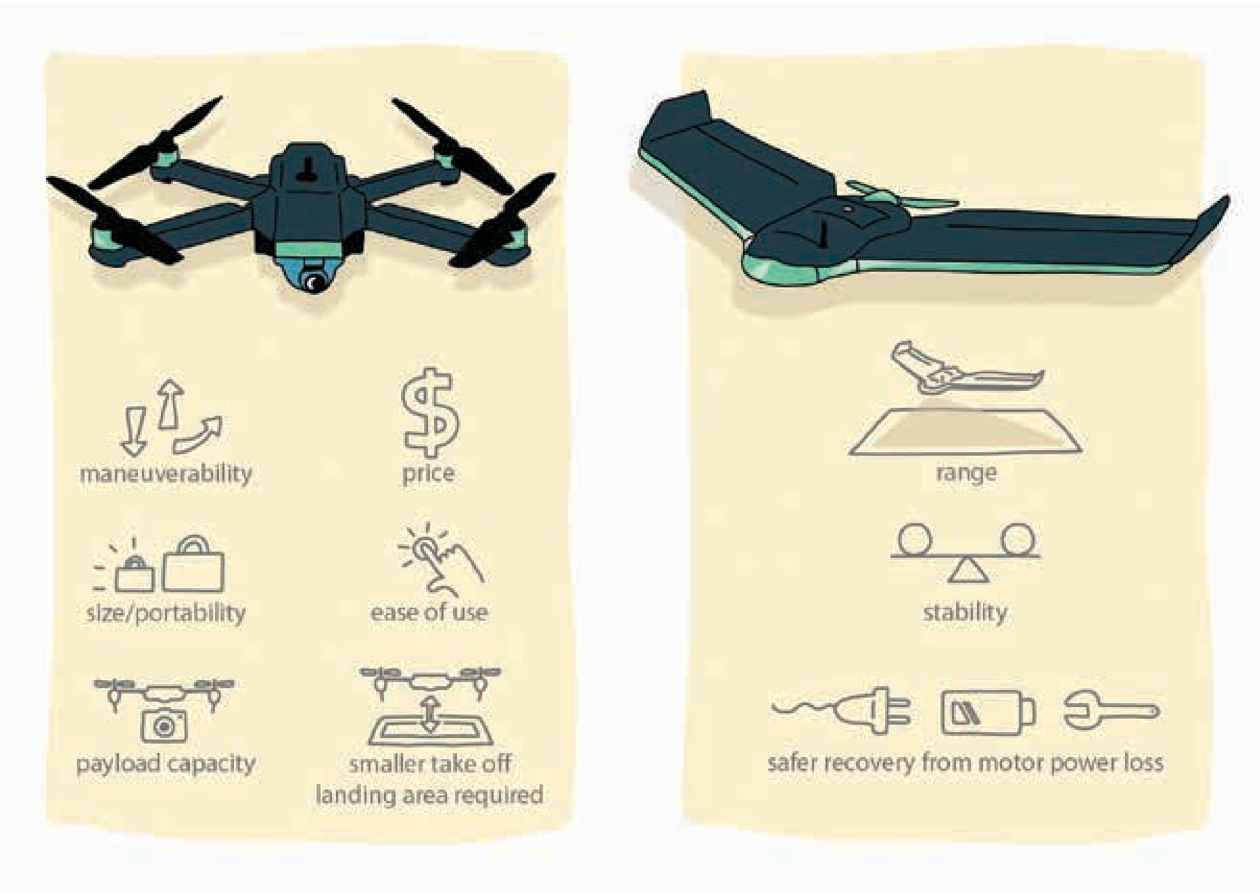
1. It affects the area that can be surveyed (because different platforms fly at different altitudes and have different ranges).
2. It affects the potential downtime of the survey (because some platforms are more weatherproof than others);
3. It affects the areas where it can be operated (specifically the landing and takeoff areas);
4. It affects the spatial resolution of the data, which can be adjusted using various sensors, lenses or by adjusting flight altitude above ground level.

The ultimate choice of platform (fixed-wing, rotary wing, or hybrid, size; propulsion system; etc.) really depends on one question: which platform can carry the sensor necessary to collect the data required (that is, data of the desired coverage, resolution, and type)? To ensure that the platform can perform as needed under the given conditions, any decision must be based on thorough research. The remainder of the chapter discusses key considerations in deciding which UAV platform to use, including the type of sensor (camera) needed for the survey.

In deciding on a UAV for mapping, a major consideration is whether to use a rotary or fixed-wing platform. Figure 3 compares the advantages of the two. Rotary UAVs (multi-rotor drones[10]) are popular and relatively cheap for mapping; this category includes quadcopters (drones with four propellers) that can be carried in a backpack-size case. Their portability, price, and ease of use make them the obvious choice for those starting out in UAV mapping on very small survey sites. One downside of using small rotary multicopters is their limited flight time, which is on average a maximum of 30 minutes, covering an area less than 0.5 km^2 per flight. Small fixed-wing UAVs can usually fly longer by taking advantage of their gliding capability, and they fly significantly longer distances than rotary UAVs. A relatively new type of platform is the hybrid UAV combining both rotors and fixed wings. This design allows the UAV to take off and land vertically and make use of wings for extended range. Table 3 compares some popular portable UAVs for mapping.

10. The words Drones and UAV can be used interchangeably.

Figure 3. **Advantages of rotary (left) and fixed-wing (right) small UAVs.**



Source: PacDID. 2017

TABLE 3. Comparison of Popular UAVs for Mapping

UAV MODEL	TYPE	ENDURANCE	MTOW (KG)	RANGE (KM^2)[A]	COST (US$)	WIND RESISTANCE (M/S)[B]
DJI Mavic Pro	Rotary	20 minutes	0.7	0.3	1,000	10
DJI Phantom Pro 3	Rotary	23 minutes	1.4	0.4	1,500	10
DJI S 900	Rotary	18 minutes	8.2	0.3	1,200	10
DJI Matrice 100	Rotary	23–40 minutes[c]	3.6	0.6	3,300	10
SenseFly eBee Classic	Fixed-wing	50 minutes	0.7	1.5	15,000	12
SenseFly eBee X	Fixed-wing	90 minutes[d]	1.5	5	17,000	12.8
Delair DT18	Fixed-wing	120 minutes	2	20	30,000	13.8
WingtraOne	Hybrid	55 minutes	4.5	10	20,000	12
Alti UAS Transition	Hybrid	12 hours	16	45	105,000[e]	13
UAV Factory Penguin B	Fixed-wing	20 hours	21.5	36	100,000	Unknown
V-TOL Goshawk III Surveyor	Fixed-wing	150 minutes	5	20	38,000	12
Wingcopter 178	Hybrid	90 minutes	15	5	80,000	15

Note: MTOW = maximum takeoff weight.

a. Where specs were unavailable, this number was calculated from the combination of maximum speed and endurance values.

b. These are claimed levels, but actual levels are likely lower for quality image acquisition.

c. Time depends on battery configuration.

d. Time indicates the endurance when the endurance extension is used.

e. Value includes Real-Time Kinematic/ Post-Processed Kinematic positioning capability.

Source: Information on UAVs compiled form manufacturers' materials

Other issues to consider when deciding on a UAV for mapping include the following:

- **What is the area of the average site to be surveyed?** If the area is larger than 1 km^2 (~0.4 square mile), a fixed-wing UAV is preferred. Rotary multicopter UAVs could be used for mapping larger sites, but they require several flights and good ground access in order to take off and land within each flight distance range.
- **What is the typical terrain type around the survey site?** Rugged terrain and obstacles on the ground may not allow the use of fixed-wing UAVs, which normally require open spaces (e.g., soccer fields) for takeoff and landing maneuvers. A fixed-wing hybrid with vertical takeoff and landing capabilities would be preferred in this case.
- **What is the budget available?** Typically, small rotary quadcopter UAVs are cheaper than fixed-wing or hybrid models. They also may require less advanced piloting skills.
- **What type of data needs to be collected?** The most basic onboard imaging sensors are small optical digital cameras. These allow capturing images in the visible spectrum range for producing typical red-green-blue (RGB) orthomosaics. Other sensors such as LiDAR and multispectral cameras can range greatly in size and may be used on board larger UAVs for collecting other types of data.

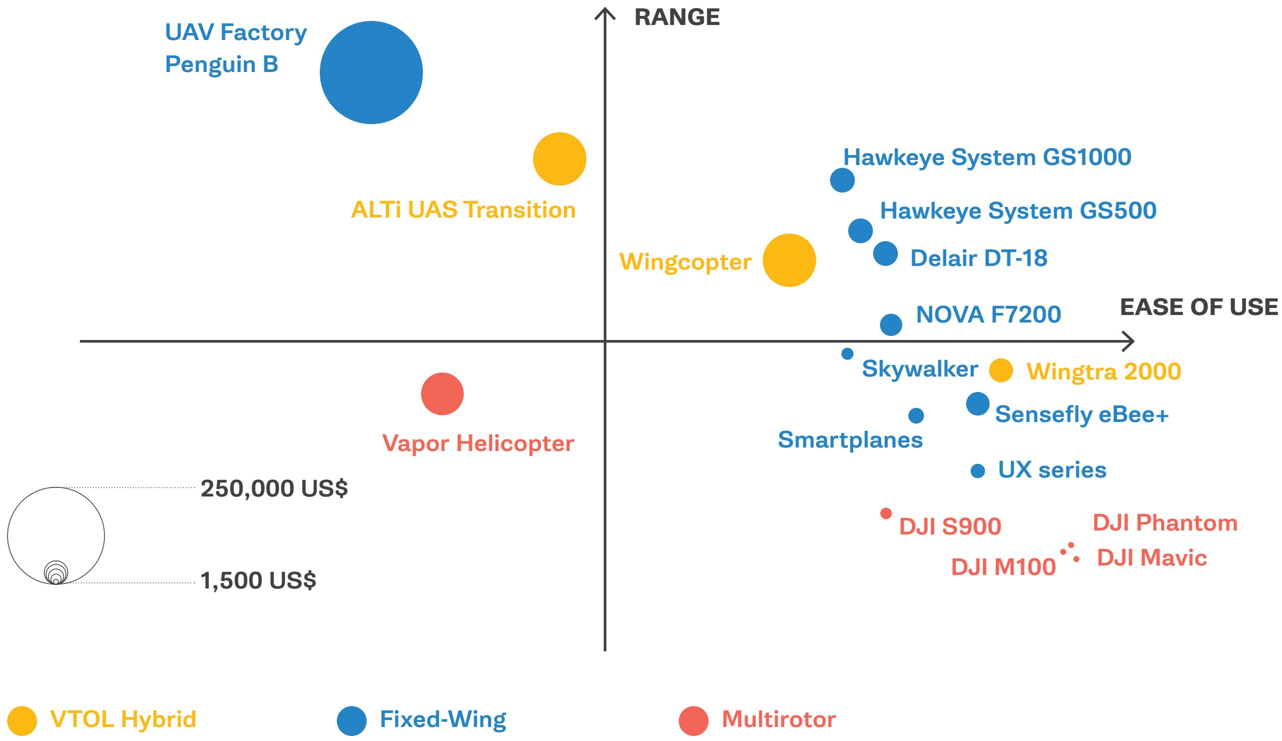
In the context of small islands, or to cover areas of 10 km^2 and more, a high-endurance multirotor, a fixed-wing or a hybrid platform with these characteristics is recommended:

- Proven reliability,[11] for instance as measured in flight hours. When in doubt, inquiries regarding reliability in the setting of its intended use should be made towards the manufacturer before purchasing the platform.
- Foam construction or easily replaceable parts for ease of repair can be helpful in maintaining the craft over the long term. Alternatively, craft that can be serviced close to the location of their use should be preferred.
- Total weight of more than 1.5 kg with a profile that will handle wind and weather conditions on small islands will minimize necessary downtime due to inclement weather. Yet keeping in mind that few to no battery-powered UAVs on the market in early 2019 are rain-proof, the technology is evolving quickly.[12] Wind resistance should be 10m/s or higher when possible.
- In addition, a platform with a flight time longer than 45 minutes is preferable in order to minimize landings, the part of the flight when damage to the platform is most likely to happen.
- Reliable and trialed UAV systems that have streamlined workflows are best suited to high-stress situations such as following disasters.

Figure 4 shows the various UAV platforms available on the market, plotted according to the range, price, and ease of use. If budget is not an issue, use of several platforms could be considered according to the objectives and nature of the survey, where the user would select the optimal platform for the different objectives. **Small multi-rotor UAVs will be useful when quick deployments for aerial images over small areas are needed. Large fixed-wing UAVs lend themselves to large- area mapping.**

11. Choosing a system that has been in use for many years and has a good track record—rather than a prototype or new system—is recommended.
12. Heavy platforms are not recommended for new or inexperienced pilots due to the higher risk these platforms present.

FIGURE 4. **Price, range, and ease-of-use comparison of various UAV platforms available on the market.**



Source: Based on experience from the UAV4Resilience Challenge, aerial surveys after cyclone Gita in Tonga, and informational interviews with professionals and manufacturers.

Note: VTOL = Vertical Takeoff and Landing.


Aircraft

6. Choosing the sensor

Many survey mapping UAV platforms come with built-in or recommended cameras, which are already configured for optimal mapping outcomes. However, built-in cameras may also limit the user's ability to customize optimal sensor configurations.

PREFERRED CAMERA SPECIFICATIONS

The UAV's flight altitude and sensor determine the spatial resolution of the imagery. To put this another way, the focal length, sensor size (size of the chip that detects light), and density of detectors on that chip all influence the altitude required to collect data of a given spatial resolution (i.e., minimum resolvable object size). Most survey mapping UAVs use digital RGB cameras that capture imagery in the visible range of the light spectrum. When the camera can be selected separately, the following characteristics may be desirable:

- **Large detector size.** A larger detector size means that the imagery collected will be of higher quality or fidelity. This is in part because larger detectors are typically found in larger, higher-quality cameras, but also because larger detectors can collect more energy from a given pixel and therefore typically have a much higher signal-to-noise ratio.
- **Uncompressed image formats.** Many cameras record only compressed formats (JPG), which reduces the radiometric quality of the imagery. Sensors that are capable of recording in RAW, TIFF, or other uncompressed formats produce higher-quality images.
- **Trigger control.** Ideally, the camera shutter is triggered by an external system that records the location and time of each shot. This is typically the flight control system (autopilot) or a separate GPS sensor. Many professional-grade cameras have software that enables remote control, but consumer cameras often lack remote trigger ability unless custom modifications are made. For these consumer cameras, the shutter must be triggered continuously by time interval (though not all cameras have even this capability). If triggering by time interval is the only option, the sensor must have a buffer sufficient to enable continuous acquisition at the rate required to collect the forward overlap selected.
- **High-quality prime lenses.** When possible, high-quality prime lenses (i.e., lenses of fixed focal length) should be used. Many smaller sensors do not allow for the use of prime lenses. Where they are absent, the camera should be operated only at the extremes (minimum or maximum of the focal range) for digitally controlled "zoom"; or in the case of variable focal length lenses controlled manually, tape can be physically applied to the focus wheel to ensure that the focal length remains consistent throughout and between flights, which is critical for processing. Wide-angle lenses (~ < 24 mm in 35 mm equivalent) increase view angle distortions and can severely affect the geometric and radiometric quality of the resulting orthomosaic.

- **Calibrated camera model.** Images collected with digital cameras are subject to a certain degree of geometric distortion. A fundamental prerequisite of automatic triangulation (AT) and mosaicking is the accurate calibration of the sensor to undistort captured images correctly. The set of parameters describing sensor and lens geometric properties is called a camera model. For optimal photogrammetric results, each sensor should be calibrated by a specialized laboratory for each lens combination. Several UAV photogrammetric software programs automatically calculate camera models as part of the AT processing routine.
- **Global shutter.** Most consumer cameras employ a “rolling shutter,” which can greatly affect image quality when placed on fast-moving UAVs. In recent years, manufacturers have developed “global shutter” sensors that greatly reduce distortion and image geometry issues.

Increasingly, mapping-UAV manufacturers provide cameras that are already optimized for mapping, minimizing the effort that end users must make to ensure appropriate cameras and calibrations.

Ultimately, the payload capacity of available platforms will determine which cameras can be carried. Some systems have embedded cameras that cannot be swapped, while others allow for different sensor configurations. Digital single-lens reflex (DSLR) cameras with full-frame sensors can be carried only by larger multirotor UAVs. Most portable small UAVs have either embedded sensors or compact cameras that typically weigh less than 500 g. Table 4 compares three common RGB cameras used on mapping UAVs.

TABLE 4. Comparison of Popular UAVs for Mapping

CAMERA	SENSOR SIZE	RESOLUTION (MP)	WEIGHT (G)	PRICE (US$)
Mapir Survey3W	6.17 x 4.55 mm (1/2.3 in.)	12	76	400
Sony A6000	25.1×16.7 mm (APS-C)	24	468	800
Canon EOS 5D Mark IV	36 x 24 mm (full frame)	30	890	3,000

Source: Information on cameras compiled from manufacturers’ materials

TAGGING IMAGES USING GPS

GPS tags matter! For post-processing, each frame taken by the camera needs to be tagged with its GPS location. This is an important process to ensure positional accuracy of the output. If the camera is linked to an onboard GPS, the tagging can be achieved automatically by triggering the sensor through the computer managing the flight (e.g., as waypoints or by time) on the ground. This approach insures that the trigger is included as part of the flight record along with the location and orientation information, permitting extraction of location information for each frame from the flight log.

When operating a sensor system that is not linked to a GPS by design, the only option is post-flight syncing of GPS data with the camera time exchangeable image file format (EXIF) tags. Even when done correctly, this introduces significant error into the location estimates for each frame and is not recommended. Most cameras record frames at only 1 hz (once per second) frequency, which means that syncing to a 1–5 hz GPS record can introduce up to two seconds of error in the syncing process. When compounded with GPS error, this can result in location errors of tens of meters, depending on the flight speed. To achieve the best mapping results, **the sensors and systems used should be linked to a GPS and able to tag image frames automatically.**

OTHER IMPORTANT CONSIDERATIONS

There are other important considerations for choosing a UAV sensor in addition to the camera specifications and ability to tag images:

- **Obstacle avoidance.** Even UAVs that are small and relatively inexpensive (less than US$1,000) now are equipped with basic “sense and avoid” systems that allow the aircraft to detect any obstacle in its path and automatically change course to avoid it.
- **RTK/PPK GPS correction technology.** For accurate data capture, an alternative to using ground control points (described in chapter 7) is to use UAVs equipped with high-precision GPS, which is able to record the position of the aircraft much more precisely than standard GPS receivers. Real-Time Kinematic (RTK) allows high-precision measurements of locations by using a base station with known coordinates that are accurately measured and a radio link or other means to send and receive the correction data from the base station, thus performing “live” triangulation corrections while the UAV is flying. Post-Processed Kinematic (PPK) is similar to RTK, except that the corrections to the GPS positions are calculated not during but after the flight. Both PPK and RTK systems can be purchased as additional features on many professional mapping UAVs.

7. Preparing for the UAV Mission

TIME MANAGEMENT

The actual flying of UAVs is the least time-consuming part of the process. Figure 5 shows the relative proportion of time needed for each step of the entire UAV mapping process, starting from preparation and including flying and post-processing. If the UAV mission will fly under circumstances that require special approvals, it can take anywhere from a few weeks to a few months to obtain these approvals; in addition, the approvals may be expensive, especially in cases where approval to fly higher than 400 ft is being sought. The decision tree shown inFigure 1—taken from the Airshare (n.d.) website—identifies the types of approvals required under different scenarios.

The preparation of flights and post-processing of data consume far more time than the actual flying and data collection. Before any disaster occurs, it is important to have a streamlined approval process and work flow in place for emergency mapping. Having a good relationship with the local CAA is also important to enable smooth operations and communications to avoid risks.

When on site, the following three tasks will be most time-consuming.

1. **Finding an area of operation for takeoff and landing.** The operator should identify potential sites remotely (e.g., through existing satellite imagery) and dedicate a day or more to visually assessing whether the operation sites are acceptable (Figure 6).
2. **Reorganizing priorities due to weather or other unforeseen issues.** Although weather-related changes may be difficult to foresee, budgeting extra days for them can be helpful.
3. **Processing and delivering the data.** This task is particularly important and should be given ample consideration. Based on experience during the Tropical Cyclone Gita response in Tonga, the recommended approach is to complete the delivery of data on site with at least one person working solely on post-processing. This approach is critical under tight deadlines, such as in post-disaster situations.

FIGURE 5. Time needed for the steps of a UAV deployment as a share of the whole process. As indicated by the red arrow, the actual flying of the platform occupies only a small proportion of time.

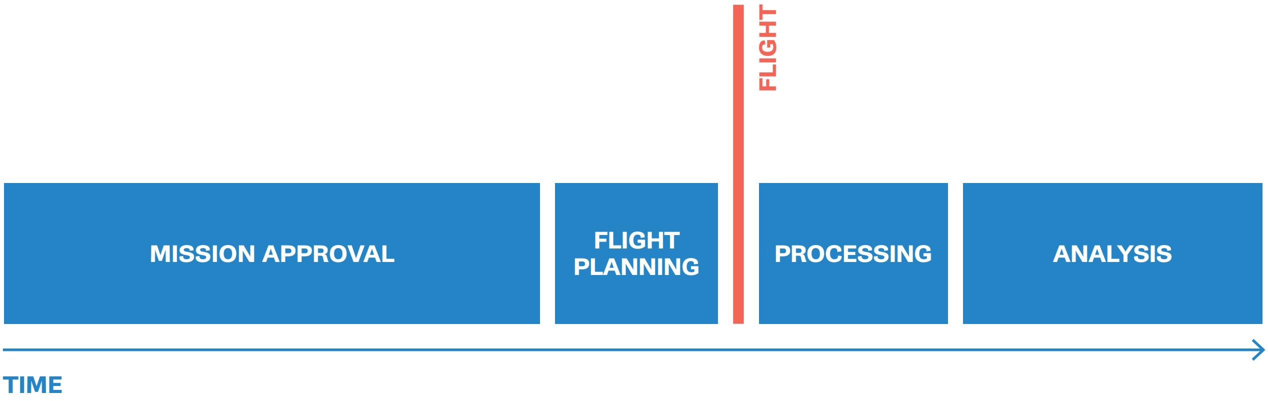


FIGURE 6. A large, open field selected to launch and land the fixed-wing UAV in Tongatapu, Tonga.

Credit: UAV4Resilience 2017

TAKEOFF AND LANDING SITES

The selection of takeoff and landing sites is particularly important if a fixed-wing UAV is being operated. The type and size of platform will determine the area/space needed for landing procedures. An open space with an even surface (such as a sports field) is often ideal. Site selection should begin with a desktop assessment using maps and images, and then include an in-person visit to ensure that the location is suitable for takeoff and landing.

DEFINING THE AREA OF INTEREST AND COORDINATION

The area of interest (AOI) where images will be collected is determined by the mapping needs and environmental conditions. It is useful to plan the mission using preexisting imagery in a geographic information system (GIS) as a backdrop; this step allows checking for obstacles on the ground that could impede takeoff or landing and also offers a view of the topography, land cover, and road accessibility of the operational base (takeoff and landing site).

Airspace designation charts published by CAAs show the classification of airspace and should always be consulted when determining if a UAV mission in the AOI is feasible. Once these factors are reviewed and AOI defined, the AOI polygon along with basic metadata on desired image specifications (e.g., target ground sample distance) can be exported from a GIS and used as input in the flight-planning and coordination software.

FIGURE 7. **Mission planning for the LiDAR survey in Fiji during the October 2017 field testing.**

Credit: UAV4Resilience 2017

With increasingly widespread use of UAVs, the sky can quickly become crowded with flying imaging platforms, both manned and unmanned. This scenario is particularly likely when multiple UAV teams come together after a natural disaster event to map the impacted areas for rapid damage assessment and support to response operations. Coordination with the local CAA is paramount to ensure safety.

To optimize mapping activities, online tools are being developed to allow easy sharing and coordination of "who's flying where." The Imagery Coordination Service,[13] for example, offers an open source platform for requesting imagery collections and facilitates coordination between UAV pilots and other traditional imagery providers (e.g., satellite-imaging companies).

FLIGHT PLANNING

When flying, UAV sensors collect images by frames. After the flight, the frames need to be stitched together to create a mosaic image that shows the entire area seamlessly. The image collection for UAVs assumes a pattern of parallel flight lines and a fairly stable aircraft. Aircraft that are less stable — a category that includes many UAVs — necessitate some changes in the collection strategy.

For example, AT processing requires significantly greater forward and side overlaps to achieve accurate results. Further, images should be collected at a vertical (nadir) or near-vertical angle. Slightly oblique images may still be processed, but results will vary greatly because features on the ground will appear from different perspectives and make it more challenging for the mosaicking software to find matching patterns.

Forward and side overlap — the amount of overlap between frames in the forward and lateral direction from the perspective of the platform's direction of movement — must be properly handled to create seamless mosaics that represent the location of the features in the image. The highest overlap possible should be collected, with a **minimum forward overlap of 60 percent and minimum side overlap of 30 percent** to create a mosaic with good positional accuracy (Figure 8). During operations, there is a tradeoff between the time available for the survey and the overlap. The more overlap, the more time is required to complete the flying. **To produce accurate terrain models, a minimum forward overlap of 80 percent and a minimum side overlap of 75 percent are recommended** to maximize the number of observations of landscape features.

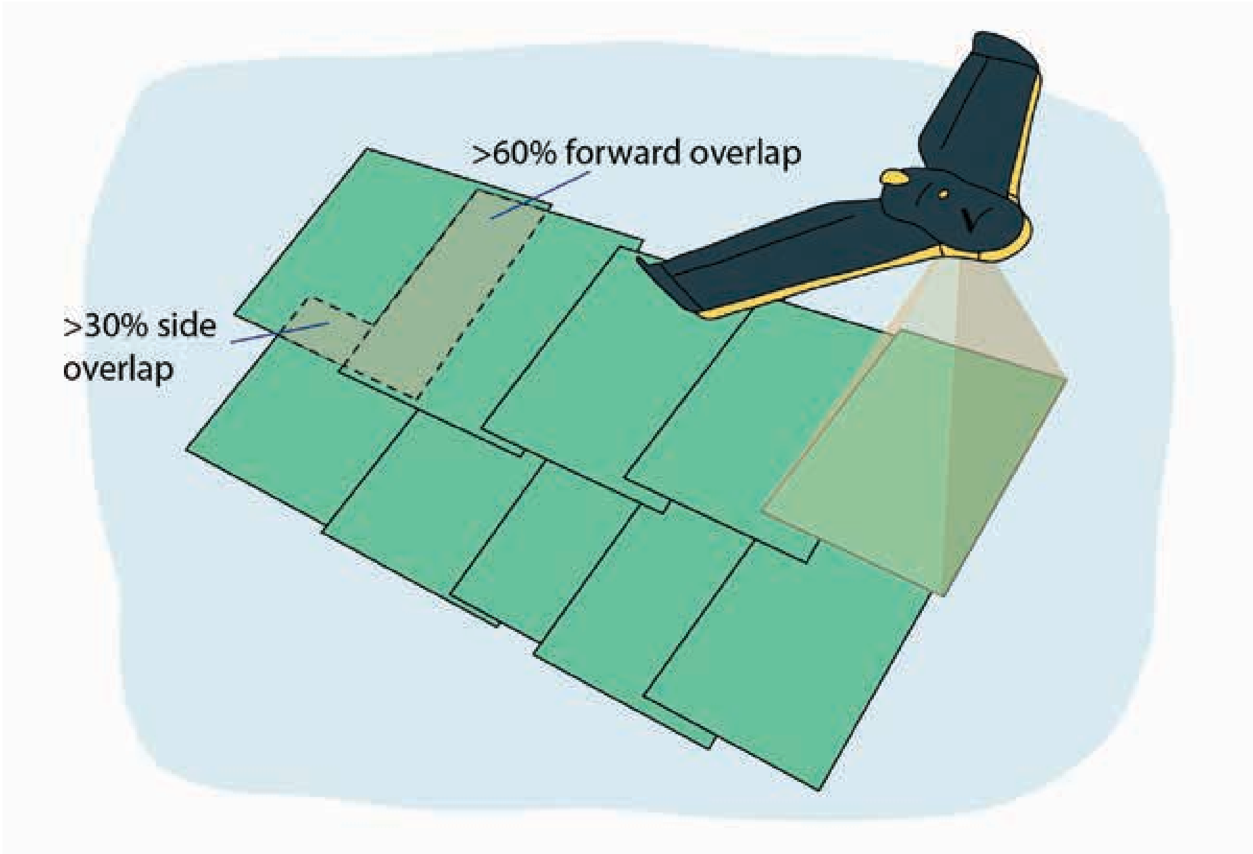
When creating a flight plan, it is important to include extra flight lines and frames outside of the AOI to cover all perimeter zones with enough frames. As a rule of thumb, two extra frames at the end of each flight line and one extra flight line on each side of the AOI are normally enough to ensure proper coverage. Most professional flight-planning software will already account for the need of additional overlap.

Flight altitude should be set at a fixed value above mean sea level for areas with homogeneous ground elevation and should be adjusted above ground level when elevation changes significantly (e.g., mountainous areas). This ensures a consistent overlap ratio between frames even when the distance between platform and target ground changes.

Several UAV vendors provide software to design and create flight plans based on input AOI files, and UAV and camera specifications. These programs can be installed on laptop computers, tablet devices, and smartphones. These applications provide interactive methods for selecting the desired ground sample distance and overlap, as well as for optimizing flight patterns based on the maximum altitude (ceiling) allowed by law, aircraft speed, and camera specifications (sensor size and focal length).

13. Imagery Coordination Service, https://coordination.openaerialmap.org.

FIGURE 8. **Recommended forward and side overlaps to create a mosaic with good positional accuracy.**



Source: PacDID. 2017

FIGURE 9. **Working with the Ground Control Station for mission planning and live monitoring of the flights**

Credit: UAV4Resilience 2017

TARGET LANDSCAPE LIMITATIONS

AT and mosaicking rely on automatic extraction of point features from input images. In the case of imagery collected over visually homogenous pattern areas such as water, bare desert, or snow and ice, it is almost impossible for AT software to discriminate unique points and match frames correctly. Accurate IMU (inertial measurement unit) information may sometimes compensate for the lack of feature points in these areas and provide enough positional information for correct orthomosaicking.

GROUND CONTROL POINT TARGET PLACEMENT

Ground control points (GCPs) are used to ensure high positional accuracy of the final UAV image in case PPK or RTK tools are not available. GCPs are a set of identifiable features in the collected images with known spatial coordinate information. GCPs are normally collected with survey-grade GPS devices that provide centimeter-level precision. These features can be either existing physical objects (e.g., corner of a road intersection) or custom targets manually positioned in advance of a UAV survey across the target AOI (Figure 10). The GCPs should be well distributed across the AOI; otherwise, they could end up skewing the positional accuracy of the final images.

The manual positioning of custom targets can be very time-consuming, as it requires identifying access routes to the areas where targets should be placed, then recording each location with an accurate GPS device. Targets should be large enough to be seen in multiple (at least three) overlapping aerial shots and should be anchored to the ground so they are not accidentally moved by people or wildlife. Depending on the environment, it is good practice to include a note next to each target that explain its purpose; this should minimize interference from residents.

For countries that are serious about establishing UAVs as an accessible platform, investment in robust and durable control points will be worthwhile. If known control points are available, creating a denser network of benchmarks could be recommended. The resolution of UAV imagery is such that the positioning accuracy of GCPs is often less than a few centimeters. To match existing data sets, to compare pre- and post-disaster damages with some degrees of automation, or to conduct engineering surveys, a local geodetic system is required.

When the timeliness of the data is important, **setting up ground control points to achieve high absolute accuracy may not be cost- or time-effective**. In these situations, **a UAV equipped with an RTK or PPK system should be used instead.**

FIGURE 10. **Placing of a ground control point. The accurate coordinates of this GCP are surveyed on the spot using high-accuracy GPS.**

Credit: UAV4Resilience Challenge 2017

8. Managing work flow in the field

UAVs are often small enough to be carried in backpacks, but usually a motor vehicle such as a small pickup truck is used to carry the associated equipment, including the survey equipment (base station) if GCPs are being used. A vehicle also provides shelter in case of inclement weather, and the vehicle battery or cigarette lighter plug can be used to recharge UAV batteries and laptops in the field during long survey missions.

Teams in the field should include at least two people: a pilot who monitors the UAV's flight on the computer screen, and a pilot who maintains sight of the UAV and surrounding airspace at all times while flying within line of sight.

At the takeoff location, the team's designated safety officer ensures that all precautions are taken before, during, and after flights.[14] At this point, it is assumed that all legal prerequisites to fly a UAV have been obtained, including special permissions and communications instructions, especially those applicable during an active disaster response scenario. To identify cases where New Zealand–based UAV regulations require special permissions, please refer to the Airshare website (Airshare n.d.).

A generic pre-flight **safety checklist** can include the following steps:

- Verify proper distance from residential areas, people, overhead power lines, trees, etc.
- Inspect takeoff site; identify alternative options for landing
- Communicate with air traffic control and provide updated flight plans
- Check weather conditions, particularly wind speed and direction
- Inspect UAV, batteries, and radios for any anomaly
- Ensure that batteries are fully charged
- Test telemetry link and (if available) failsafe sensors/mechanisms
- Acquire GPS lock and verify home location recording
- Ensure safe distance between aircraft and any bystander
- Verify flight plan perimeters.

14. The safety officer may be a third person, or one of the two pilots who takes on this additional role. The safety officer is responsible for ensuring all pre-flight checks are followed and that conditions to fly are appropriate (i.e., wind and cloud ceiling at minimum thresholds, clear skies). Depending on the procedures that have been agreed, the safety officer may also be responsible for communications with ATC for airspace deconfliction.

Most commercial UAV platforms come with a safety pre-flight and post-flight checklist that should be followed. At every step from launch to landing, the designated safety officer should coordinate actions and communications (with loud voice signals). While in flight, the aircraft should be kept within visible range unless special permission has been obtained and tracking equipment is available for flying beyond the visual line of sight. After each flight the aircraft should be inspected for any anomaly.

Light and weather conditions are important. To minimize shadows in the image, it is best to fly during the day when the sun angle is high. The color depth and tone of imagery is also best when collected in full sun. Clouds, even light haze, obscure the signal in the scene and make use of the imagery challenging, if not impossible. High or even moderate winds may likewise pose difficulties, as many light UAVs do not operate well in such conditions. The day and time chosen to collect the imagery is therefore critical. Data collection should ideally be done between 10 a.m. and 2 p.m. to minimize shadows and on a clear day to minimize haze and cloud effects; it should also take into account the limitations of the platform with respect to wind and operating range (Figure 11).

It is always important to modify settings to suit local lighting conditions prior to each flight. Preferred sensor settings are listed below (in order of preference where more than one setting appears).

- Focal length: fixed
- Operating mode: manual, shutter priority (shutter 1/1000–1/1500)
- Format: RAW, TIFF, low-compression JPEG
- Focus: infinite
- Flash: off
- Auto-rotate: off
- Optical/digital stabilization: off
- Metering mode: full-frame metering rather than "spot" metering (to reduce exposure issues)

The most important step before starting a UAV mission is to upload the flight plan to the aircraft onboard computer. This can be done in different ways, but usually from a laptop or mobile device that provides a screen visualization of flight patterns over preexisting imagery or maps. This visual check allows for verification of the home (takeoff) setting and its relative position to the flight extent.

FIGURE 11. Checking conditions and following safety measures in the field.

Source: PacDID. 2017

FIGURE 12. **Launch of a multirotor UAV, which requires less open space than for a fixed wing.**

Credit: UAV4Resilience 2017

Once the flight plan has been uploaded into the aircraft computer and final checks have been performed (and all necessary approvals have been obtained and communicated), the UAV is cleared for takeoff.

It is important to note that all mapping UAVs must be flown in autonomous mode following a predefined flight plan in order to obtain images suitable for creating a mosaic. In general, manual flights where pilots maneuver the aircraft remotely cannot ensure that the correct pattern is being followed and enough overlap is maintained between frames and flight lines.

After takeoff, the aircraft should be checked for any anomaly (through visual and telemetry feedback) before starting the autonomous mission. The pilot should always be ready to take over in manual control mode if needed.

Once the UAV has landed, images and GPS logs are transferred to a local device either through the radio link or by physically removing the storage medium (typically an SD card) from the aircraft for copying files to a laptop. When multiple flights are planned, data are transferred at the end of the mission and only the battery is swapped between flights. It is still important to sample image quality by transferring a few full resolution files from the camera to a device used for inspection. In case of any issue, the camera settings should be checked and adjusted.


DO NOT MOVE

9. After the flight: processing the data

Flying and collecting imagery is often the easiest step in UAV mapping, while preparing and processing imagery often requires significant computing and human efforts. Photogrammetric software that employs processes such as Structure from Motion (SfM) is actively and continuously improved to reduce the level of effort required and to automate the processing work flow.

PROCESSING SOFTWARE AND HARDWARE

Most software used to process UAV data is developed by commercial firms and offered through pricey subscription options or permanent desktop licenses. Some of the same companies also offer cloud-based processing services that allow for uploading imagery to scalable cloud computing infrastructure.

In environments with limited Internet connectivity, this option is often not suitable for UAV mapping projects, which require uploading massive amounts of data (tens to hundreds of gigabytes) to the cloud before processing can start.

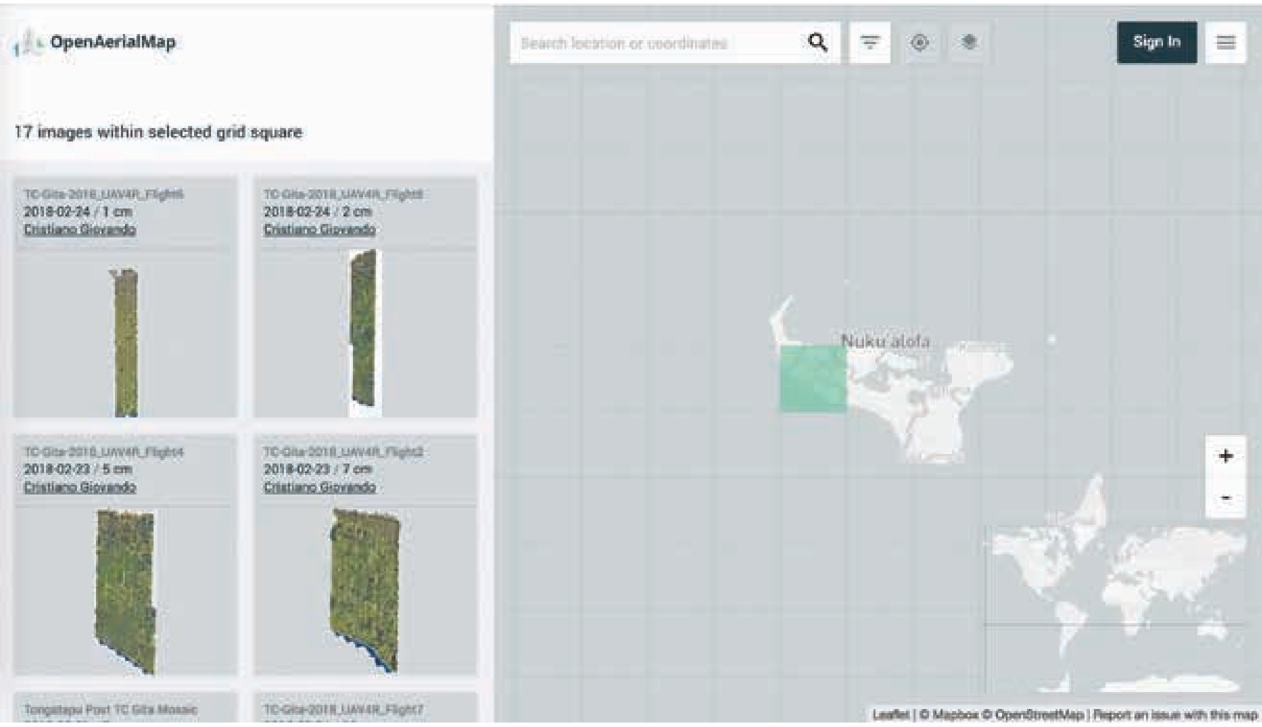
As of 2018, the open source options for UAV imagery processing software are quite limited. The most popular and mature programs are OpenDroneMap and its sister project WebODM. Table 5 lists some of the most popular UAV processing software available and its pricing.

TABLE 5. Comparison of Popular UAV Image Processing Software Programs

SOFTWARE	OPTIONS	LICENSE	MONTHLY / PERMANENT PRICE (US$)
DroneDeploy	Cloud	Commercial	399 (monthly only)
Pix4Dmapper	Desktop + cloud	Commercial	350 / 8,700
Photoscan	Desktop	Commercial	3,499 (permanent only)
Correlator3D	Desktop	Commercial	295 / 5,900
OpenDroneMap	Desktop	Open Source	Free

Source: Information on software compiled form manufacturers' materials

FIGURE 13. User interface of OpenAerialMap.org showing UAV images that are available for Tonga.



Source: Open Imagery Network contributors. Licensed under Creative Commons Attribution 4.0 International (CC BY 4.0), https://creativecommons.org/licenses/by/4.0/legalcode.

Several UAV manufacturers offer processing software along with their UAVs, which can result in a significantly lower final cost than if UAV hardware and software are bought separately. It is worth inquiring before purchasing a mapping platform what software is included in the purchasing price. Using software that is provided with the mapping platform is often the best option.

The average amount of data processed in UAV mapping is large, often larger than in traditional GIS projects. Like many remote sensing projects, UAV mapping requires intensive computations and large storage and memory capacity for data processing. This type of processing is normally done on large workstations set up with multicore CPUs, at least 16GB of RAM, and fast solid-state drive (SSD) disks. Some key processing steps employ computer vision (CV) algorithms, which require advanced graphics processing units (GPUs) that are typically found only in expensive scientific and gaming video cards.

Desktop workstations for UAV image processing can cost anywhere from US$2,000 (low end, for projects up to ~1,000 image frames) to US$10,000. As processing often needs to be done in the field or while deployed in a disconnected environment, a bulky workstation is not the ideal solution. A valid alternative for small to medium-size projects (100–5,000 frames) is offered by gaming laptops, which are often already equipped with configurations similar to those needed for UAV image processing (advanced CPU, SSDs and large storage, sizable RAM, a dedicated video card). In addition, if processing is to be conducted in the field, it is advisable to use ruggedized equipment and to have several charged battery packs as backup options.

POST-PROCESSING WORK FLOW TO CREATE ORTHOMOSAICS

Whether on a desktop, on laptop, or in a cloud computing environment, the processing work flow to obtain orthomosaics from UAV-collected imagery is very similar. The main steps involved, mostly performed automatically by the software, are the following:

1. Import image files (and optionally create overviews).
2. Import GPS log and match with images (not necessary if GPS information is already available through image EXIF metadata).
3. Select processing parameters and algorithm types (if choices are available).
4. Extract features/points from each frame.
5. Create camera model.
6. Carry out feature matching and automatic triangulation.
7. Carry out bundle block adjustment and AT model refinement.
8. Import GCPs and carry out manual matching to corresponding image features.
9. Conduct color balancing.
10. Generate dense point cloud and digital surface model (DSM).
11. Extract digital terrain model (DTM) from DSM (with optional manual editing).
12. Carry out seamline generation and make manual adjustments.
13. Carry out orthomosaic generation (with optional overviews generation).
14. Issue output of final products in GIS-compatible formats (e.g., GeoTIFF).

Processing 200 image frames locally on a gaming laptop to produce an orthomosaic typically requires one to two hours to complete. Some of the manual steps include importing input files (images, GPS log, etc.) and matching GCPs. Everything else can follow predefined processing parameters and eventually be scripted to run fully autonomously.

A processing report is usually generated by the software, including quality control and assurance indicators about the processing work flow and the final data products. For example, it's possible to use a number of GCPs as "checkpoints" to verify the internal and absolute positional accuracy of the output model compared to known reference locations. Root-mean-square error tables and charts are often available in the report to assess each point's horizontal and vertical accuracy against predicted values.

DATA PROCESSING FOLLOWING 2018 TC GITA RESPONSE SURVEY

During the field surveys conducted in February 2018 (see chapter 11 for more details), the imagery data were processed by individual flight. As a result, the island of Tongatapu was divided into strips of smaller orthomosaics that each corresponded to a UAV flight. To improve the accuracy of the results and radiometric quality across the whole island, all the imagery was subsequently processed into one large block, generating a seamless mosaic that covered the entire island area (more than 260 km^2). To make this large orthomosaic easy to share with end users, the large GeoTIFF file was then divided into 1 km^2 tiles. Figure 13 shows some of the strips from the original UAV flights (on the left of the image), while Figure 14 shows the boundaries of the reprocessed 1 km^2 tiles. The orthomosaic of the whole island was uploaded to OpenAerialMap.org.

FIGURE 14. **Image showing location of the structures assessed as damaged (in orange) and destroyed (in red).**

Source: Open Imagery Network contributors. Licensed under Creative Commons Attribution 4.0 International (CC BY 4.0), https://creativecommons.org/licenses/by/4.0/legalcode.

SHARING DATA AND IMAGERY

All geospatial data produced by UAV data processing software should be outputed into formats that can be readily consumed in common GIS programs such as ESRI ArcGIS and Quantum GIS. Data created using UAVs can be shared in various ways. For instance, DTMs, DSMs, and point clouds can be shared on opentopography.org as open data. Orthomosaics can be shared by uploading onto the OpenAerialMap platform (Figure 13). These orthomosaic datasets are foundational layers of information used in many humanitarian and surveying project applications, from baseline mapping (tracing) to remote damage assessment.

Sharing of UAV data and imagery must take into account both product formats and privacy issues:

- **Product formats.** The generated output imagery mosaic is often a very large raster file (from tens to hundreds of gigabytes), with three bands of RGB value combinations representing colors in the visible range of the electromagnetic spectrum. The most common format for output is GeoTIFF. In order to facilitate handling and opening of such large files, the full mosaic may be split into same-size tiles, labeled in a grid sequence, and indexed by a shapefile or other schema file (e.g., VRT). Other options for portability and sharing include lossless (e.g., LZW) and lossy (e.g., JPEG 2000) compression algorithms that can drastically reduce the final file size.
- **Privacy issues.** Compared to typical satellite images, UAV imagery offers an incredible level of detail. This feature allows for novel applications, such as identification of damaged structures after a hurricane or earthquake. But it also raises privacy issues, especially when such high-resolution imagery is shared with others outside of the project for which UAV flying was authorized. The UAViators' code of conduct (UAViators, n.d.) and summary of best practices (UAViators 2015) can help guide decisions on how to handle and share collected imagery. If necessary, measures such as downsampling or blurring can be taken to protect people's privacy or respect the sensitivity of specific areas.


FRAGILE
DO NOT MOVE

10. Handling project management

Managing a UAV project requires attention to a number of concerns:

- **Lithium batteries.** Lithium polymer (LiPo) batteries used in UAVs are highly flammable and must be transported in LiPo safety bags when traveling. On commercial flights, passengers are allowed a maximum of two 100–160 Wh batteries, which must be kept in carry-on luggage.[15] Quantities of smaller batteries are not usually limited, but some airlines or airport security staff may take away what they perceive as excessive quantities of batteries. Before traveling with batteries related to a UAV mission, it is advisable to obtain the airline's transport policy in writing so there will be no question of permissibility.
- **Power supply.** When working in the field, power can be limited. A good power supply should be ensured both on site and at the facility where processing of the data will take place (e.g., solar charger or car inverter in the field; reliable electricity or on-site generator at the hotel or office).
- **Food, water, shade.** UAV missions should plan for food, water, and a source of shade in the field. In some locations, and particularly after a disaster has occurred, it may be difficult to purchase food and water on site. Because UAV operations require outdoor work during the hotter hours of the day, it is also important to have an umbrella or tent to protect people and equipment from overheating.
- **Daily planning.** The hours available for UAV flights can be limited by weather and sunlight. It is advisable to plan all aspects of the day's work, including worst-case scenarios, on the preceding evening. This approach ensures that valuable daylight hours are used for flying rather than planning and coordination.
- **Mission reports.** During the mission, the operator should keep a daily log that records flights, any issues encountered, and recommendations for future missions. This gathering of small but key details of the day-to-day operations—such as turnaround time, number of failures, potential for schedule delays—can be helpful in estimating potential extra costs and improving budgeting, planning, and execution of future missions.

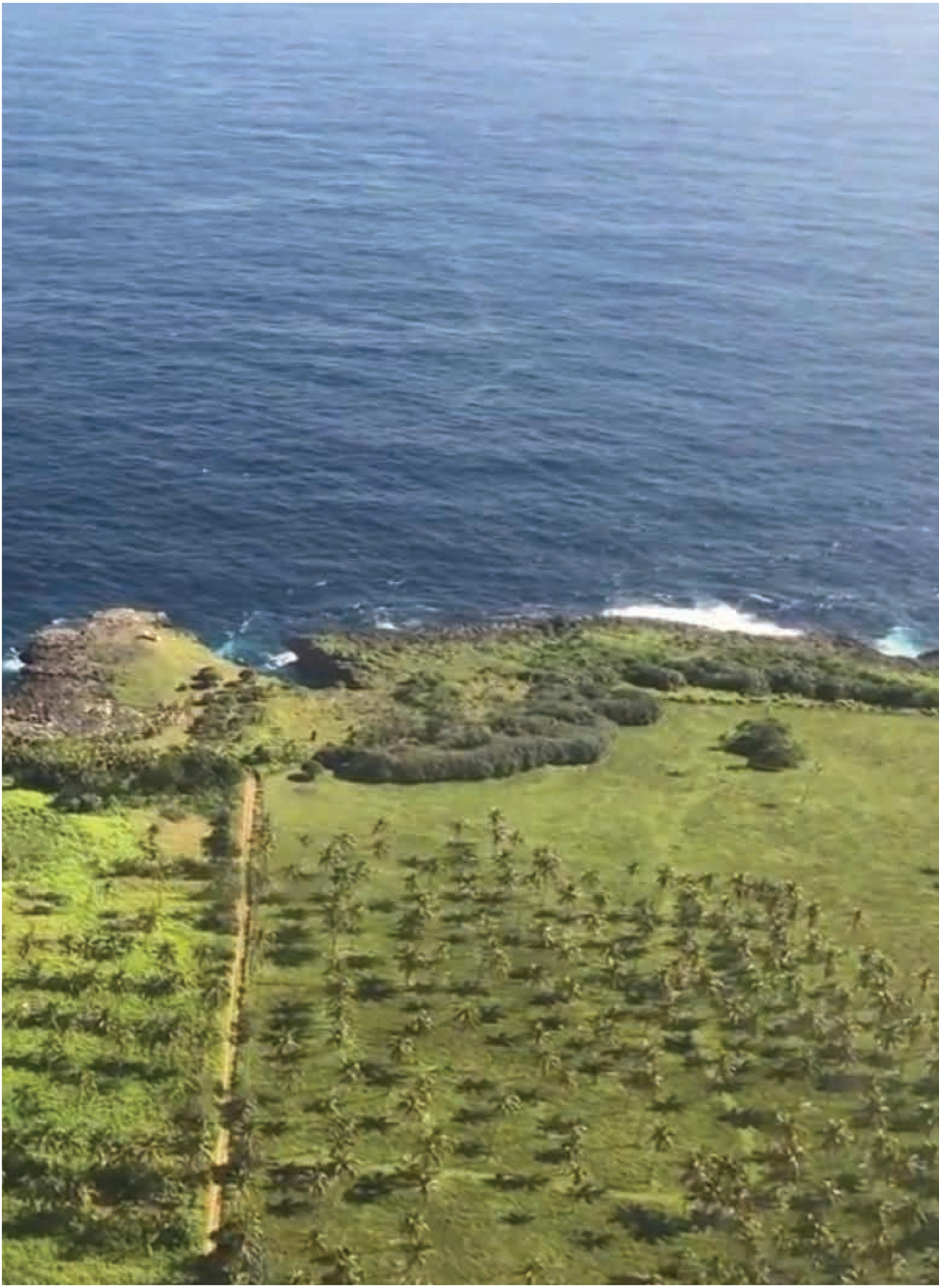
15. For more information, see IATA (International Air Transport Association) guidance at http://www.iata.org/whatwedo/cargo/dgr/Pages/lithium-batteries.aspx.

- **Collaborators and service providers.** In many situations, hiring local professional service providers can be an efficient way to implement a survey. Local professional firms are likely to have already met relevant regulatory requirements (i.e., are likely certified or registered), so this approach can save time. It can also simplify logistics because local service providers know the operational context, the terrain, and the population. Finally, it can save money, since it obviates shipping of equipment and hiring of international experts. Of course, any local service providers hired must have the adequate expertise and experience for the project. Table 6 offers some guidance on skills profiles and equipment that may be needed for various types of mapping.
- **Maintaining skills.** Flying UAVs during and after emergencies requires a high level of skill. To ensure readiness in these high-stress situations, training should be ongoing. More specifically, operators should regularly practice and train in the piloting skills that are needed during emergencies. All flights during emergency operations must be premeditated and based on training with the responsible emergency personnel and authorities; otherwise well-meaning operators risk seriously interfering with emergency response activities.

TABLE 6. Sample Sensor Types and Experts Needed for Various UAV Data Applications. Table created by the UAV4Resilience team.

PROJECT TYPE	SENSOR TYPE	RESOLUTION	ACCURACY	Experts
Crop monitoring	Red edge or multispectral	As low as 30 cm/pixel	5 m	Remote sensing specialist; agronomist
Urban mapping	Standard RGB camera	2–10 cm/pixel	< 10 cm; requires use of GCP or RTK/PPK	Urban planner; machine learning specialist
Disaster mapping	Standard RGB camera	10 cm/pixel[a]	1 m	Disaster recovery management specialist; machine learning specialist for damage assessment (if crowdsourcing is not used)

a. UNICEF Malawi uses 7 cm/pixel resolution for flood mapping.



11. Case Study: Post–Tropical Cyclone Gita Mission in Tonga

On February 12, 2018, Tropical Cyclone Gita hit the island nation of Tonga as a Category 4 hurricane, causing major damage across Tongatapu, the main island, as well as the neighboring island of Eua. The total economic loss was estimated at approximately 38 percent of gross domestic product, triggering international support for long-term recovery. At the request of Tonga's National Emergency Management Office, the UAV4Resilience (UAV4R) team deployed to Tonga to capture post-disaster UAV aerial images.

The main challenge was to fly as quickly as possible while still meeting all regulatory requirements. Because the plan was to fly above 400 ft, the team had to seek additional permission from the Civil Aviation Authority, just as for the October 2017 field-test missions. The approval process took three weeks to complete and modifying any flight plans for complex airspace operations took between one day and one week (more detail is in annex 1). The logistics involved in reaching the island were also challenging. Eventually, the Australian Department of Foreign Affairs and Trade (DFAT) emergency response team offered the UAV4R team transport from Brisbane to Tonga on a C17 military aircraft.

COLLECTION OF POST-CYCLONE UAV DATA

As is often the case with emergency response flights when time is of the essence, a balance had to be struck between high absolute positional accuracy and speed of flying and post-processing. The UAV4R team compromised on positional accuracy in favor of faster flying and data processing. Having flown UAVs in Tonga just four months prior to the cyclone, the team already had a valid Part 102 New Zealand certificate to fly and also knew all the takeoff and landing sites, which saved time.

Moreover, the collection of baseline data only a few months before Tropical Cyclone Gita hit Tonga proved to be invaluable. It not only provided usable data for post-disaster comparison, thus facilitating accurate damage assessments; it also acted as a trial run for the actual disaster, thus enabling the development of procedures, location of suitable flight areas, and rectification of problems. Figure 15 shows an example of the same structure before and after the Cyclone.

From the two data collection processes — one before and one after the disaster — two main lessons emerged:

1. **A three-person crew works well in a post-disaster setting.** In a post-disaster scenario, where rapid data are critical, UAV operations are typically carried out for as long as the weather and light permit. The full day of flying means that hours are spent at night ensuring batteries are charged, data backed up, missions planned, and equipment ready for the next day. Experience suggests that it is useful to operate with a three-person crew, with two in the field collecting data and operating the aircraft, and the third serving as ATC liaison and processing data from the day before. Rotating the third person through the data collection and flight crew to serve as ATC liaison provides crew members with a rest, while also ensuring progress on data collection/processing.

2. **Additional technology may be necessary to improve situational awareness in the airspace.** When operating in post-disaster airspace, air traffic controllers will be hesitant to allow atypical operations that they do not have clear situational awareness of. They may find that use of a dedicated real-time positioning system such as UTM (Unmanned Traffic Management), or an existing technology such as ADS-B (Automatic Dependent Surveillance–Broadcast), provides a layer of comfort and routine to the nonroutine operations. Smoother ATC in turn can facilitate extended UAV operations.

The two missions combined represent a total budget of about US$0.5 million, which includes many experimental elements during the field test. The amount of information collected from these two missions represents millions of dollars in field work and data interpretation. Not only did the UAV collect images of urban damage, it also collected images of cropland and shoreline. In one two-hour flight, the UAV covered more than 12 km^2, or 24,000 acres, acquiring more detailed imagery than could be produced by a satellite — and doing so more than 10 times faster than a ground crew conducting the same work.

FIGURE 15. **Images showing pre- and post-event status of the same structures.**

Credit: Open Imagery Network contributors, UAV4R Team (World Bank and VTOL Aerospace)

APPLICATION OF POST-CYCLONE UAV DATA

The UAV data collected in Tonga following Tropical Cyclone Gita was used for several purposes:

- **Crowdsourced building damage assessment by the Humanitarian OpenStreetMap Team (HOT).** The pre- and post-event UAV images were used to carry out a crowdsourced damage assessment. A small subset of volunteers from HOT were tasked with doing the visual interpretation of the damage to housing. A simple classification scheme was used: houses that appeared to be more than 50 percent damaged were labeled "destroyed," and those that appeared to be less than 50 percent damaged were labeled "damaged" (Figure 16).

This classification scheme is rather different from the three-class system (destroyed, damaged, not damaged) that engineers on the ground used, so it is difficult to compare the two sets of results. The ground survey by the National Emergency Management Office initially identified approximately 3,000 houses as damaged, whereas HOT estimated the number at around 2,500. Both sets of numbers must be taken with a pinch of salt, as both have continued to fluctuate. However, in terms of order of magnitude, the two are aligned. To improve the accuracy of housing damage assessments, and also to make the two approaches comparable, a unified damage classification scheme must be developed.

FIGURE 16. **A house destroyed by Tropical Cyclone Gita in Longolongo village, Tongatapu, Tonga.**

Credit: World Bank

- **Supporting the claims validation process.** The housing sector bore the brunt of the damage caused by the cyclone. The rapid assessment conducted by the World Bank, Asian Development Bank, and other partners indicated that approximately 25 percent of the housing stock had been damaged or destroyed. In May 2018, the government decided to provide support to households whose housing had been affected by the cyclone. The cash transfer beneficiary list was developed based on the damage assessment conducted by the government; and in keeping with common practice globally, grievance redress systems were put in place to allow homeowners to appeal the government's decision on the damage to their house. Problems arose when homeowners started repairing their houses after the event without waiting for the government assessment to take place. Thus by the time the government damage survey was carried out, some of the houses had already been repaired — meaning that the beneficiary list failed to include some homeowners whose house had indeed been damaged by Tropical Cyclone Gita. The UAV images, however, showed the condition of structures two to three weeks after the event, and thus were instrumental in supporting the claims validation effort.
- **Quantifying the damage and recovery needs of school buildings.** The pre- and post-event images were used in the detailed first-order estimates of the reconstruction and repair needs of schools, which suffered significant damage in the cyclone. Some 75 percent of the schools on Tongatapu, for example, reportedly were affected by the cyclone. The UAV images were sufficiently detailed to allow quantification of the number of classrooms, staff quarters, toilets, etc. that were damaged or destroyed; the images were also used to develop the repair and reconstruction plan for the education sector.

12. Conclusions

The agility and versatility of UAVs as data collection platforms stand to significantly improve the availability of timely spatial data to small island countries. UAV technology should be harnessed to further improve resilience, risk reduction, and disaster response work in small island contexts. To ensure that this work can go forward, adequate capacity building, training, and preparation are needed. This Guidance Note has discussed the most important factors to take into account in using UAVs and UAV technology effectively.

Given the myriad of options available for platforms, software, and sensors, there exists no one-size-fits-all approach to UAVs. Instead, interested parties are encouraged to experiment with various systems and configurations while also building on best practices. The field is rapidly and constantly evolving; as new technology becomes available, it opens up new possibilities and optimizations in this work.

Last but not least: while the innovation around UAVs is surely exciting and experimentation is encouraged, the safety of airspace users and those on the ground is of utmost importance and should always take precedence over other objectives. Any serious UAV operator or user of UAV technology should seek professional training in how to fly responsibly in the relevant airspace. Exemplary and careful use of the technology will help build trust among the public, governments, and private sector and help ensure that UAV technology and related innovations can be used for beneficial applications going forward. Every operator has a role to play in shaping a responsible community of UAV operators.

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Annex 1. Applying for Approvals in Fiji and Tonga for October 2017 UAV Field Testing

FIJI

CAA Fiji outlined the following path to obtaining necessary approvals for UAV operation:

1. Submit completed Form OP138 to CAA, accompanied by the following documents:
    - Proposed pilots' remote pilot licenses
    - Letter of intent from the sponsoring organization, such as the World Bank
    - UAV operations manual
    - Third-party liability insurance cover letter
2. Obtain permission from the operator of the airspace—i.e., Nadi Airport Tower (the air services provider at Nadi Airport for Airports Fiji Ltd.)—to operate up to 400 ft AGL via a NOTAM (Notice to Airmen) request.
3. File a TAF2000 form to obtain an import permit from the Telecommunications Authority of Fiji for all transmitting devices.

After processing submitted materials, CAA Fiji granted the approval to operate up to 200 ft AGL. However, for permission to operate up to 400 ft AGL, Airports Fiji Ltd. required submission of a NOTAM and provided the standard NOTAM request form to be filled out.

Table 7 presents the time needed for obtaining approvals in Fiji. The durations are based on the experience of an Australia-based firm with experience working and training with CAA Fiji and should thus be considered best-case scenarios.

TONGA

The following list provides a breakdown of the documents that are required to be completed and submitted to obtain the Part 102 Exposition under the New Zealand CAA regulations which is valid for Tonga;

- RePL's and Police checks of the proposed pilot's
- Letter of intent from the World Bank
- Insurance cover letter
- Part 102 Exposition*
- Part 101 Compliance Matrix*
- Part 102 Compliance Matrix outlining the element by element compliance with the Part 102 Rules*
- UAV Operators Safety Management System
- UAV Operators Maintenance System Manual
- Aircraft/ Platform Flight Manuals
- Aircraft/ Platform Maintenance Manuals
- Fit and Proper Persons tests for key personnel.

TABLE 7. Time Needed for Obtaining Approvals in Fiji

APPROVAL DOCUMENT TYPE	DURATION (FROM REQUEST TO APPROVAL)
OP 138	5 Weeks
NOTAM	4 Days
TAF 2000	2 Days
TOTAL DURATION	**6 WEEKS**