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A Stabilization System for a Large Aperture Reconnaissance Camera

Daniel L. Crabtree
Michael Bown

CAI, a Division of RECON/OPTICAL, INC.
550 W. Northwest Highway, Barrington, IL 60010

ABSTRACT

Performance requirements for Long Range Oblique Photography (LOROP) cameras are a principal driver for system stabilization requirements. Systems analysis can predict the stabilization level required for a given Ground Resolved Distance (GRD) under specific conditions. This information is used then as a basis for the stabilization design in which choices for bearings, passive isolators and active devices can be selected. In this paper, we show examples of GRD's versus residual rate errors for various ranges of a panning system. We also discuss how both active and passive isolation techniques can be used to achieve a desired performance level. The CA-990 LOROP camera system is used as an example of how multifaceted stabilization techniques can be used to create a very precise panning camera system in a high-vibration environment.

1. INTRODUCTION

The desire for improved performance in LOROP camera systems has forced designers to pay careful attention to all systems aspects of the camera. In some areas, such as optics, stabilization and electro-optical detectors, the designer has some control over performance. In other areas, such as air turbulence and atmospheric attenuation of signals, the designer has no control, but the operator can choose operating times to optimize results. Systems analysis techniques can be used to predict overall camera performance, given certain reasonable assumptions and initial conditions, and in this way set error budgets for different system elements. In this paper, we focus on the stabilization system for a large-aperture LOROP camera. We begin with background information about performance predictions to give some rationale for the requirements, and then show our resulting stabilization system implementation, given specific design parameters and tradeoffs, of the CAI-developed CA-990 LOROP camera.

2. BACKGROUND

Our goal is to show how the GRD is affected by choices made in the individual system elements, in particular, the stabilization system. But because this is only one of the variables, we need to establish how it fits into overall camera performance. The systems analysis method is well known and is shown here only to the extent required to discuss the stabilization performance. We begin by establishing an acceptable system signal-to-noise ratio (SNR). The system SNR at a specified spatial frequency of N (SNR_N) is affected by the system Modulation Transfer Function (MTF) and the system SNR at zero frequency (SNR_0). The SNR_0 is independent of spatial frequency and is dependent on very specific conditions such as the sun elevation angle, visibility conditions, scene reflectance, target reflectance and contrast ratio, and sensor parameters including altitude and depression angle. A minimum SNR_N of 3:1 at any spatial frequency for detection of tri-bar targets is a generally accepted threshold criterion. The SNR at a specific spatial frequency is given as

$$SNR_N = SNR_0 \times MTF_N \tag{1}$$

where:

SNR_N = system SNR at a particular spatial frequency N
SNR_0 = system SNR at zero frequency
MTF_N = overall system MTF at a particular spatial frequency of N

The system MTF, from which MTF_N is taken, is defined as the product of the individual MTF's and is given by

$$MTF_{sys}(N) = \prod_{n=1}^{n=k} MTF_n(N) \quad (2)$$

where:

k = total number of individual MTF's in the system
N = spatial frequency (lp/mm)

The right side of equation 2 can be expanded to show the contributions of the individual elements:

$$MTF_{sys}(N) = MTF_1(N)MTF_2(N)MTF_3(N)MTF_4(N) \quad (3)$$

where:

$MTF_1(N)$ = optical system (lens) MTF
$MTF_2(N)$ = E-O detector MTF
$MTF_3(N)$ = stabilization MTF
$MTF_4(N)$ = atmospheric turbulence MTF

Figure 1 shows the impact of individual MTF's on system MTF. Both plots show four individual MTF's and resultant system MTF's. Other MTF's that might be included, such as recording or display devices, are not discussed here. In addition, the E-O detector MTF includes the deliberate smearing required for Time Delay and Integration (TDI). The plots show the effects on system MTF, and ultimately the GRD, for two levels of stabilization. Figure 1a shows the results for 250 μrad/s residual rate error and figure 1b shows the results for 1000 μrad/s residual rate error. The lens MTF, atmospheric turbulence MTF and the CCD MTF are the same for both curves. The figures show only effects in the crosstrack (panning) direction for the case of 64 TDI. Note that each MTF is a degrading factor. Figure 1 shows that at lower spatial frequencies, the stabilization impact is low. However, as frequency increases, the impact becomes very dramatic. System MTF rolls off quicker with frequency for the higher residual rate error. In this case, the desired SNR_N would more easily be met by the system (figure 1a) with lower residual rate error. We pursue this further below.

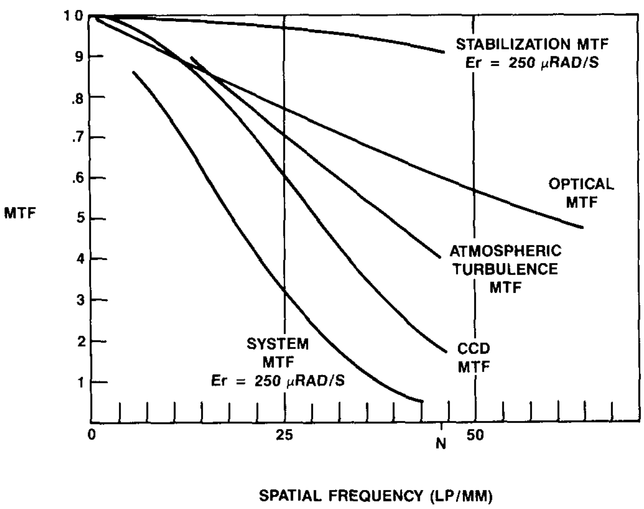

Figure 1a System MTF with ε_r = 250 μrad/s

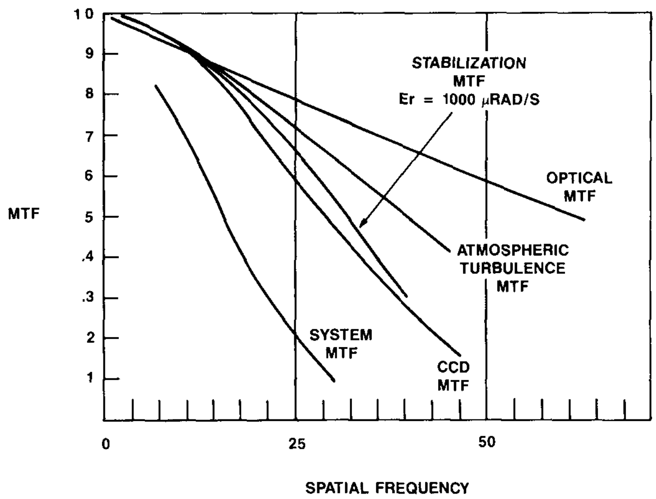

Figure 1b System MTF with ε_r = 1000 μrad/s

Undesirable motion can greatly reduce system performance. Sources of the undesirable motion are typical of those found onboard an aircraft: rotating machinery, air turbulence, aircraft maneuvers and mechanical resonances in the aircraft structure. Desired motion includes the scanning motion required to produce an image.

We have discussed the stabilization MTF and its impact on system performance. The MTF of a panning camera stabilization system is defined by

$$MTF = SINC\,[\,\pi\,(2/\pi\varepsilon_r\, fl\; t_e)N] \quad (4)$$

where:

SINC = (sin x)/x
ε = residual rate error the stabilization system does not remove (μrad/s)
fl = focal length of the optical train
t_e = integration time of the E-O detector
$2/\pi$ = most probable value of a sine wave
N = spatial frequency

Equation 4 reveals some very important information about the stabilization requirements of a panning camera. Notice that the MTF at a particular spatial frequency (N) is controlled by the variables of residual motion, camera focal length and detector integration time. An increase in either focal length, for improved range capability, or an increase in integration time, for improved SNR, requires that the stabilization error be reduced to maintain the same MTF. Notice also that the equation makes no demands on the physical implementation of the stabilization system. All that is required to satisfy the equation is removing unwanted external disturbances. Whether system implementation is done completely with active components or with combinations of active and passive devices does not invalidate the equation. Similarly, if the system achieves the required MTF, its implementation in two degrees of freedom or three degrees of freedom is not driven by the equation, but by complexity, cost and a very clear understanding of the operational requirements and environmental conditions in which the system must operate.

The purpose of the LOROP camera is "to see what is going on -- far away." Therefore, the minimum size that can be resolved, the GRD, is of primary concern. The GRD is defined as

$$GRD = \frac{R}{Nfl} \tag{5}$$

where:

R = slant range to the target
N = spatial frequency (c/cm)
fl = focal length of the optical system

The GRD is tied to system MTF and SNR_N by finding the spatial frequency (N) from figure 1 that provides the required SNR_N, and then calculating the GRD with equation 5. Equation 5 clearly shows that an increase in the spatial frequency (N) at which the desired SNR_N occurs improves the GRD. Consequently, the designer's desire is to maximize N by maximizing the system MTF. For our discussion, this requires maximization of the stabilization MTF.

Our goal has been to look at GRD as a function of the stabilization system performance. We can now fix certain parameters in the camera system and examine effects of residual rate errors on the GRD. This has been done via computer analysis, and a representative plot is shown in figure 2. The following parameters have been fixed for this case:

- Altitude = 40,000 ft
- Sun elevation angle = 30°
- Ground plane visibility = 25 km
- Initial contrast ratio = 10:1
- Focal length = 2.8 m

The plot shows three cases of standoff ranges. As expected, shorter standoff ranges require lower performance from the stabilization system as a direct result of the lower impact stabilization has at lower spatial frequencies. The curves tend to flatten out at the lower residual vibration values. A point of diminishing returns is reached at the Nyquist limit for approximately 500 μrad/s in the 25-nmi case and approximately 200 μrad/s in the 50-nmi case. The 75-nmi case shows the tradeoff of increased resolution for improvement in stabilization. Complexity and cost increase dramatically with increased stabilization performance requirements. The system end user should be very certain that an improvement of a very small percentage in GRD warrants a major increase in system cost.

3. CA-990 STABILIZATION SYSTEM

We have briefly discussed how the stabilization system relates to the LOROP camera system performance to provide some rationale for a design. We now turn our attention to the CA-990 camera stabilization system. The CA-990 camera design goal is to resolve 2.5 ft/lp at a standoff range of 50 nmi under the following conditions:

- Altitude = 40,000 ft
- Sun elevation angle = 30°
- Ground plane visibility = 25 km
- Initial contrast ratio = 10:1
- Known aircraft angular motion = 1°/s at 1 Hz and 1°/s at 10 Hz

Figure 2 shows that the GRD requirements are achieved at a residual vibration rate of 250 μrad/s.

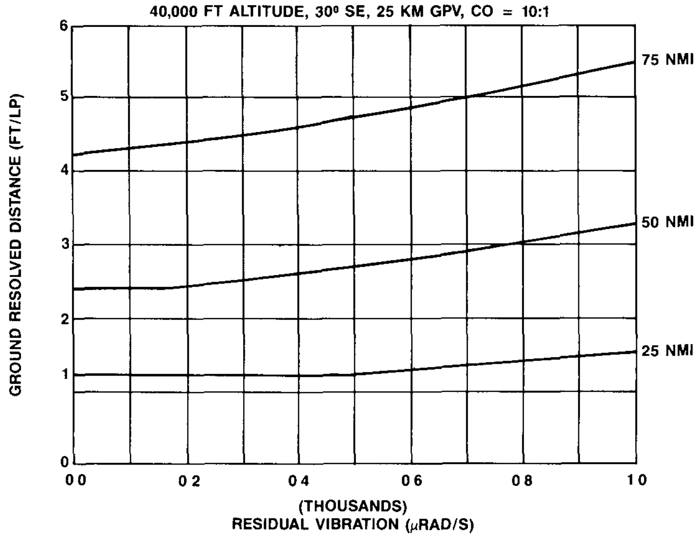

Figure 2 Camera GRD vs. Residual Vibration

The purpose of the stabilization/servo system is threefold: inertial stabilization of the Line of Sight (LOS), pointing of the LOS to a desired depression angle, and generation of the scanning motion at a particular angular rate to produce image motion across the focal plane. The scan rates are selectable from three values: 1.35°/s, 2.7°/s and 20.8°/s. The camera stabilization system is shown schematically in figure 3.

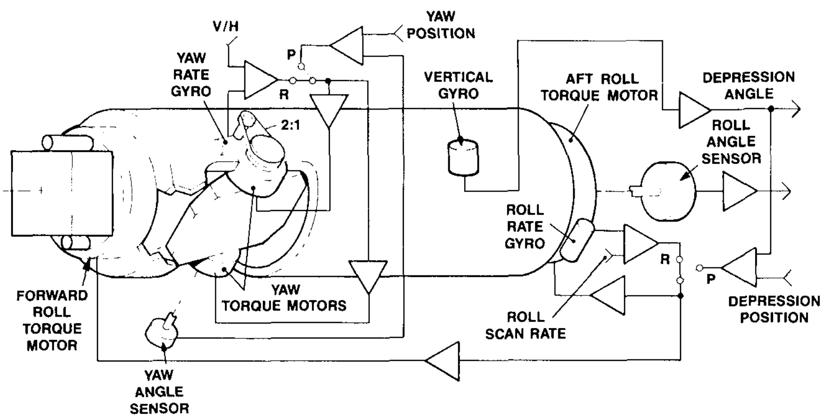

Figure 3 CA-990 Active Stabilization

The CA-990 is configured so that the entire optical train including the focal plane, the scan mirror, the primary mirror, the field corrector optics and the E-O detector/film magazine rotate as a single unit. One advantage of this approach is that image derotation at the focal plane is not required. Rotation of the optical train about the roll axis provides the required scan motion for TDI operation; rotation of the scan mirror about its axis provides Forward Motion Compensation (FMC).

The stabilization system comprises both active and passive elements. Helical springs and rotary vane fluidic dampers were chosen for the passive system; they provide high-frequency vibration isolation in three axes. This technique has been used successfully for many years [1,2]. Transmissibility of the passive system is shown in figure 4. Springs and dampers where chosen over elastomeric isolators because of their ability to adjust the damping factor. In addition, the springs and dampers transmission is very predictable, in contrast to the elastomers which tend to be very susceptible to temperature variations, loading range and variations in input disturbance amplitudes [3]. Figure 4 shows that the vibrations in five axes are attenuated extremely well. In addition to this isolation, the camera lens barrel is balanced about the roll axis to reduce the effects of linear vibrations on any remaining mass imbalances. Precision bearings with a dynamic friction amplitude on the order of 2 ft-lb reduce angular disturbances to the lens barrel even further during the scanning operation. The bearings have been designed to operate at their low frictional values over a wide variation in temperature.

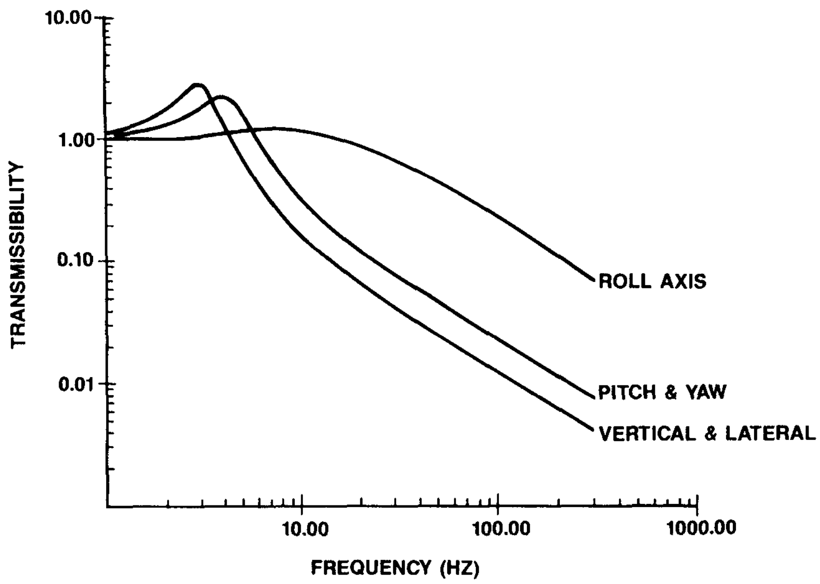

Figure 4 Passive Mount Transmissibility

The active system contains low-drift, very low-noise, gas-bearing gyros that provide inertial angular rate information at a closed-loop bandwidth of 150 Hz to the servo system. This wide bandwidth in the rate sensor allows the inertial rate controller bandwidth to be 80 Hz in the mirror axis (scan mirror) and 30 Hz in the roll axis (lens barrel), while allowing adequate gain and phase margins for loop stability. The gas-bearing gyro also circumvents noise induced into the high-gain servo loops typically occurring in conventional bearing gyros. The servo uses a proportional-plus-integral scheme for accurate tracking of input commanded velocity profiles. The servo is composed of dc torque motors at both ends of the lens barrel (for reduction of torsional effects), compensation electronics, power amplifiers and the gyro feedback element. The scan mirror servo is similar in implementation to the roll servo.

The roll axis stabilization design goal is an angular disturbance residual error during the scanning operation of 250 μrad/s Root Sum Square (RSS) at the known disturbance frequencies of 1 and 10 Hz. The scan mirror axis goal is 370 μrad/s residual rate error. Testing is performed by mounting the camera on a two-axis motion simulator (figure 5) and then comparing the residual rate of the camera body to the input rate using an HP 3562 dynamic signal analyzer. The input to the table is then swept through the frequency range of interest. Results of performance testing and verification of the stabilization system are shown in figure 6. These results show the composite transmissibility (combined active and passive) of the stabilization system under the worst-case scan rate; i.e., the slowest scan rate of 1.35°/s. The test results show that at 1 Hz, performance is extremely good. The results at 10 Hz are reduced due to power bandwidth limitations of the servo. The residual error achieved thus far is 250 μrad/s. From figure 2, a GRD of 2.5 ft/lp can be achieved for this residual rate error for the 50-nmi case, and in the 75-nmi case, a GRD of 4.5 ft/lp can be achieved. Tests have also been performed with yaw disturbances and roll disturbances occurring simultaneously, and the system shows very little performance variation. Performance data for the scan mirror were not available for this paper; however, it has been tested in a manner similar to the roll axis.

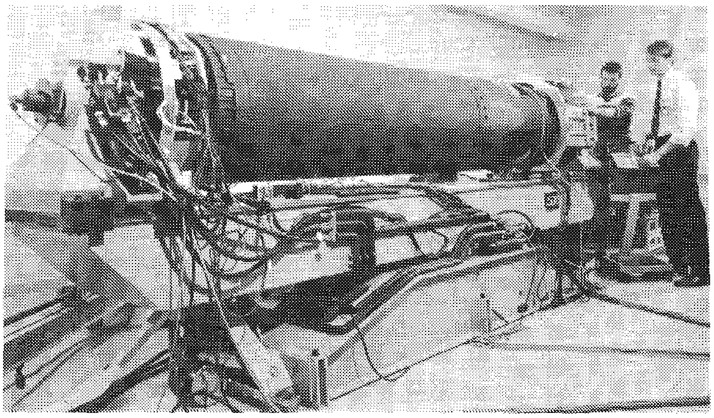

Figure 5 CA-990 Mounted on a Two-Axis Motion Simulator

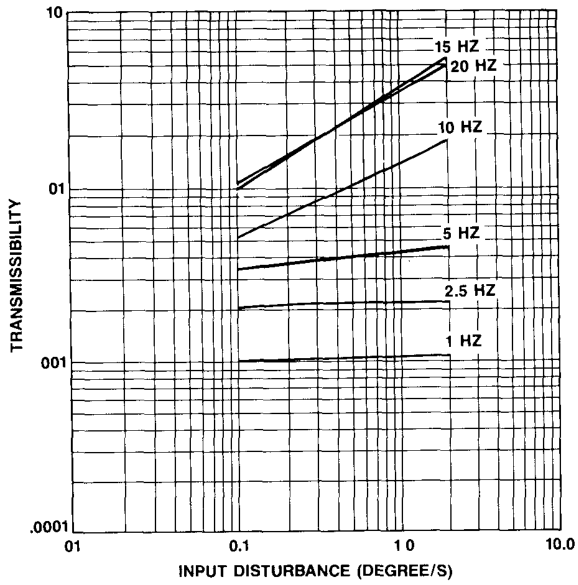

Figure 6 CA-990 Roll Axis Composite Transmissibility

4. SUMMARY

We have presented background information on the effects of the stabilization system on camera system performance. We have also shown GRD plots that can be used as a basis for tradeoffs concerning required stabilization to achieve desired resolution. Having established some rationale for a design, we have presented the CA-990 camera stabilization system and shown some of the ongoing testing results.

5. REFERENCES

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