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Multi-objective design of optical systems for space situational awareness

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ABSTRACT

The successful implementation of Raven-class telescopes to detect, track, and characterize space objects has led to their widespread adoption. Selection of commercial-off-the-shelf components that optimizes the performance of such systems for a specific optical environment or mission is addressed. A collection of multi-disciplinary relationships and relevant assumptions necessary to create a physics-based optical systems model is presented. Several performance metrics are developed to quantify the utility of such systems. These metrics are used in a multi-objective optimization framework to produce optimal design points lying on the efficient frontier. Several trade studies are presented to demonstrate the efficacy of Raven-class telescopes.

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1. Introduction

In 2001, the Rumsfeld Commission Report concluded that improvements in Space Situational Awareness (SSA) are needed to protect the United States and its allies as well as maintain its economic and diplomatic objectives [1]. Joint Publication 3-14, “Space Operations”, defines the high level activities of SSA, which includes the detection, tracking, characterization, and analysis of space objects (SOs) [2]. Space objects consist of active satellites and orbital debris, e.g. inactive satellites and rocket bodies [3]. The United States Strategic Command Joint Space Operations Center (JSpOC) operates the Space Surveillance Network (SSN) and currently tracks in excess of 21,000 objects with diameters greater than 10 cm [4]. A key element of JSpOC responsibility is determining whether the orbits of SOs might bring them into close proximity, an event known as a “conjunction”, and the conditional probability of SO collision [5]. Other SSA stakeholders include NASA Johnson Space Center's Orbital Debris Program Office, which has primary responsibility for characterizing members the orbital debris population below the SSN detection limit [6].

The need for SSA is demonstrated by the often cited Chinese anti-satellite test in 2007 [7] and the Iridium/Cosmos collision in 2009 [8]. The increase in the number of debris objects from incidents such as this required the ISS to make 5 debris avoidance maneuvers in 2014 [4]. Other recent events, such as the uncertainty of an alleged conjunction between the Russian Ball Lens In The Space satellite and debris from the Chinese anti-satellite test, only serve to further illustrate the growing need for persistent SSA [9]. Recent DARPA studies indicate that as the potential number of cataloged SOs grows to nearly 500,000, as many as 100 individual sensors would be needed to “maintain awareness to identify potential threats to space capabilities”, while as many as 10,000 sensors would be necessary to “provide real-time awareness of all threats to space capabilities” [10]. The resultant catalog maintenance problem is a challenge that can be addressed using autonomous telescopes [11].

The era of prolific autonomous telescopes began in the late 1990s. One example is the Raven program, which began as an R&D effort at the Air Force Research Laboratory Directed Energy Directorate's Air Force Maui Optical and Supercomputing site. Physically, the Raven system is a combination of several components: the telescope and dome, electro-optical (EO) sensor, computer, weather station, and a GPS receiver and timing system. However, a Raven-class telescope system is not rigidly defined by a specific combination of hardware. Rather, it is a design paradigm where commercial off-the-shelf (COTS) hardware and software are combined to fulfill designated mission requirements [12]. The COTS component emphasis of the Raven paradigm has led an increasing number of institutions to embrace Raven-class telescopes as cost effective research testbeds. These Ravens are used for the

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Nomenclature

c	Cassegrainian-type optics
c	speed of light, m/s
$\bar{d}$	digitization offset, ADU
g	optical throughput, 1/sr
h	Planck's constant, J/s
$\mathbf{h}$	measurement model
k	incident photons
m_v	apparent visual magnitude
m	number of pixels occupied by SO image
n	pixel binning factor
n_{SO}	SO number density per square degree
$\bar{n}$	average background level, ADU
$\mathbf{p}$	design parameters
p	size of pixel, m
q_p	photon flux, e⁻/s/pixel
q	photon flux, e⁻/s
r	radius, m
s	secondary mirror
$\hat{s}$	unit vector from Sun to observer
t	integration time, s
$\mathbf{v}$	measurement uncertainty
$\mathbf{x}$	design variable
$\mathbf{z}$	measurement
z	number of pixels used in background determination
A	area, m^2
C	total count on any pixel i, ADU
D	aperture diameter, m
E	irradiance, W/m^2
$\mathbf{F}$	Information Matrix
F_r	reflectance function
G	CCD gain, e$^-$/ADU
$\mathbf{H}$	linearized model matrix
I	radiant intensity, mag/arcsecond^2
J	performance objective
L	photon radiance, photons/s/m^2/sr
M	excitance, W/m^2
N	f-number
$\mathbf{R}$	measurement covariance
R	range, m
S	total signal from source, ADU
T	effective black body temperature, K
atm	atmosphere
dark	CCD dark current
opt	telescope optics
sky	background sky
SO	space object
$M(\lambda)$	spectral excitance, W/m^2/nm
$\mathrm{SNR}_{\mathrm{alg}}$	SNR required by algorithm for detection
QE	quantum efficiency of CCD
Γ	photons
$\mathbf{\Phi}_{\mathrm{STM}}$	state transition matrix
Φ	photon flux density, photons/s/m^2
α	albedo
κ	Boltzmans constant, m^2 kg/s^2/K
λ	wavelength, m
μ	mean
ω	relative velocity, radians/s
ψ	solar phase angle, radians
ρ	component of reflectivity
σ	standard deviation
τ	transmittance
θ_S	angular diameter of point source due to seeing
θ_A	angular diameter of point source due to diffraction
θ_I^B	rotation matrix from inertial to body frame
$\odot$	Sun
0	apparent visual magnitude source
$\oplus$	Earth

development of SO detection and characterization algorithms, and to investigate novel autonomy architectures [13–15].

To those interested in assembling a Raven system, it is important to determine which combination of COTS components yield the best performance given the mission and local optical environment. The current literature reveals no systems engineering studies of optical systems that utilize COTS components to complete SSA missions [16–21]. Therefore, the design metrics and methodologies outlined in this work are intended to provide a high level methodology for quantifying performance tradeoffs among design parameters which are typically controllable when selecting COTS components. It is emphasized that the approach presented is not intended to replace traditional, detailed optical design. Rather, it is hoped that the contributions in this work are used during the conceptual design phase to help designers narrow the design space and to identify families of designs which represent feasible solutions to user specific mission requirements.

As the SSA research field rapidly grows, those interested in constructing a Raven system might come from backgrounds other than optical design or physics. Thus, the tacit radiometric models and assumptions utilized in the literature to derive performance estimates of optical systems may not be readily apparent. The background knowledge necessary to conduct such a study is currently scattered among the fields of astronomy, information theory, optics, statistics, and systems design. Therefore, the first contribution of this paper is the collection of multi-disciplinary equations necessary to create a radiometric model of optical systems utilizing a consistent nomenclature.

Additionally, quantifying the performance of SSA assets is challenging. SSA sensors have three main goals: to determine SO orbits as accurately as possible, to detect the dimmest SOs possible, and to detect as many SOs as possible. Accordingly, the second contribution of this work is the development of three novel performance metrics that quantify the ability of an optical system to meet these three goals.

The third contribution is the combination of these metrics in a multi-objective optimization (MOO) context. No novel MOO techniques are presented, but that this approach provides first principles performance based estimates of optical systems capabilities. This MOO framework enables the creation of Pareto frontiers, allowing the system designer to quantitatively compare competing SSA sensor designs and identify “knee-in-the-curve” points in the continuum of feasible designs [22].

Because these performance metrics are analytic, it also enables a sensitivity study of optical systems tasked with SO detection, which has previously not been possible. Thus, the fourth contribution of this paper is the analytical determination and evaluation of the Jacobians of these metrics. These sensitivities identify the design variables and system parameters which have the greatest impact on an SSA sensor tasked with detecting and tracking SOs. This information is critical when analysts are evaluating marginal performance increases afforded by system upgrades.

Also, recent shifts within the community have begun to emphasize

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