The Falcon Telescope Network: A Newly Upgraded Global Array of Optical Telescopes

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CONFERENCE PAPER

The Center for Space Situational Awareness Research (CSSAR) in the Department of Physics and Meteorology (DFPM) at the United States Air Force Academy (USAFA) developed and operates the Falcon Telescope Network (FTN) – a low-cost, commercial-off-the-shelf, network of small telescopes for the purpose of conducting education and research in non-resolvable space object identification (NRSOI). The FTN currently consists of 12 observatories across the world; seven sites in Colorado, one in Pennsylvania, two in Australia, and one-each in Chile and Germany. As we enter the second decade of operating the FTN, there is a need to upgrade and modernize, increase the reliability of the system, and enable the latest observation techniques. The FTN upgrade program includes a larger format CMOS camera, dual filter wheels, a direct-drive mount, an all-sky imager, and a redundant weather station. The dual filter wheels have photometric filters (Kron-Cousin and Sloan), transmission gratings (100- and 200-grooves per millimeter), and both linear and circular polarization filters. In addition to single filter measurements, the dual filter wheels allow us to collect double filter measurements such as polarized spectra. We present more details of the FTN upgrades and provide examples of the different image types and optical signatures that we can obtain for non-resolved satellite characterization. We also present details of the image processing pipeline that was developed to process raw FTN imagery to final photometric, spectroscopic, and polarimetric signatures. Finally, the FTN upgrade program allows us the opportunity to look back on what has been achieved with the FTN over the past decade and look forward to what is planned using the upgraded network. We highlight the opportunities afforded by having the individual components of the FTN upgrade designed to be identical, enabling research possibilities comparing and combining output from the network that cannot be achieved with the single sensor.

1. INTRODUCTION

The United States Air Force Academy (USAFA), through its Department of Physics and Meteorology, began designing a global network of small aperture robotic telescopes in 2012, devoted to studying artificial satellites and to astronomical studies of the near universe, named the Falcon Telescope Network (FTN). Led by the Center for Space Situational Awareness Research (CSSAR) and mainly funded through USAFA and the Defense University Research Instrumentation Program (DURIP), part of the Air Force Office of Scientific Research (AFOSR), the FTN project was conceived as a network of telescopes capable of performing simultaneous observations of an object, from different locations across the globe, and with the ability to be controlled remotely from anywhere or programmed for autonomous operation in all phases of data acquisition. The current distribution of telescope nodes of the FTN, located in North America, South America, Europe and Australia, is detailed in Table 1. During its first decade of use, the FTN facilitated research in Space Situational Awareness (SSA), Space Object Identification (SOI), as well as educational outreach. A complete listing of the peer-reviewed journal papers [1-9] and conference papers and presentations [10-39] resulting from the FTN is provided in the References to this paper.

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Table 1. The FALCON telescope network global distribution

Education or Research Institute	Telescope Location City, State	Country	Longitude (east)	Latitude	Elevation (meters)
USAF Academy (campus)	USAFA, CO	USA	255.12	39.01	2212
USAF Academy (Farish)	Woodland Park, CO	USA	255.01	39.01	2790
MITRE Corporation	Yoder, CO	USA	255.80	38.89	1961
Colorado Mesa University	Grand Junction, CO	USA	251.76	39.96	1380
Fort Lewis College	Durango, CO	USA	252.13	37.27	1880
Northeastern Junior College	Sterling, CO	USA	256.80	40.65	1177
Otero Junior College	La Junta, CO	USA	256.46	37.97	1221
Penn State University	State College, PA	USA	282.17	40.86	317
Universidad de La Serena	Vicuna	Chile	289.32	-29.99	1139
University of New South Wales	Canberra	Australia	149.17	-35.29	600
University of Western Australia (Perth)	Gingin	Australia	115.71	-31.36	18
Technische Universität Braunschweig	Braunschweig	Germany	10.55	52.28	73

After a decade of operations, the FTN is currently undergoing an equipment upgrade. The details of this upgrade and a comparison between the original FTN and upgraded FTN will be discussed in the next two sections.

2. UPGRADE

Whereas the telescope at each FTN node (Pro RC 500 Ritchey-Chrétien model, which has a 0.5-meter (20-inch) primary mirror, f/8.1 focal ratio, and 4,000 mm focal length) remains the same, most everything else in the optical train is being upgraded. This includes a new telescope mount and drive, sensor, filter wheel arrangement and selection of filters. Additionally, improved weather sensors and all-sky cameras are being added to each node to further enhance remote operations and automation. Below is a list of upgraded hardware components for each FTN node.

- Telescope: Officina Stellare 20-inch, f/8.1 Ritchey–Chrétien
- Telescope Mount: Planewave L-500 Direct-Drive Mount
- Sensor: Atik APX60-Industrial Charge-Coupled Device (CCD)
    - 9568 x 6380 pixels
    - 3.76 x 3.76 micron pixels
    - Full Frame 40.9 x 31.1mm FPA
    - 2.5FPS 16-bit Full Frame
    - 160FPS at 9600x100
    - FOV: 30'×20'
- Redundant Weather Sensors
    - Boltwood II Cloud Sensor
    - Lunático Cloud Watcher
- Alcor Omea 3C All-Sky Imager
- Diffraction Limited AFW-10-50SQ Filter Wheels
    - Two per site with dual adapter
        - No filter, single filter, double filter measurement options
    - 10 square slots per wheel
    - 50mm Square Filters

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- Kron-Cousins: B, V, R, I
- Sloan: g', r', i', z'
- Diffraction gratings (100 & 200 gpmm)
- Polarization filters
    - Linear (0°, 45°, 90°, 135°)
    - Circular (RHC, LHC)

Fig. 1 displays the upgraded FTN node configuration. Each node is comprised of two buildings: the Dome Building (yellow area) and a climate-controlled building (red area). The Dome Building includes the clamshell dome, the telescope (grey area), and peripheral electronics. Key components mounted on the telescope are the sensor, filter wheels, rotator/focuser, finder scope and camera, finder scope focuser (Robofocus), and power/data hubs. Network equipment, power supplies, and the telescope control computer are housed in a server rack cabinet in the Dome Building. The climate-controlled building contains an automation computer along with network equipment, an uninterruptible power supply (UPS), web power switch (WPS), and network attached storage (NAS). Two weather sensors, a GPS antenna, an IP camera, and the All-Sky Imager are located outside.

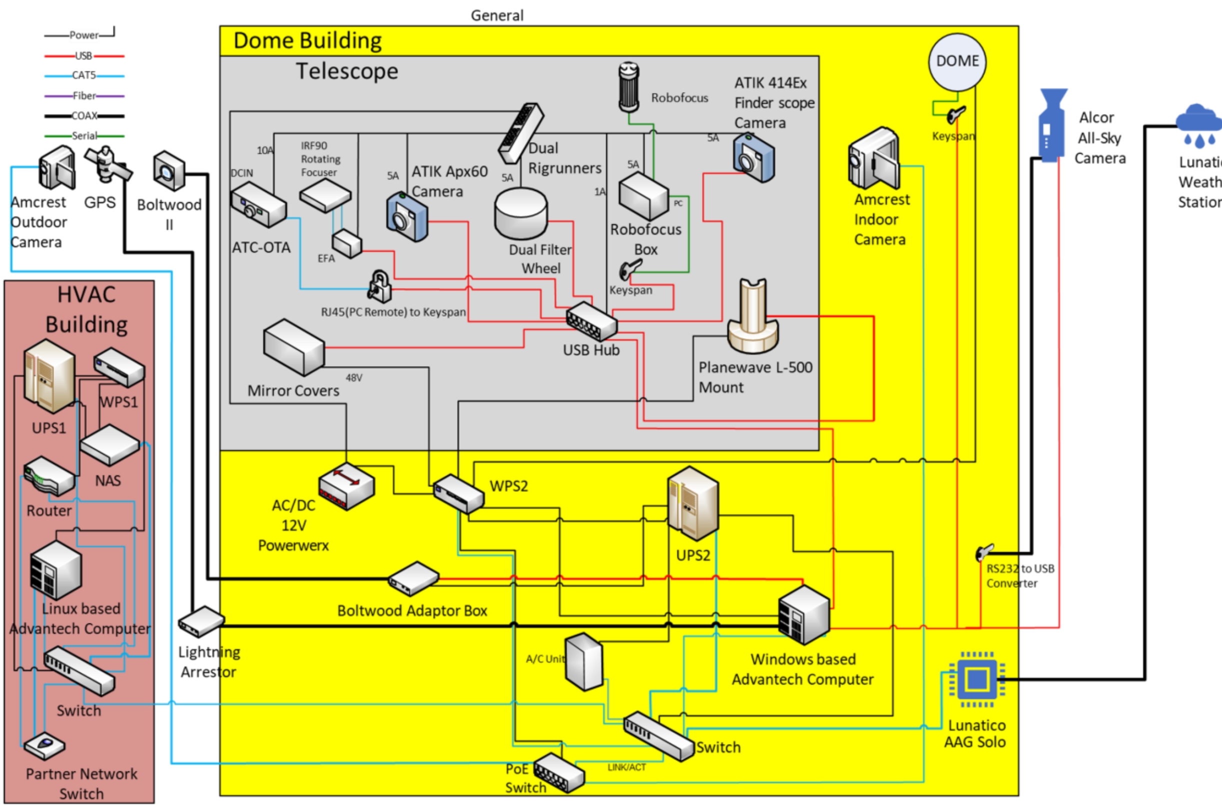

Fig. 1. *FTN node configuration*

In addition to the equipment upgrade, the image reduction and processing pipeline has also been undergoing improvements. This primarily involves converting to a Python-based code base with the goal of realizing the originally envisioned fully automated reduction, analysis, and archiving of results. This will include on-site scientific reduction (bias/dark subtraction for all images and flat field correction for photometric images), transfer to Cadet Space Operations Center (CSOC) for metrics extraction (e.g. photometric magnitudes for photometry and polarimetry, spectra for spectroscopy and spectropolarimetry), and archiving of results at CSOC for researcher access and analysis.

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This is shown schematically in Fig. 2.

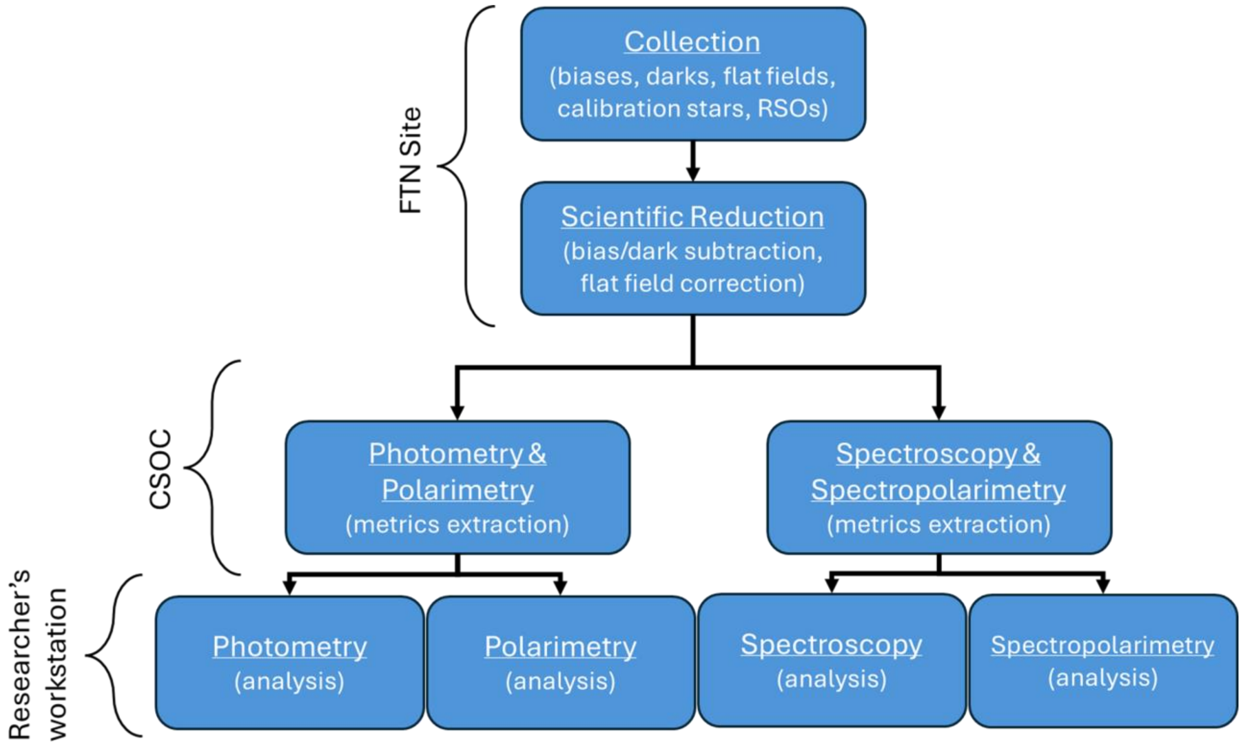

Fig. 2. *FTN's image reduction/processing pipeline.*

3. ORIGINAL FTN VS. NEW FTN COMPARISON

Table 2 lists the key differences between the original FTN configuration and the upgraded FTN configuration. Operationally, the increased field of view (FOV) will enable multiple resident space objects (RSOs) to be imaged simultaneously, as shown in Fig. 3, and the dual filter wheel will enable new SSA and SOI research opportunities (e.g. spectropolarimetry combining slitless spectroscopy using a diffraction grating with polarization filters).

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Table 2. *Comparison between original and upgraded FTN equipment*

Equipment	FTN original	FTN upgraded
Telescope	Officina Stellare 20-inch, f/8.1 Ritchey-Chrétien	Officina Stellare 20-inch, f/8.1 Ritchey-Chrétien
Mount	Software Bisque Paramount ME2 Slew Rate (Max): 4°/second HA & Dec Pointing: 13.5" - 40" rms	Planewave L-500 Direct-Drive Slew Rate (Max):50°/second both axes Pointing: 4.4" – 17" rms
Sensor	Apogee Alta F47 (1024 x 1024 pixels, 13 x 13 micron pixels)	Atik APX60-Industrial (9568 x 6380 pixels, 3.76 x 3.76 micron pixels)
FOV	11 arcmin x 11 arcmin	30 arcmin x 20 arcmin
Filters	Apogee 9-position Filter Wheel: • Kron Cousins: B, V, R, • Sloan: g', r', i', z', • 100 gpmm diffraction grating, • exoplanet filter • Polarization (0°, 45°, 90°, 135°) • Swapped with other filters as needed 9 filter selections	AFW-10-50SQ Filter Wheel #1: • Sloan: g', r', i', z' • Polarization (0°, 45°, 90°, 135°) • Dark (block) & open AFW-10-50SQ Filter Wheel #2: • Kron-Cousins: B, V, R, I, • 100 & 200 gpmm diffraction gratings • Polarization (RHC, LHC) • Neutral Density filter & open 34 different filter combinations

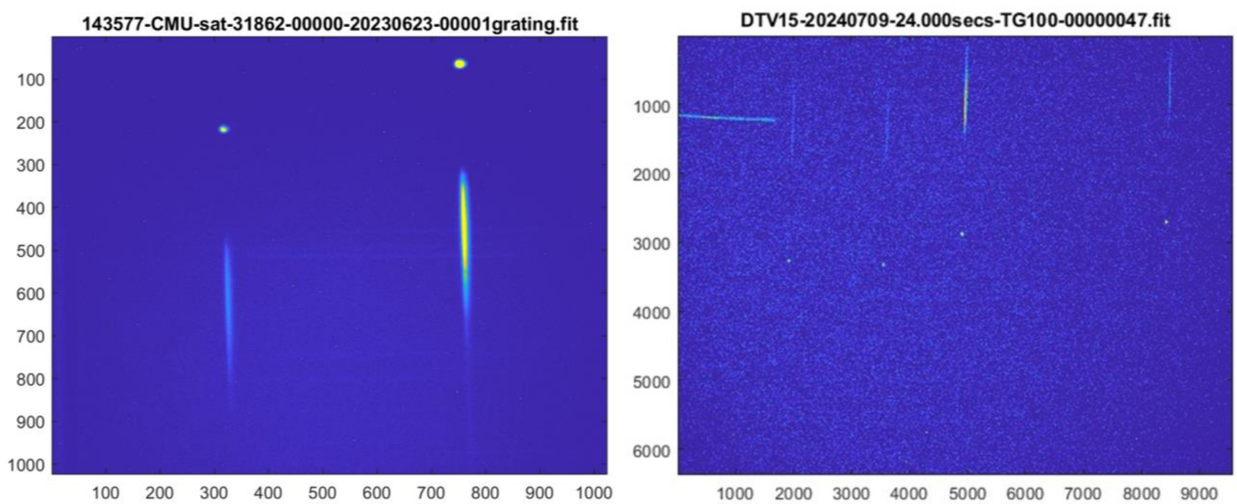

***Fig. 3**. Comparison between DTV-10 & DTV-15 cluster with 100 gpmm diffraction grating at Colorado Mesa University 2023 Jun 22, 24-s exposure (using original FTN configuration) and USAFA campus 2024 Jul 09, 20-s exposure (using upgraded FTN configuration).*

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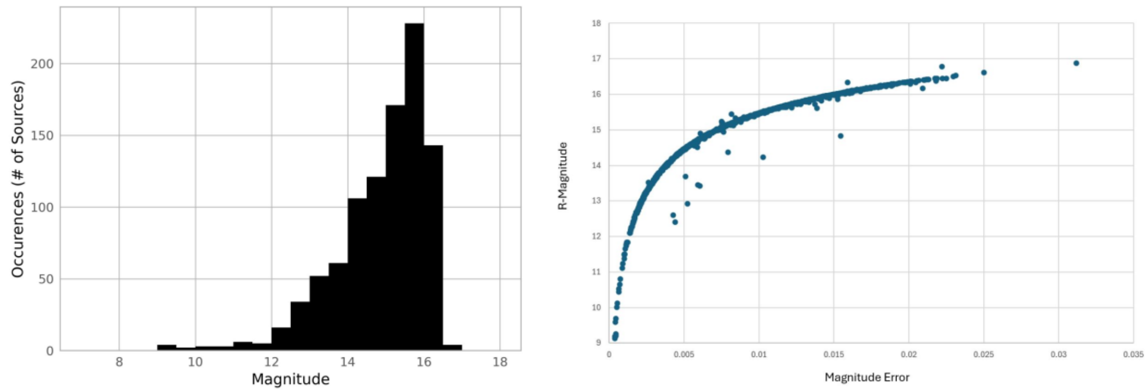

Fig. 4. *Initial results of the limiting magnitude for the USAFA-Falcon telescope using the R filter and a 300-second exposure of the SA41-SF1. The left plot is a histogram of the number of sources as a function of magnitude while the right plot is the magnitude as a function of the error of the magnitude.*

Fig. 4 shows the initial results of the limiting magnitude for the USAFA-Falcon telescope using the R filter and a 300-second exposure of the Landolt star field SA41-SF1. The left plot is a histogram of the number of sources as a function of magnitude while the right plot is the magnitude as a function of the error of the magnitude. The data looks promising in that for the R filter, the USAFA-Falcon has a limiting magnitude of 16 (±0.03). Eventually, we will conduct the same analysis to the rest of the upgraded Falcon telescopes.

4. SUMMARY

Over the past decade, the FTN has been operated and managed by the Center for Space Situational Awareness Research in the Department of Physics and Meteorology at the United States Air Force Academy with its educational and industry partners. Each observatory is an exact replica of the others and has been optimized to study low-altitude artificial satellites, to identify and characterize geosynchronous satellites based on simultaneous observations from different latitudes of the world, and to study astronomical sources in the nearby universe. Located on 4 continents, the FTN has provided world class data on man-made satellites and astronomical objects for a variety of purposes. Currently, the FTN is undergoing an equipment upgrade to both improve its performance and add new capabilities. The details of this upgrade were provided in this paper and will enable the FTN to continue contributing to SSA research and educational outreach into the future.

With the old FTN, CSSAR published 9 peer-reviewed papers (5 which had a cadet as first-author) and 28 conference proceedings papers. A complete listing of the papers associated with the CSSAR and the FTN is provided in the References to commemorate its first decade of operation. Additionally, CSSAR cadets, faculty, and research staff have given 125 research presentations at multiple international conferences and workshops. CSSAR personnel totaled 46 individuals: 13 USAFA faculty (civilian and military), 17 research contractors, 12 international faculty, and 4 Summer Faculty Fellows. Together, the CSSAR team mentored 61 USAFA cadets on 107 research projects, 1 college and 5 high school interns, and participated on 2 PhD dissertations. Internationally, our foreign partners benefitted from hosting a Falcon telescope resulting in 2 journal papers, 19 conference proceedings, 29 presentations, 3 PhD dissertations, 2 MS theses, and 2 bachelor dissertations. Furthermore, our international partners leveraged the FTN in either receiving $250,000 in direct grants or in support of their space program totaling over $25,000,000 in funding. We anticipate an even greater education and research throughput with a fully upgraded Falcon Telescope Network.

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