

# How Much Stabilization is Required for the Broad Area Persistent Surveillance Application?

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## ABSTRACT

Broad Area Persistent Surveillance (*BAPS*) is a surveillance application where a Wide Field of View (*WFOV*) sensor array is made to stare at a fixed point on the ground for a prolonged period of time. A stabilized *gimbal* system is used to stabilize and steer the sensor's Line of Sight (*LOS*) to this fixed point.

It is through persistence that patterns of behaviors and networks of activities are exposed. The data collected may be used in real time or for forensic analysis after an event. One of many potential applications for this technology relates to Vehicle Borne Improvised Explosive Devices (*VBIED*'s).

"How much stabilization is required?" is a question that *BAPS system* architects are asking. Some see high performance stabilized *gimbal* systems as expensive and performance "overkill". Some argue that stabilization is not required at all.

The purpose of this paper is to provide the reader with the information needed to make an informed decision with regard to the "How much stabilization is required?" question. We will look at this question from a *BAPS* requirement, stabilization availability, and a cost/benefit point of view.

For a detailed description of stabilization and *gimbal* technology in general, it is strongly recommended that the reader first read "Stabilization, Steering, and *Gimbal* Technology as it relates to Cinematography". This is another paper provided by PV Labs Inc. It defines a classification system for stabilized *gimbals* and discusses their attributes and weaknesses. The paper also discusses frames of reference and steering modes. A clear understanding of these principles is required to appreciate the technological requirements of the persistent stare application.

Items that appear in *italics* are defined at the end of this paper.

## INTRODUCTION

If we look at the pointing requirements of *BAPS* it should be clear that a steerable *LOS* is required. This

is necessary to compensate for vehicle motion in the orbit. The lack of steering on the *LOS* will limit the persistent area (poor efficiency). Depending on what is required in terms of efficiency, 2 or 3 axes of steering are needed. Aircraft crab and bank must be compensated for as a minimum, and image orientation can be controlled as a bonus with a 3rd axis.

For the *BAPS application* a fixed image orientation allows up to 27% more of the image area to be persistent. This efficiency comes at the expense of requiring a slip ring or *FORJ* to pass the sensor signals through the additional axis.

If an *INS* is to be used as part of the *GEO-registration*, *Orthorectification*, or *image stitching* process then a high performance *IMU* is required to measure the *LOS*'s position in space. Given this, it seems natural to use that same high performance, measuring instrument to close the steering loops. If we do close those steering loops with an inertial based sensor then we have a stabilized *gimbal* system. Beyond that we are just looking to determine the performance requirements of that stabilized *gimbal* system.

## STABILITY

When discussing stabilization technology, stability usually refers to *LOS* jitter. However, in the *BAPS* application there are three important forms of stability that the *gimbal system* is responsible for: *LOS* Jitter Stability, *GEO Steering* Stability, and *INS* Error Stability.

*LOS* jitter is high frequency and can cause smearing of the image during the integration time of the camera. The desire to extend the operating range of any given camera technology into lower light levels with longer integration times drives the requirement for jitter performance. High performance *gimbal* systems like the PV Labs LDG, reduce this jitter to below 5  $\mu$ R *RMS*.

The stability of the *GEO steering* control loop can cause the *FOV* to wander about the desired point.

This will reduce the effective area persistently covered. Target altitude errors will affect performance.

The third form of stability shows up after the images are *GEO registered*. Any inaccuracy in the *GEO location* of the LOS will cause static items in the *FOV* to move in the image. This would interfere with any automated tracking process that removes the static items from the image. There are several factors that contribute to this error: *LOS to INS alignment* errors, *INS* sensitivity, and terrain map errors.

### **STABILIZATION REQUIREMENTS**

If we have a focal plane array with a pixel pitch of 9µm and a lens with a focal length of 135mm the Instantaneous Field of View (IFOV) of one pixel will be:

$$\text{IFOV} = P_p / f = 9\mu\text{m} / 0.135\text{m} = 66.7 \mu\text{R}$$

#### **LOS Jitter Stability:**

Propeller aircraft used for the BAPS application typically have a resonance peak at between 100 – 150 Hz as the primary source of vibration. We typically see greater than 500 µR (peak) or 1mR *p-p* of angular jitter at the *LOS* without stabilization.

Therefore at 100 Hz the *LOS* can move 1 mR in 5 ms. This means the *LOS* can move 200µR/ms of integration time. In terms of pixel motion this is:

$$200\mu\text{R}/\text{ms} / 66.7\mu\text{R}/\text{pixel} = 3 \text{ pixels}/\text{ms} \text{ of integration time.}$$

If we wish to keep the pixel motion down to below ½ pixel (smearing) we must stabilize the *LOS* movement to below 33.3µR during the integration time of the camera. At 100 Hz (f) input you could allow:

$$\text{Jitter}_{p-p} = 33.3 \mu\text{R} / (T_i \text{ s} \times 2f \text{ Hz}) = 0.1665\mu\text{R} / T_i$$

Where  $T_i$  is the integration time of the camera.

$$\text{For } T_i = 1 \text{ ms the allowable Jitter}_{p-p} = 166.5\mu\text{R}$$

$$\text{For } T_i = 5 \text{ ms the allowable Jitter}_{p-p} = 33.3\mu\text{R}$$

$$\text{For } T_i = 10 \text{ ms the allowable Jitter}_{p-p} = 16.65\mu\text{R}$$

#### **Steering:**

This includes both the *GEO steering* control loops as well as any errors in the *INS* that produce *GEO steering* errors. The *GEO Steering* control loops typically produce *LOS* rates of less than 1.5 mR/s. This corresponds to a pixel motion of:

$$1.5\text{mR}/\text{s} / 66.7\mu\text{R}/\text{pixel} = 22.5 \text{ pixels}/\text{s} \text{ or } 0.0225\text{pixels}/\text{ms} \text{ of integration time.}$$

Again, if we wish to keep the pixel motion down to below ½ pixels (smearing) we must keep the *LOS* movement to below 33.3µR during the integration time of the camera. The allowable integration time would be: 33.3µR / 1.5mR/s = 22.2 ms

#### **Translation/Vehicle Motion:**

Translational motion is caused by the movement of the vehicle that the camera system is attached to. While the *LOS* is locked to a fixed point on the ground (the target) all other pixels will move due to the motion of the vehicle. With a 2 axis gimbal system mounted on an aircraft orbiting the target the dominant motion will be the roll of the image. It will rotate at the same rate that the aircraft turns.

For a given airspeed, the wind speed will vector sum with the airspeed to produce a ground speed. This will produce a higher angular rate on the down wind section of the orbit.

For a 1 mile orbit radius (5280 ft), an airspeed of 140 Kts (236.29 ft/s), and a wind speed of 40 Kts (67.51 ft/s), the maximum orbit rate is:

$$\text{LOS } \omega_{\text{max}} = 360^\circ / (2\pi R / (V_{\text{air}} + V_{\text{wind}}))$$

$$\text{LOS } \omega_{\text{max}} = 360^\circ / (2\pi 5280 \text{ ft} / (236.29 \text{ ft/s} + 67.51 \text{ ft/s}))$$

$$\text{LOS } \omega_{\text{max}} = 3.3^\circ/\text{s} \text{ or } 57.6\text{mR}/\text{s}$$

This roll motion is not typically a problem for small focal planes. The BAPS *application* calls for large arrays of focal planes. The angular rate of the aircraft multiplied by the integration time of the camera gives the angle that the array is rotated through during an exposure. The Sine of this angle is multiplied by the radius of the array (r) in pixels to give the pixel motion blur.

$$\text{Blur}_{\text{pixel}} = r \text{ Sin}(\text{LOS } \omega_{\text{max}} \times T_i)$$

For an array of six 11 Mpix focal planes (4008 x 2672 pixels) the radius to the edge of the array would be 4008 pixels.

$$66 \text{ Mpix } \text{Blur}_{\text{pixel}} = 4008 \text{ Sin}(3.3^\circ/\text{s} \times 0.001\text{s})$$

$$66 \text{ Mpix } \text{Blur}_{\text{pixel}} = 0.23 \text{ pixels}/\text{ms} \text{ of integration time}$$

For a 1 Gpix array (31623<sup>2</sup>) required for 10k x 10k at 0.5m *GSD*:

$$1 \text{ Gpix } \text{Blur}_{\text{pixel}} = (31623/2) \text{ Sin}(3.3^\circ/\text{s} \times 0.001\text{s})$$

$$1 \text{ Gpix } \text{Blur}_{\text{pixel}} = 0.91\text{p}/\text{ms} \text{ of integration time.}$$

The stability requirements are therefore, directly proportional to the maximum desired integration time for the camera. As large IR focal planes are extremely expensive and have poor availability, there will always be pressure to use these “day light” sensors into lower light levels. This can only be accomplished if the overall system design allows for the use of long integration times (>10ms).

As these three sources of pixel motion sum together to form the total pixel motion, a budget for each source must be allocated. It is desirable to keep the total pixel motion to below ½ pixel to limit its affect on resolution (*GSD*). This means the stability requirements will become more demanding.

In addition to pixel motion during exposure there are also optical sources of image blur. These optical sources combine with the motion-based blur to limit the effective resolution or *GSD* of the sensor system. The pixel motion budget becomes part of the overall system blur budget.

For a desired maximum integration time of 10ms and a ½ pixel motion limit the budget might look something like this:

*Steering:*

XY Steering = 1.5mR/s x 10ms = 15µR

15 µR / (66.7µR/p x ½) = 50 % of total budget

*Translation/Vehicle Motion:*

66 Mpix Blur<sub>pixel</sub> = .23 pixels/ms x 10ms

66 Mpix Blur<sub>pixel</sub> = 2.3 pixels or 460% of total budget

1 Gpix Blur<sub>pixel</sub> = 9.1pixels or 1840% of total budget

*Jitters Stability:*

LDG on airframe = 5µR *RMS* or 15% of total budget

LDG on POD = 10µR *RMS* or 30% of total budget  
(Note: the vibration environment on the wing of an aircraft is about double that of the fuselage).

Obviously the Translation/Vehicle motion is outside the budget. The use of a step-stare function for the roll axis could effectively eliminate the roll portion of this motion. A step-stare on the *GEO steering* function could limit the XY Steering motion also. These step-stare functions are only possible on high performance stabilized *gimbal* systems such as the PV-Labs *LDG*.

## ***STABILIZATION AVAILABILITY***

While there are many stabilized *gimbal* products available each with widely varying performance specs they can be grouped into a few technologies with similar performance capabilities. The white paper: "Stabilization, Steering, and *Gimbal* Technology as it relates to Cinematography" defines a *gimbal* technology classification system for this purpose.

### *Gen-2: The Classical Active Gimbal System*

These systems close rate loops directly about each *gimbal* axis. Rate sensors such as small mechanical sensing gyros are used to sense angular rates relative to *inertial space*. These rates are summed with the steering commands to stabilize and steer each axis.

The *actuator* can be either a direct-drive or a geared motor. The use of a geared *actuator* will increase coupling forces substantially due to friction and limit the *bandwidth* of the system (<10 Hz). The excessive friction tends to cause hysteresis that limits jitter performance.

The structure between each successive *gimbal* axis is subjected to the high frequency torques of the *actuator*. Compliance in this constraint structure will directly limit the *bandwidth* of the control system. For this reason Gen-2 *gimbals* are incapable of high *bandwidth* performance with the large payloads used in the *BAPS* application.

Our experience with high quality servo drives suitable to drive a payload in an environmental enclosure as a single *gimbal* configuration (Gen-2) shows that they are limited to a *bandwidth* of about 10 Hz. Additionally the friction in this type of drive results in hysteresis or a “step response” to direction reversals of about 100 – 300 µR (dependant on consistency of friction affecting tuning of control system compensation loops). This type of servo drive is more expensive to manufacture and maintain than the outer *gimbal* servo drives used in dual *gimbal* designs (Gen-3 or Gen-4).

### *Gen-3: The Active Follow-up Gimbal System*

This technology takes a limited travel, high performance inner *gimbal* and mounts it on an outer follow-up *gimbal*. The inner *gimbal* provides the high *bandwidth* stabilization and fine steering performance, while the outer *gimbal* provides the coarse steering over a large field of regard. The inner *gimbal* uses high performance, direct drive *actuators* and the outer *gimbal* uses geared *actuators*. The high frequency torques are still applied through the inner

*gimbals'* constraining structure. With the large payloads of the *BAPS* application the compliance of this structure limits the *bandwidth* of the stabilization system.

With the use of Fiber Optic Gyros (*FOG's*) the stabilization performance of this type of *gimbal* approaches 10µR to 50µR *RMS*. It has better stability and steering than the Gen-2.

*Gen-4: The Unconstrained Actuator Active Follow-up Gimbal System*

The PV-Labs XR and *LDG* avoid the *bandwidth* limitation of the Gen-3 *gimbal* system by using a patented process of torquing across the constraining structure instead of through it. The high frequency torques is applied directly from the outer *gimbal* to the camera base plate. The inner axes torques to produce enough torque to accelerate a typical payload at better than 300°/s<sup>2</sup>. Combined with a high performance *FOG* based Inertial Measurement Unit (*IMU*), this stabilization system can reach closed loop steering *bandwidths* of up to 80 Hz with *LOS* stability of better than 5µR *RMS* jitter. The structural compliances of the payload are typically the limiting factor.

The Directed Perception D-300 is a small, heavily geared, Gen-2 *gimbal* with a steering resolution limited to 112 µR. With this steering resolution limitation it is doubtful that the achievable *LOS* stability could be better than 200 µR *RMS*.

The Atlantic Positioners SPS-1000 is a larger, heavily geared, Gen-2 *gimbal* with a steering resolution limited to 25 µR. The manufacturer suggests that the *actuators* are capable of 100 µR *RMS* jitter stability with the use of a *FOG* but warns that compliances in the structure will further limit the final system level jitter stability.

When it comes to jitter stability as a requirement for the *BAPS* application the whole system including the airframe must be considered. In order to get into the ballpark of 50-100µR *RMS* jitter operationally (out in an air stream) you need a dual *gimbal* configuration (Gen-3 or Gen-4). Add in the high grade *INS/IMU* and there is no real cost penalty in going to the 5µR *RMS gimbal*. This makes for a system that is largely platform/installation independent.

**COST/BENEFIT ANALYSIS**

A pan/tilt head at about \$200k is just a two axis *gimbal*. For a complete system you will still need to add all of the other components listed in Table 1. This will get you to a lower performance system at a

similar price. The added stability margin of the *LDG* makes many of the other system components less critical. When you are on the edge of the stability required the *passive isolation* and aircraft installation will become more critical. Saving money on the *LOS* stability is false economy when the entire system is considered.

PV-Labs *LDG* unit pricing broken down by function in comparison to a typical Pan/Tilt head.

Description	LDG Qty 1	LDG Qty 10	Pan/Tilt Head
2 Axis Gimbal	200k	165k	200k
Stabilization	75k	55k	?
Passive Isolation	40k	30k	?
Environmental Enclosure	98k	74k	?
INS and GEO Steering	125k	97k	?
APU	20k	16k	?
Cables	10k	10k	?
Custom UI (cTune)	10k	5k	?
3 <sup>rd</sup> Axis with FORJ	100k	80k	?
Test/Handling Stand	10k	8k	?
Reusable Shipping Cases	12k	10k	?
			?
<b>Total unit price</b>	<b>700k</b>	<b>550k</b>	<b>?</b>

Table 1

Notes on Table 1:

- 1) The PV-Labs *LDG* outer *gimbal* is a Roll/Pitch *gimbal* with optional 3<sup>rd</sup> axis for image roll. It does not have a *gimbal lock* in the look down region. Its bearings are not setup in a cantilevered load configuration. This allows the *LDG* to ferry at much higher airspeeds (up to 350 kts).
- 2) The *LDG* stabilization is 5µR *RMS* operational (in flight). Given the specs on the D-300 and SPS-1000 I believe that they would be hard pressed to get 200µR *RMS* operationally with the wind loading and buffeting. *Gimbals* that

achieve 50 $\mu$ R *RMS* operationally are usually dual *gimbal* construction (Wescam, FSI, Gyron, Cineflex, etc).

- 3) The *passive isolation* on the *LDG* is internal and not subject to aerodynamic loading and buffeting. The D-300 or SPS-1000 will require external isolation that will be larger, heavier, and more expensive to produce.
- 4) The image sensor needs to be housed in an environmental enclosure. This is because the system is expected to operate in extreme environments. The *LDG* environmental enclosure includes seals, breather valves, humidity indicators, desiccant, and an optical window and window cover. The aerodynamics of the enclosure to be designed for the D-300 or SPS-1000 will affect the jitter stability and torque loading.
- 5) The *LDG* includes a high grade *IMU* (LN-200), *GPS* (Novatel OEM-4), and *INS* (PV-Labs) with the steering algorithms to *GEO steer*. The *LDG* also includes the *CGI* data stream that reports the *LOS* information to the capture system. The D-300 or SPS-1000 will require a similar quality of *IMU* and *INS* to measure the *LOS* regardless of the possible use of an auto-tracker. Good auto-trackers are expensive.
- 6) The *LDG* includes an *APU* capable of powering the system on the ground or in flight. The *APU* provides automatic reset circuit protection.
- 7) The *LDG* includes all required cables.
- 8) The *LDG* includes a custom made user interface application for the *BAPS* application. This allows *gimbal* control and monitoring during flight.
- 9) The *LDG* includes a third axis and *FORJ* that allows the image orientation to be maintained while the aircraft orbits ("North-Up" mode). This increases the efficiency of the capture system by up to 27% and allows for a more square and stackable persistent area.
- 10) The *LDG* also includes a test stand/ground handling cart and reusable shipping cases.

This leaves the system architect with 3 basic choices:

A) High quality Az/El *gimbal* (2 axis Gen-2 *gimbal* system with low *bandwidth*), environmental enclosure, and no passive vibration isolation.

The structural resonances, buffeting, and vibration characteristics will drive system performance. The *LOS* motion (vibration and steering) will dictate the integration time limitations. The cost of this *gimbal* will be higher than that of a comparable outer *gimbal*.

B) Above with the addition of external passive vibration isolation.

A good *passive isolation* system will limit transmission of vibration from the vehicle to the *gimbal* system. This type of isolator is usually larger, heavier, and more expensive than a typical internal isolator. In order to maximize performance the isolator will need to be tailored to the characteristics of the aircraft. Buffeting of the enclosure will bypass the isolator (or resonate it) and go directly to the payload platform.

C) High performance dual stage (Gen-3 or 4) *gimbal* configuration (high *bandwidth* inner *gimbal*) with internal passive vibration isolation such as the PV-Labs *LDG*.

## **CONCLUSIONS:**

Because of the additional stability margin that the high *bandwidth* inner *gimbal* provides the system is largely platform independent. The internal isolator is smaller, lighter, and less expensive. The outer *gimbal* drives are smaller, lighter, and less expensive (low *bandwidth*, backlash tolerant).

The inner *gimbal* or *SU* for the *LDG* and *XR* is about \$75,000 USD (sell price based on the low volumes we are currently manufacturing). Given what it provides in this *BAPS* system its value is high compared to its cost. Low volume production of specialized *gimbal* systems is a significant contributor to cost. Computer disk drives have similar *gimbal* and *actuator* technology used in their head positioning servo systems, but the volume that they are consumed in makes their cost low.

All in all I think you would be hard pressed to save cost in a *BAPS* solution by eliminating the *gimbal* or any of its components. The cost drivers tend to be in the structure and size of the program.

## **DEFINITIONS:**

**Actuator:** A servo motor. It may be direct-drive or geared. Direct-drive actuators are capable of higher *bandwidth* and produce high frequency forces on the constraining structure.

**APU:** Auxiliary Power Unit or AC to DC power supply.

**Bandwidth:** The bandwidth of the stabilization system is the frequency range over which the system is considered to be effective (i.e. 0 to X Hz).

**BAPS:** Broad Area Persistent Surveillance is a surveillance application where a Wide Field of View (*WFOV*) sensor array is made to stare at a fixed point on the ground for a prolonged period of time.

**CGI:** Computer Graphics Interface: This refers to the data that is captured and used either in real time or in post production for key framing animated effects.

**FOG:** Fiber Optic Gyro: An angular rate sensor using a laser diode and a spool of optical fiber.

**FORJ:** Fiber Optic Rotary Joint.

**FOV:** Field of View is the angular field that the sensor array can see.

**GEO location:** A *gimbal* system function that uses the INS to determine the geographic location of the *LOS* on the earth's surface.

**GEO registered:** The process of registering images to a geographic reference system using the *GEO location* information provided by the *gimbal/INS*.

**GEO Steering:** This is a steering mode that allows the *LOS* to be steered *WRT* the Earth's frame of reference. For the purpose of this discussion we are talking about targets entered in terms of Latitude, Longitude, and Altitude.

**Gimbal:** In its simplest form a gimbal is just a mechanical contrivance to constrain the motion of an object about a single rotational axis. Combined together, several gimbals can constrain the motion of an object about each successive axis (i.e. Pan, Tilt, and Roll). *Gimbal* is often used to refer to a stabilized gimbal system.

**Gimbal lock:** A phenomenon, where 2 or more of the *gimbal* axes align, thus reducing the effective number of *gimbal* axes. Control systems often can't cope with this condition.

**GSD:** Ground Sample Distance.

**Image Stitching:** The process of joining multiple images from multiple focal planes together into a single image as though they were captured from one large focal plane.

**IMU:** Inertial Measurement Unit: A sensor unit containing an array of 3 gyros and 3 accelerometers.

**Inertial space:** Is independent of the earth's frame of reference. It is referenced to the star system.

**INS:** Inertial Navigation System: A typical INS uses an *IMU* and a GPS or other position reference to constantly compute its position and attitude relative to the earth.

**LDG:** Look Down Gimbal – a Gen-4 gimbal system (by PV-Labs) specifically designed and configured for the BAPS application.

**LOS:** Line of Sight: The optical axis of the lens.

**Orthorectification:** Orthorectification converts imagery into map-accurate forms by accurately removing sensor and terrain-related distortions from raw imagery.

**p-p:** Peak to Peak.

**Passive isolation:** Isolation that is not actively controlled with a servo system.

**RMS:** Root Mean Square.

**SU:** Stabilizing Unit

**VBIED's:** Vehicle Borne Improvised Explosive Devices.

**WRT:** With Respect To.

## **BIOGRAPHY:**

Mike Lewis is the director of technology for PV Labs Inc. (formerly Wescam) with over 23 years of experience in stabilized *gimbal* technology. He holds a Bachelor of Technology degree in Mechanical Engineering and an Aerospace Engineering Technology diploma from Ryerson Polytechnical Institute in Toronto.

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