

SATNOGS OPTICAL UNOFFICIAL GUIDE

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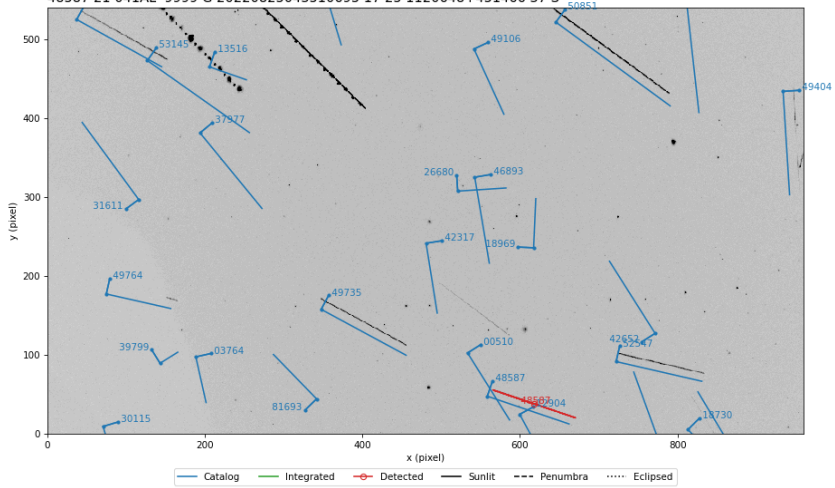
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SatNOGS Optical

Unofficial

Guide

Jeff Moe



Loveland, Colorado, USA

2022

SatNOGS Optical Unofficial Guide

by Jeff Moe

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Dedicated to free users

*Space should be claimed the libre
way.*

Libre Space Foundation

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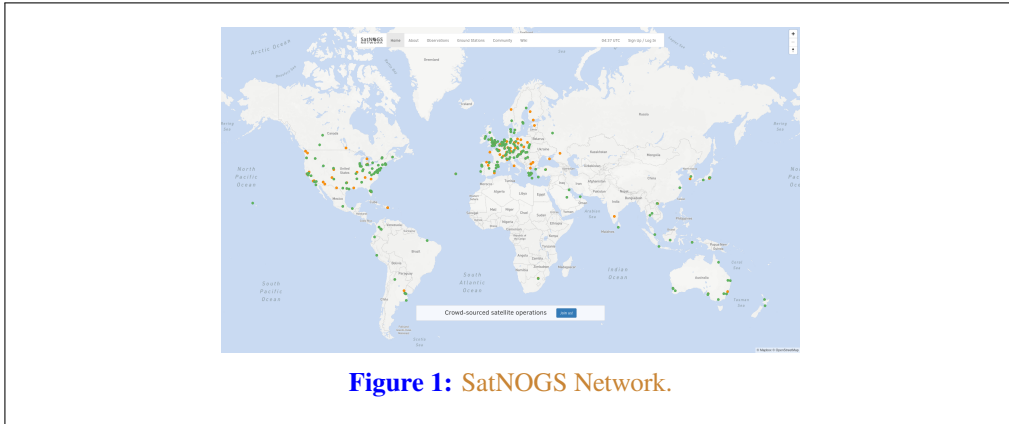
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Introduction

SatNOGS Optical

The SatNOGS Optical Unofficial Guide documents how to set up and run an optical ground station for the Libre Space Foundation (LSF)'s SatNOGS network.



Unofficial Guide Overview

First, an overview of the this text, then the LSF and some of it's key projects, such as the SatNOGS network. A cursory review of satellites and existing radio frequency (RF) ground stations will be followed by a big picture view of acquiring and processing images of satellites. Hardware is reviewed, then software to run on it, with many options, including what is best. Finally, what to do with the data. The chapters that follow are listed below.

Satellites — What are we looking at?

Ground stations — How Earth talks to satellites and back.

Toolchain and Process — The big picture of what hardware and software is needed to set up an optical ground station for use on the network.

Hardware — Details on appropriate hardware configurations, and example setups.

Software — A look at the myriad software related to satellites, and what works best at present for SatNOGS Optical.

Acquire — Convert photons to bits. Pointing a camera at the sky works.

Solve — Pictures of stars reveal the time and location of the photo. Plate solvers reviewed.

Detect — The plate solver says where the photo is, now detect if are there moving trails that aren't star trails that could be satellites.

Identify — With time, location, satellite detection, two-line element sets (TLEs) are overlaid and compared with detected satellites. Satellite identification by computers and humans.

Upload — When ready, data will be pushed to the SatNOGS network.

Support — Where development is occurring and questions answered!

Libre Space Foundation

The LSF supports “free and accessible space for all, creating Open Source space technologies.”¹

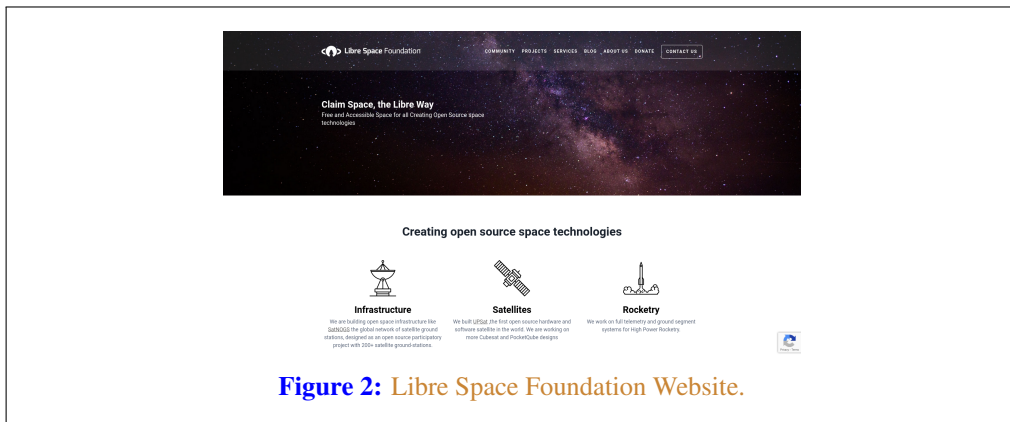


Figure 2: Libre Space Foundation Website.

Select LSF projects:

SatNOGS — Global network of satellite ground stations

<https://satnogs.org>

UPSat — First open-source hardware (OSH) and open-source software (OSS) satellite in the world

<https://upsat.gr/>

SatNOGS Network

SatNOGS is the LSF’s global network of satellite ground stations.

Optical Network Status

The SatNOGS RF network has been running successfully for years. Adding a SatNOGS Optical network is a new development. At present there are zero nodes on the network.

¹<https://libre.space>

Introduction



Some software already exists, some is being ported from C to Python, and other parts remain to be done. There is software available for acquiring optical data of satellites. There is no facility at present for pushing data back to the network.

Satellites

Artificial Satellites in Space

1.1 Overview of Satellites

This chapter gives a brief overview of satellites, with particular attention to ones using amateur radio bands.

1.2 SatNOGS DB

The SatNOGS DB is a database that lists satellites, many of which can be tracked by ground station operators on the SatNOGS network.

The screenshot shows the SatNOGS DB website interface. On the left is a dark sidebar with navigation options: Home, About, All Satellites, All Transmitters, and Statistics. The main content area is titled 'Welcome to SatNOGS DB' and includes a search bar and 'Sign Up / Log In' links. The page is divided into three columns: 'New Satellites', 'Latest Data', and 'Recent Contributors'. The 'New Satellites' column lists several satellites with their call signs, frequencies, and status (e.g., 'No Data'). The 'Latest Data' column shows recent data points for satellites like TECHSAT 1B and TIGRISAT. The 'Recent Contributors' column lists users and the number of frames they have contributed, such as Piszkesteto UHF with 13845 frames.

Figure 1.1: website.

Individual satellites can be viewed, such as the RamSat CubeSat.

The screenshot displays the detailed page for the RamSat satellite. The page has a dark sidebar on the left with navigation options. The main content area is titled 'RamSat' and includes a search bar and 'Sign Up / Log In' links. The page is divided into several sections: 'Mission information', 'Image', 'Description', 'Status', and 'Mission timeline'. The 'Mission information' section lists the name (RamSat), satellite ID (VJWC-7364-7085-7563-0113), NORAD ID (48850), website (https://sites.poo...), and country of origin (United States of America). The 'Status' section indicates the satellite is operational. The 'Mission timeline' section shows a launch date of 2021-06-03T00:00:00+00:00 and a deploy date of 2021-06-14T05:05:00+00:00. The 'Image' section shows a photo of the satellite. The 'Description' section provides a brief overview of the satellite's mission and origin.

Figure 1.2: RamSat web page.

1.3. LIBRE SATELLITES

For some satellites, telemetry is available in a Grafana dashboard. See the RamSat telemetry dashboard.

1.3 Libre Satellites

Below are satellites in orbit, decayed, or designs on Earth that generally support the libre way. These are some select libre satellites:

UPSat — First libre OSH and OSS satellite in the world. Created by the LSF.
<https://upsat.gr/>

RF Observations can be scheduled on the SatNOGS network. See figure 1.5, page 19 for a example list of observations of the RamSat CubeSat.¹

Individual RF observations are uploaded to the SatNOGS network, as can be seen in the example observation of the RamSat CubeSat by SatNOGS ground station “2380 - Piszkesteto Ultra High Frequency (UHF)” run by volunteer bcsak (username).

1.4 Satellite Orbits

Satellite orbits. See Simplified General Perturbations (SGP) and Simplified Deep Space Perturbations (SDP).

See TLE.

¹https://network.satnogs.org/observations/?future=0&norad=48850&observer=&station=&start=&end=&transmitter_mode=&page=2

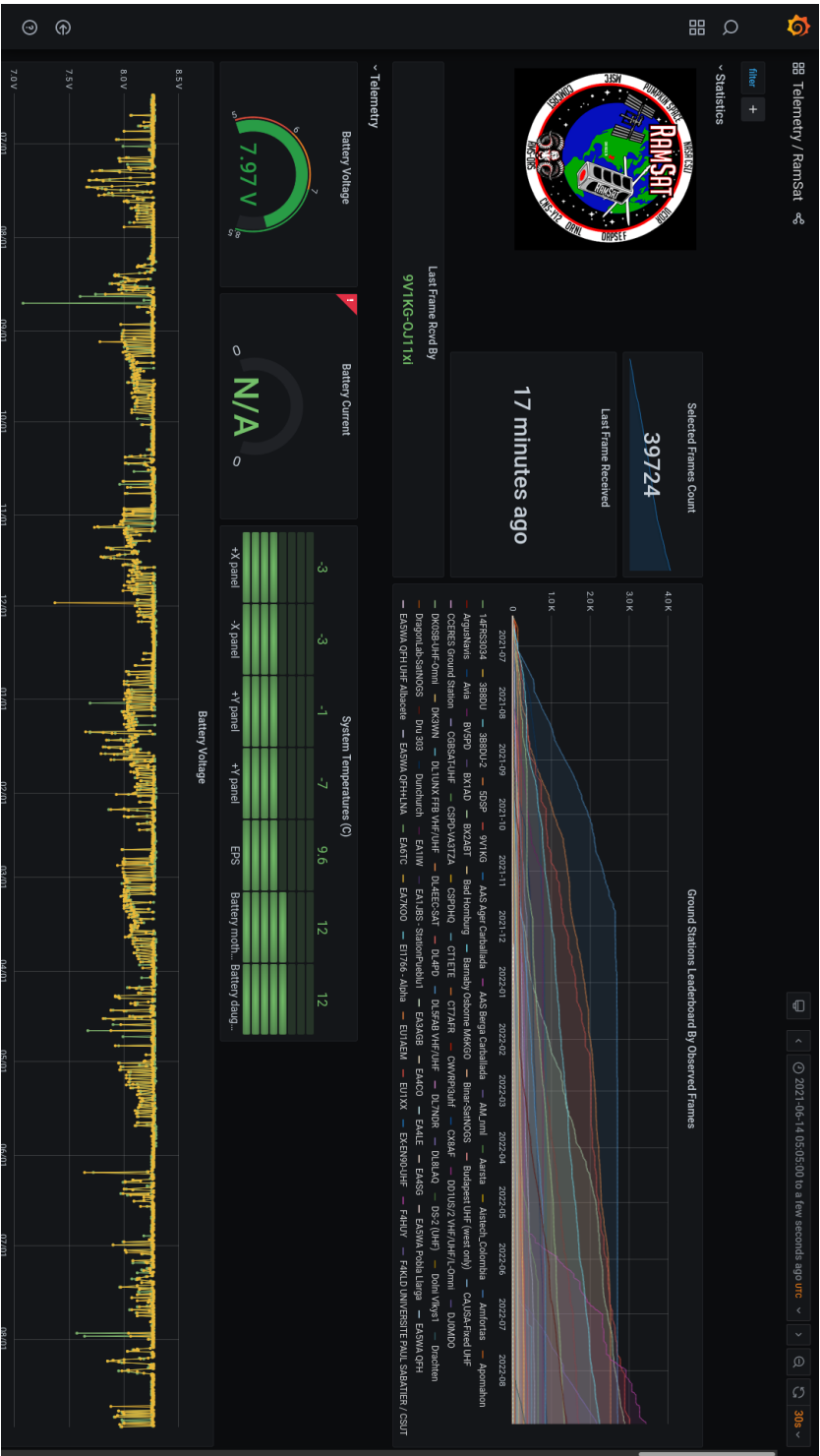


Figure 1.3: RamSat web page.

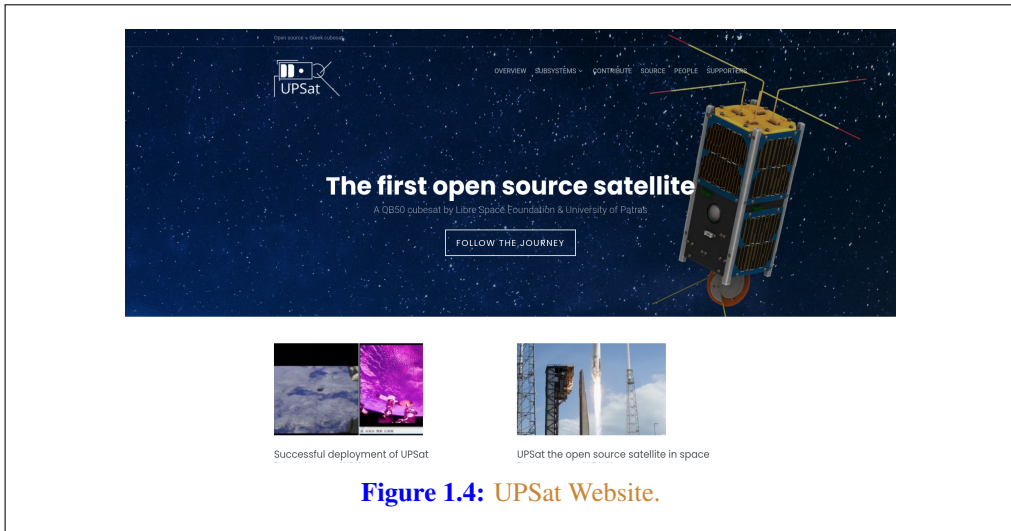


Figure 1.4: UPSat Website.

Observations

ID	Satellite	Frequency	Mode	Timestamps	Results	Observer	Station
10000000	RamSat	436.300 MHz	FSK 9600	2022-08-30 00:07:31 2022-08-30 00:12:58	✓	antony	1307 - FANUP
10000001	RamSat	436.300 MHz	FSK 9600	2022-08-30 00:06:16 2022-08-30 00:12:03	✓	pa2br	1416 - PE2BR-Freemove
10000002	RamSat	436.300 MHz	FSK 9600	2022-08-30 00:09:09 2022-08-30 00:14:32	✓	Anthony Vitez	2125 - W0GJL
10000003	RamSat	436.300 MHz	FSK 9600	2022-08-30 00:09:05 2022-08-30 00:14:17	✓	m2pjo	2155 - W0ZAO Ground Station 2 - AHT
10000004	RamSat	436.300 MHz	FSK 9600	2022-08-30 01:02:37 2022-08-30 01:09:25	✓	Janob D.C. Schwaib	1597 - Y880H
10000005	RamSat	436.300 MHz	FSK 9600	2022-08-30 00:35:51 2022-08-30 00:42:00	✓	sp7hr	2012 - SP7THB-LNF
10000006	RamSat	436.300 MHz	FSK 9600	2022-08-30 00:35:28 2022-08-30 00:39:28	✓	barvek	2769 - F4NSEC
10000007	RamSat	436.300 MHz	FSK 9600	2022-08-30 00:33:00 2022-08-30 00:42:42	✓	tszak	2410 - G4D LNF
10000008	RamSat	436.300 MHz	FSK 9600	2022-08-29 21:37:19 2022-08-29 21:39:09	✓	Felix Baku	1334 - SV3GW - RTL-SDR Bkg v3
10000009	RamSat	436.300 MHz	FSK 9600	2022-08-29 18:04:21 2022-08-29 18:09:50	✓	Kevin Kulk	2869 - Z56XNA
10000010	RamSat	436.300 MHz	FSK 9600	2022-08-29 15:45:08 2022-08-29 15:51:09	✓	LuigiGrazzi	2550 - USU GAS Isp Az+E
10000011	RamSat	436.300 MHz	FSK 9600	2022-08-29 15:23:53 2022-08-29 15:28:07	✓	neonsk	2159 - ITSDLAB54H005
10000012	RamSat	436.300 MHz	FSK 9600	2022-08-29 14:12:02 2022-08-29 14:18:00	✓	Jeff Mcc	2753 - spacostrut
10000013	RamSat	436.300 MHz	FSK 9600	2022-08-29 14:09:29 2022-08-29 14:19:10	✓	LuigiGrazzi	2550 - USU GAS Isp Az+E
10000014	RamSat	436.300 MHz	FSK 9600	2022-08-29 12:28:58 2022-08-29 12:42:57	✓	Jeff Mcc	2753 - spacostrut

Figure 1.5: List of observations of the RamSat , example.

Observation #6401760

◊ Firmly in site in UTC

Satellite	48850 - RamSat
Station	23810 - PrizmaKerido UHF
Observer	DSCJK
Status	Good
Transmitter	Mode U - FSK9K6
Frequency	436.300 MHz
Mode	FSK 9K60
Transmit time	2022-08-30 02:08:37 2022-08-30 02:18:11
RA	283.0°
Dec	35.0°
Alt	82.0'
Client Version	1.6
Receiver	
Power F1BC	

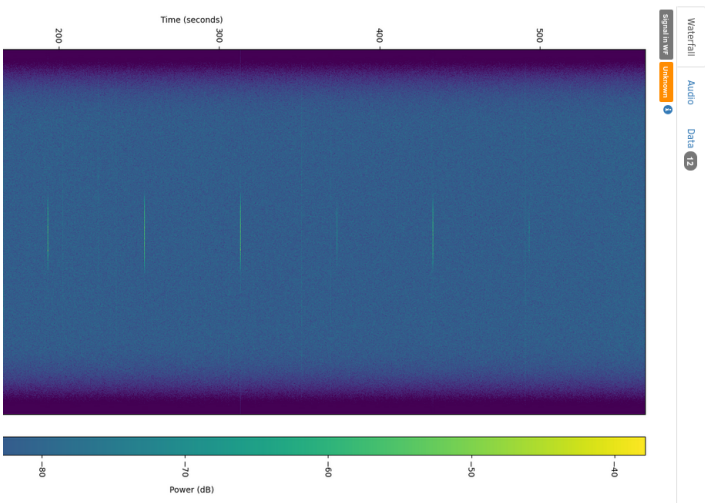
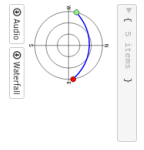


Figure 1.6: Sample observation of RamSat on SatNOGS website.

Ground Stations

Looking up from Earth

2.1 Overview of Ground Stations

Ground stations are a setup of equipment such as embedded systems, cameras, Software-defined radios (SDRs), antennas, and receivers, located on Earth, observing space.

2.2 SatNOGS Ground Stations

The LSF built the SatNOGS network using distributed, volunteer-run, RF ground stations using SDRs, such as in figure 2.1, page 23.¹ It shows a SatNOGS ground station with Very High Frequency (VHF) (right) and UHF (left) antennas on a mast with an altazimuth mount rotator. SDRs can be used as RF receivers.²

Ground stations can be viewed on the SatNOGS network website, such as as the example in figure 2.2, page 24.³

2.3 SatNOGS Optical Ground Stations

The LSF is developing SatNOGS Optical to add optical ground stations to the network.

Prototype optical ground stations are being developed. An example setup, using a Sky-Watcher EQ6-R Pro telescope tripod and tracking mount, can be seen in figure 2.3, page 25.

¹<https://spacecraft.org/assets/i/spacecraft-rotator.png>

²Wikipedia contributors. *Software-defined radio* — Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Software-defined_radio&oldid=1107093398. [Online; accessed 28-August-2022]. 2022

³<https://network.satnogs.org/stations/2733/>



Figure 2.1: with antennas.

2733 - spacecraft

Information

Future Passes

owner Jeff Moe

QTH locator DN70jn

Coordinates(latitude) 40.569° , -105.226°

Altitude 1865 m

Min Horizon 15°

Antennas Yagi (UHF)

Success Rate

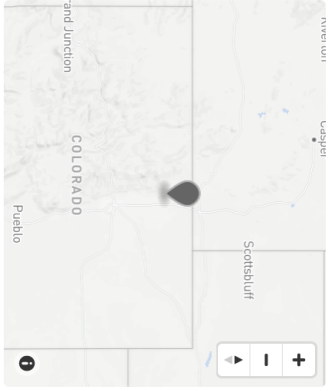
Observations 5758 [View all](#)

Creation Date 1 month, 2 weeks ago

Client version 1.7

online Last seen 0 minutes ago

Uptime 19 days, 8:59:53 [Log](#)



UHF and VHF yagi antennas on fiberglass crossboom from M2. Yaesu GS-5500 rotator. GS-232B serial controller with patched hamlib 3.3. Raspberry Pi4. Nooelec SmartTree RTL-SDR and Flamingo FM filter. In canyon. Feel free to schedule as often as you like! <https://spacecraft.org/spacecraft/satellite-ground-station>

Figure 2.2: Ground station viewed on SatNOGS website, example.



Figure 2.3: prototype.

Toolchain and Pipeline
Make Old Photons Count

3.1 SatNOGS Optical HOWTO

SatNOGS Optical is the nascent distributed network of optical ground stations.

This chapter gives a top level review what is needed in terms of hardware and software to build an operating optical ground station.

3.2 Toolchain

See below for a SatNOGS Optical Process Overview.¹ See figure 3.1, page 29, described below.

Hardware — Hardware, such as cameras and embedded systems, is to be selected and set up.

Software — The best currently available software is to be downloaded, installed, and configured.

Acquire — Data samples, typically in the form of Flexible Image Transport System (FITS) file photographs, need to be acquired by running a camera outside at night taking pictures of the sky.

Plate solver — Acquired data samples in FITS files need to be processed by a plate solver. See section 7.1, page 68.

Detect satellites — Using TLEs and the “solved” plates, detect satellites. See section 8.1, page 72.

Identify satellites — With satellites detected in the previous step, identify what they are. See 9.1, page 76.

3.3 Hardware

Discussed in this section are some of the hardware options to be explored. More explicit instructions of a particular hardware installation can be see in section 4.1, page 34. Discussed below are camera options, for details on embedded systems and other parts, also see hardware in section 4.1, page 34

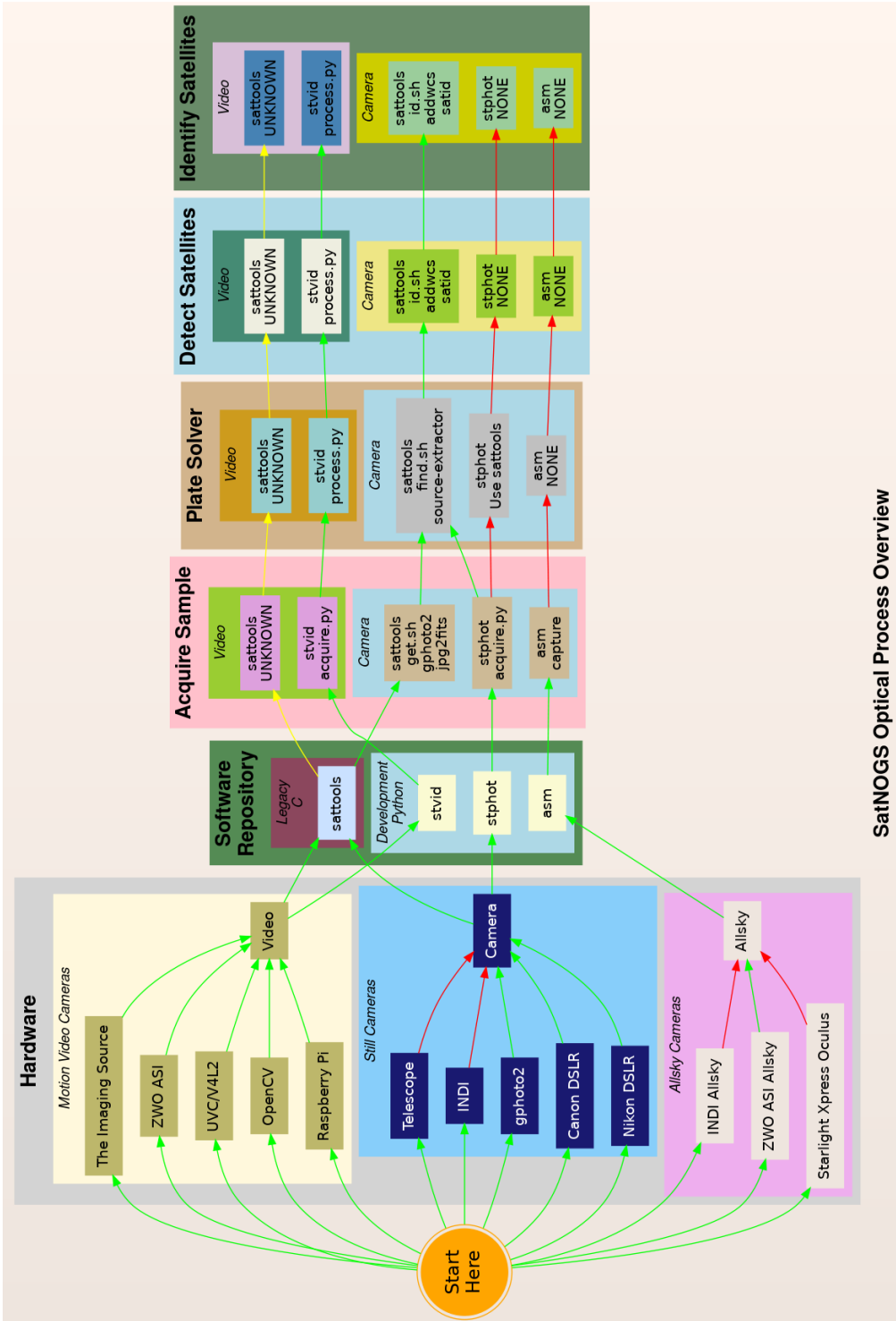
For the purposes here, there are three main categories of hardware. Depending which category of equipment is selected, it impacts everything else, such as the software used. Main categories:

Motion video cameras — Moving images.

Still camera — Still photos.

Allsky cameras — Views of all, or nearly all of the sky.

¹<https://spacecraft.org/spacecraft/SNOPO>



SatNOGS Optical Process Overview

Figure 3.1: Process Overview

Different types of equipment can be used in different categories. Some can be used in multiple setups, most just in one. If available, using motion video cameras will work best for detecting satellites with the developing SatNOGS toolchain. Examples of motion video camera sources that could be used:

The Imaging Source Cameras based on IMX174 — Known to work. Recommended. High quality cameras, believed to be usable following Debian Free Software Guidelines (DFSG).

ZWO ASI based on IMX174 — Known to work. Not DFSG compatible. Uses proprietary Software development kit (SDK). Currently in prototype development.

USB video device class (UVC)/Video for Linux v2 (V4L2) — “Any” video camera that works with the Linux kernel. Typically, the device will appear similar to `/dev/video0`. A camera that works with the software isn’t necessarily sensitive enough to detect satellites, however, as most are designed for brighter environments.

OpenCV — cameras that work with OpenCV can be used, same as UVC. To work well, they need to be sensitive.

Raspberry Pi — The PiCamera can be used. A good lower cost option. Recommended. Many non-Raspberry Pi devices, such as Odroid are also compatible with the Pi Mobile Industry Processor Interface (MIPI) interface.

Still cameras can also be used productively. The current Python toolchain is in very early development and not completely usable yet.

See the list below for still camera options:

Telescopes — Can definitely take images of satellites. Not the best tool at present, as it isn’t well integrated into the SatNOGS Optical toolchain. The Field of View (FoV) is generally too small. The mounts are optimized for different types of tracking than satellites. This is changing, and longer term could be well-supported. Using Rowe-Ackermann Schmidt Astrograph (RASA) style astrographs is likely the best option.

Instrument Neutral Distributed Interface (INDI) — Typically used for control of telescopes and associated instrumentation, such as tracking mounts and cameras. Cannot be used directly with the current developing SatNOGS toolchain. It is not seen as the future path forward as it isn’t well optimized for SatNOGS Optical usage. That said, it is very useful at present for running a tracking mount with KStars and Ekos, for example, in lieu of a better option. Camera software in the INDI platform typically produce image FITS files.

gPhoto — The Linux kernel recognizes many cameras that can be used with gPhoto tools and drivers, available in Debian. This is the recommended option at present for still cameras. digital single-lens reflex (DSLR) cameras, such as from major manufacturers Canon and Nikon, are used with gPhoto.

3.3. HARDWARE

Considering the hardware options above, they need to be matched with corresponding software. Not all options work (at all), and some cannot be easily used to perform all steps needed.

There are also broader “paths” that need to be considered:

sattools — Deprecated because it is in C, and the decision by upstream and the LSF was made to move forward with applications primarily written in Python. Sattools is the most complete toolkit, however, so no matter what path is chosen, some parts of it will likely be used for now. It can be used with motion video cameras and still cameras. It includes many other software tools related to satellites.

stvid — This is the best path if a motion video camera is available. It is in Python and is the tool the SatNOGS Optical project is using as the basis for future development. It still depends on some C tools from sattools.

stphot — Written in Python this is what the SatNOGS Optical project will likely use in the future for still cameras. It is in very early development, but can acquire data (take photos) with gPhoto-compatible cameras.

asm — All Sky Monitor for taking pictures of all, or nearly all of the sky, such as with a 150 or 180 degree view. The asm application is in pre-development, but is in Python and could be the basis for future SatNOGS Optical development. The difficulty with all sky cameras is the plate solver isn’t written to use images from the “fish-eye” view of an all sky camera.

Other — There are many other satellite and telescope software packages freely available on the Internet. Perhaps some could be adapted for usage.

Hardware

Design and Set Up Equipment

4.1 Overview of Hardware

Hardware considerations for a SatNOGS Optical ground station.

Main hardware components in an optical ground station:

- Lens.
- Camera.
- Embedded system (computer).

Other components:

- Ethernet cable.
- Universal Serial Bus (USB) cable.
- Enclosure.
- Power supply.
- Tripod.
- Manual or tracking mount.
- Power source, grid or alternative.
- Internet, wifi or ethernet.

4.2 Camera

Cameras being evaluated:

- The Imaging Source IMX174 based, monochrome.
- ZWO ASI174MM, monochrome.
- ZWO ASI1600MM Pro, monochrome.
- DSLR camera.
- PiCamera.

NOTICE:

ZWO/ASI cameras require proprietary non-libre software on host computer and is not DFSG compatible.

4.3 Lenses

For lenses, the faster the better. F1.2 works well. F1.8 is the maximum recommended.
Lenses being tested:

- Kowa 50mm f1.4 C-mount.
- Canon EF 50mm f1.2 Ultrasonic motor (USM).

4.4 Embedded System

Embedded systems, such as Raspberry Pi, that can be used.

Odroid N2 — Confirmed working.

Odroid M1 — Testing.

Raspberry Pi 3 — ?

Raspberry Pi 4 — ?

Intel Next Unit of Computing (NUC) — ?

4.4.1 Embedded Systems Comparison

Comparing embedded systems for SatNOGS Optical.

Make	Model	Architecture	Max RAM	eMMC
Odroid	N2	ARM64	4 GB	Yes
Odroid	M1	ARM64	8 GB	Yes

Table 4.1: Comparison of embedded systems

4.5 Example Optical Ground Station with Tracking

This is an example of a tracking ground station. It is a prototype, so there are lots of mis-matched, overbuilt/underbuilt parts. The full setup on tripod, can be seen in 2.3, page 25.

A close up of the setup can be seen at 4.1, page 36, showing the Sky-Watcher telescope tracking mount, a Bosch Power over Ethernet (PoE) camera enclosure, and through the glass the camera lens. In the background is a white antenna for Global Navigation Satellite System (GNSS) (Global Positioning System (GPS)) and a solar power setup.



Figure 4.1: SatNOGS-Optical ground station prototype.

4.5. EXAMPLE OPTICAL GROUND STATION WITH TRACKING

The camera lens is protected by the enclosure glass, which is Ingress Protection code 67 (IP67) (XXX) rated. See a close up of the front of the enclosure and camera lens in figure 4.2, page 37.



Figure 4.2: Camera enclosure, front side, showing glass and lens.

As seen in figure 4.3, page 38, the left side of the enclosure has a hinge for opening. The bottom white component is part of the telescope mount.

Figure 4.4, page 38, shows the right side of the enclosure. Two mounting bolt access points can be seen on each end. These are unscrewed with a hex head tool (supplied) to open the enclosure.

The enclosure is opened from the right side, as shown in figure 4.4, page 38.

Inside the camera enclosure, as shown in Figure 4.6, page 41, is:

- The Imaging Source DMX camera with Sony IMX174 Complementary metal-oxide-semiconductor (CMOS).
- Kowa 50mm f1.4 C-mount lens.
- Odroid N2 running Debian GNU's Not Unix! (GNU) Linux system.
- Odroid N2 plastic enclosure, large half, hole drilled for ad-hoc mounting.
- Blower fan on top, with power cable (came with Bosch enclosure).



Figure 4.3: Camera enclosure, left side, showing hinge.



Figure 4.4: Camera enclosure, right side.

- Fan, maybe not so useful, with power cable (came with Bosch enclosure).
- Camera mounting plate (came with Bosch enclosure).
- Camera mounting screws, M6x25 (?).
- Ethernet cable, internal, short white (came with Bosch enclosure).
- PoE ethernet cable, external, plugged into PoE switch for data and power.
- USB 3 cable, internal, way too long, needs replacing, from Odroid to camera. XXX flat connector
- USB 3 cable, external, from Odroid to telescope mount. XXX large rectangle connector



Figure 4.5: Camera enclosure, right side, opened.

- “Custom” 12Volt (V) Direct current (DC) power cable from Bosch PoE to Odroid.
- Assorted nuts, bolts, and washers for an ad-hoc standoff height.

The top of the enclosure shows weather protection and a sun visor. See figure 4.7, page 42.

4.6 Tripods

The camera setup can be mounted a wide variety of ways, from just setting the camera somewhere (worst option), to a heavy duty pier with tracking mount (best option).

At present, most prototype optical ground stations are using static mounts on tripods.

Tripod and similar options include:

No mount — Quick and dirty, just hang the camera out somewhere sitting on something.

Small tripod — There are small desk tripods than can be used with lighter setups, such as used with a Raspberry Pi PiCamera.

Photography Tripod — Using a common camera tripod, of which there is a wide variety, from light to heavy.

Telescope Tripod — Similar to photography tripods, but typically heavier weight.

Telescope Portable Pier — Similar to a telescope tripod, but much heavier, typically with a larger center pier post. Still movable, and folds up similar to a photography tripod.

Telescope Pier — A wide variety, such as making a roughly 1.5 meter permanent cement post.

4.7 Mounts

For mounts, there are two main types: tracking or static. By the latter “static” mounts, it is meant that the camera, the tripod, and the mount all stay motionless. This is what you would get using a camera with a common photography tripod and a simple mounting plate.

Static mounting options include:

Camera plate — Commonly used on cameras and readily available for mounting cameras to tripods.

Enclosure plate — A flat plate with holes drilled in it to mount the camera inside an enclosure.

“Security” camera enclosure mount — Various mounts exist to mount security cameras to posts, walls, etc.

Tracking mount options to consider include:



Figure 4.6: Camera enclosure, opened.



Figure 4.7: Camera enclosure, top.

Sky-Watcher EQ6-R Pro — Telescope mount using INDI.

Celestron — Wide variety of telescope mounts using INDI.

iOptron — Telescope mount with (untested) satellite tracking.

INDI Telescope Mounts — A wide variety of other INDI compatible telescope mounts.

Yaesu G-5500 — Antenna rotator.

hamlib — Other hamlib compatible rotators.

Teledyne FLIR PTU-5 — High Performance Pan-tilt-zoom (PTZ) Unit designed for security cameras (untested, no drivers?).

Misc PTZ — Other security camera PTZ mounts.

Tracking mounts aren't widely used, but there is support for them in `stvid` when acquiring data. The tracking needs to be set up independently of `stvid`. At present, I use KStars with Ekos to control a Sky-Watcher EQ6-R Pro tracking mount.

For tracking, there are a few different ways to track:

Static — No tracking, just point at one place in the sky. Generates star trails. Generates satellite trails.

Sidereal tracking — Tracks stars. Generates stars as points. Generates satellite trails.

Satellite tracking — Tracks satellites. Generates star trails. Generates satellites as points or potentially larger images of the satellite structure.

4.7.1 Sidereal Tracking Mounts

Sidereal tracking (“telescope tracking”) is what Commodity off the shelf (COTS) tracking “GoTo” telescopes from Celestron or Sky-Watcher do, for example. They track the stars, countering the rotation of the Earth to keep the same view of the sky in the camera’s FoV. Stars remain as points, even after multi-minute or multi-hour imaging. This is what is used for “pretty” pictures of stars, nebula, galaxies, etc. This is the most common tracking set up, as it has been widely used in astronomy communities for decades.

Within sidereal tracking mounts, there are yet more options:

Fork — Fork mount.

equatorial (EQ) fork — Fork on EQ mount.

German EQ — Most common EQ mount.

More — Endless variety of available telescope mounts.

Also related to sidereal tracking is lunar and planetary tracking, but for our uses all three will be included under sidereal tracking.

To use a sidereal tracking mount for imaging satellites, the camera must “leap frog” the satellite. At present, my practice is to use a sidereal mount, point at a location with KStars, start stvid. Then stop stvid, move to new location using KStars, start stvid.

See Software section 5.5, 50 for information on using tracking mounts.

4.7.2 Satellite Tracking Mounts

Of the options between a static mount (no tracking), sidereal tracking, and satellite tracking, the latter is by far the least common. In this case, the tracking mount is tracking the satellite itself. This is much more complex than tracking stars, which it builds upon. It requires, such as:

Time — Accurate time, such as from GNSS or Network Time Protocol (NTP).

Location — Accurate location, also available from GNSS.

TLE — Need to know the satellites’ orbit (accurately!).

Variable speed tracking — Satellites are moving at different speeds above, the mount needs to be capable of that.

Alignment — On top of all the gear and software needed, the equipment needs to be accurately aligned.

Most tracking equipment for telescopes, cameras, and antennas usually has just a few speeds, such as a slew speed and a sidereal star tracking speed. Sometimes there will be a few steps of these speeds (e.g. slew speeds from 1-9), but not the finely tuned tracking speeds needed to track a satellite. Oftentimes the telescope tracking maximum speed will be too slow for satellite tracking.

Variable speed tracking (XXX phrase?) is needed for tracking satellites if the goal is to keep the satellite in the (near) center of the image frame and leave star trails. The speed the mount moves needs to be calculated based upon a recent orbit calculation, such as from a TLE.

There are highly skilled amateur astronomers that have captured detailed pictures of artificial satellites, such as the International Space Station (ISS) and astronauts doing space walks, using hand guided telescopes with low cost charge-coupled device (CCD) imagers.

There are few options for satellite tracking mounts. Some new iOptron telescope mount firmware supports tracking satellites. This has been largely untested so far, but at present is likely the best option, if a satellite tracking mount is wanted.

4.8 Future Designs

There is some discussion of using much larger “lenses”, such as a RASA “telescope” (See: astrograph). The primary concern is the lack of satellite tracking mounts, because telescope mounts are generally too slow, and need to “leap frog” the satellite. Rotators used for antennas aren’t typically stable enough for a camera.

Software
Satellite Applications on Earth

5.1 Software Overview

See 5.1, page 46 for a diagram with an overview of the software process.

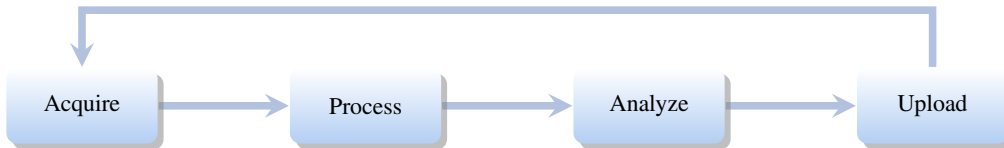


Figure 5.1: Operation Pipeline

5.2 Setup Optical Ground Station Software

HOWTO set up and configure a SatNOGS Optical ground station prototype. Note: the SatNOGS network is not yet ready for optical data.

For a description of installation using Docker, see section 5.9, page 61. For a “manual” install, see immediately below.

Setup an embedded system, such as a Raspberry Pi or an Odroid N2, with Debian stable (11/Bullseye) or testing (Bookworm).

See each software repository for latest documentation.

Install dependencies from the Debian software repository:

```

sudo apt update
sudo apt install python3-virtualenv python3-pip python3-dev \
source-extractor astrometry.net \
libeigen3-dev giza-dev libx11-dev \
astrometry-data-tycho2 astrometry-data-tycho2-07 \
astrometry-data-tycho2-08 astrometry-data-tycho2-09 \
astrometry-data-tycho2-10-19
  
```

Next, install the hough3d-code dependency.

```

git clone https://gitlab.com/pierros/hough3d-code
cd hough3d-code
make all
sudo cp -p hough3dlines /usr/local/bin/hough3dlines
  
```

Install satpredict from using either the cbassa or spacecraft software repository.

```

cd ../
git clone https://spacecraft.org/spacecraft/satpredict
# Or
#git clone https://github.com/cbassa/satpredict
cd satpredict/
make
sudo make install
  
```


5.3. CONFIGURE SOFTWARE

Now install `stvid`, the main acquisition and processing application. It is written in Python. Either use the spacecruft `git` software repository or the cbassa one.

```
cd ../
git clone https://spacecruft.org/spacecruft/stvid
# Or use upstream:
#git clone https://github.com/cbassa/stvid
```

Optionally, set up a Python virtual environment and use Package Installer for Python (PIP):

```
cd stvid
virtualenv -p python3 env
source env/bin/activate
pip install --upgrade pip
```

Install dependencies. Numpy needs to be installed first, or the install fails.

```
pip install --upgrade numpy
pip install --upgrade -r requirements.txt
```

If the system `python3-numpy` conflicts, you could try installing `numpy` with PIP in the `virtualenv` thusly:

```
pip install --upgrade --ignore-installed numpy
```

Debian in bug #941466 changed the name of the `sextractor` dependency to `source-extractor`, so a symlink is needed for now:

```
sudo ln -s /usr/bin/source-extractor /usr/local/bin/sextractor
```

5.3 Configure Software

Configure the embedded system.

```
cd stvid/
cp -p configuration.ini-dist configuration.ini
# Edit
# Note for fields st-username and st-password, *don't* use quotes.
# Set:
vi configuration.ini
```

Edit various `configuration.ini` fields:

```
# For example:
observer_cospar = 9999          # COSPAR number of observer's site
observer_name = Jeff Moe      # Name of observer
observer_lat = 40.568912      # Latitude of location in decimal degrees
observer_lon = -105.225852    # Longitude of location in decimal degrees
observer_height = 1860        # Elevation of location in meters

observations_path = ./data/obs # Path for raw acquisitions
tle_path = ./data/tle         # Path where TLEs are stored (and updated)
```

```

results_path = ./data/results # Path for results of processed obs

st-username = foo
st-password = bar

# Path to source-extractor
sex_config = /usr/share/source-extractor/default.sex

```

Store downloads here:

```
mkdir -p ./data/obs ./data/tle ./data/results
```

The ST_DATADIR variable is still used, from sattools. Maybe set all these in `~/.bashrc` (suit to fit directory setup):

```

export ST_DATADIR=$HOME/sattools
export ST_TLEDIR=$HOME/TLE
export ST_OBSDIR=$HOME/satobs
export ST_LOGIN="identity=foo@no:pass"

```

Set `astrometry.net` to run in parallel, assuming you have enough Random-access memory (RAM): (This doesn't appear to work? Breaks?).

```

sudo vim /etc/astrometry.cfg
# Uncomment:
inparallel

```

5.4 skymap

Use `skymap` for viewing satellite orbits trails projected on a map of of the sky. `Skymap` is part of `sattools`. `Skymap` isn't a required part of the toolchain, but it is useful to see what satellites are visible at a particular time and location.

Source:

* <https://github.com/cbassa/sattools>

My fork:

* <https://spacecraft.org/spacecraft/sattools>

NOTICE:

The main upstream `sattools` package requires non-libre `pgplot` on the host computer which is not DFSG compatible.

Described below is how to build and install my fork of `sattools` to use `skymap` instead of upstream. Upstream requires non-libre software which also happens to be very difficult for most users to compile. My fork uses the `Giza` library which replaces `pgplot`. It is much easier to build.

```

# Install dependencies
sudo apt install giza-dev git make dos2unix source-extractor wcslib-dev \
    libgs1-dev gfortran libpng-dev libx11-dev libjpeg-dev libexif-dev

# Clone repo
git clone https://spacecraft.org/spacecraft/sattools

```

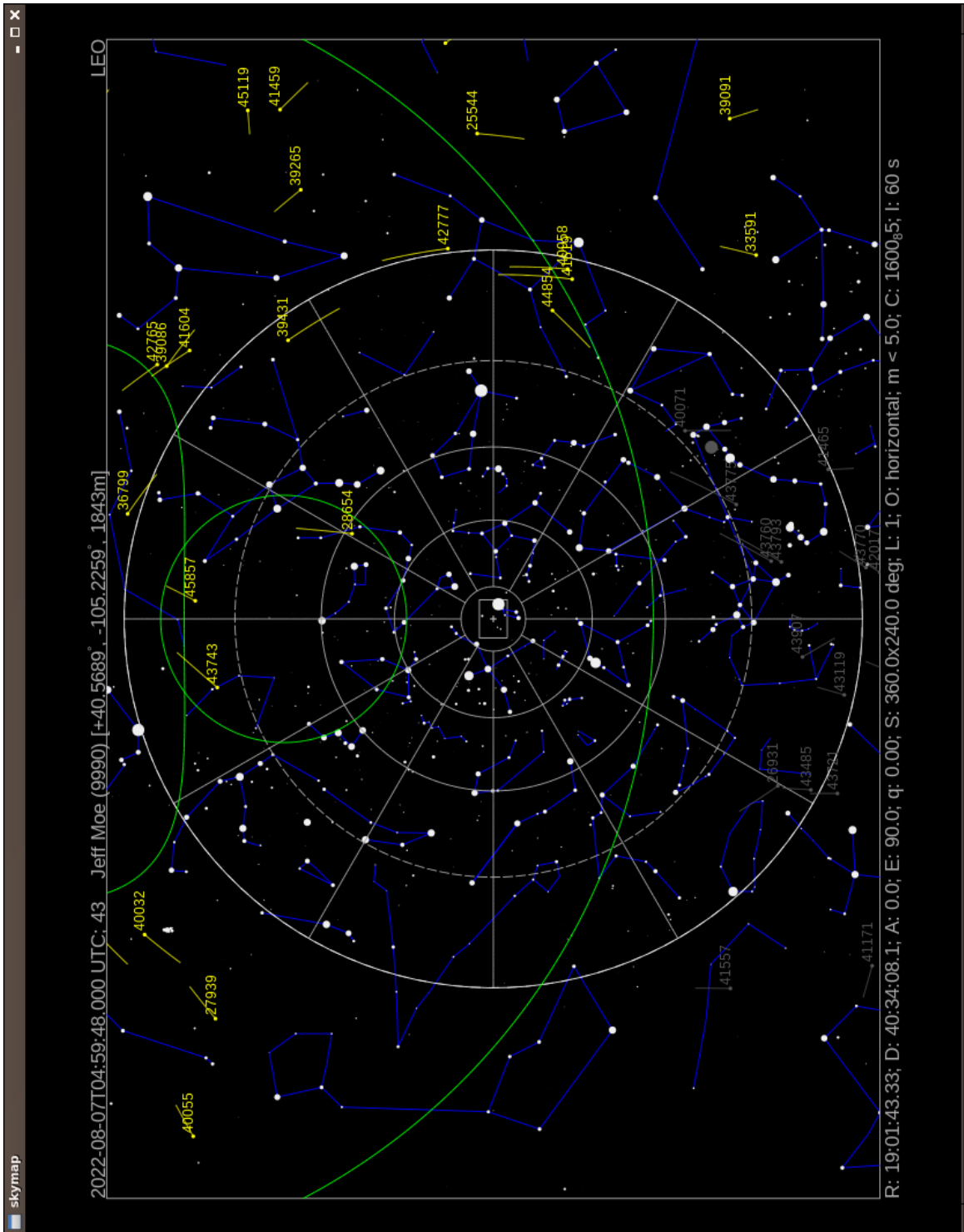


Figure 5.2: example screenshot.

```

# Or use upstream (needs more steps)
git clone https://github.com/cbassa/sattools

cd sattools/
# Build
make

# Install
sudo make install

# Clean
make clean

# To rebuild
make clean
make

# To uninstall
sudo make uninstall

```

See below for skymap (fork) usage:

```

tleupdate

# set config in ~/.bashrc XXX

skymap --help
Usage: skymap [OPTION]
Visualize satellites on a map of the sky.

-t, --time      Date/time (yyyy-mm-ddThh:mm:ss.sss) [default: now]
-c, --catalog   TLE catalog file [default: satnogs.tle]
-i, --id        Satellite ID (NORAD) [default: all]
-R, --ra        R.A. [hh:mm:ss.sss]
-D, --decl      Decl. [+dd:mm:ss.ss]
-A, --azimuth   Azimuth (deg)
-E, --elevation Elevation (deg)
-w, --width     Screen width (default: 1024). Set height too.
-g, --height    Screen height (default: 768). Set width too.
-n, --nmax      nmax line resolution/speed (default 128)
-S, --all-night All night
-Q, --no-stars  No stars
-a, --all-objects Show all objects from catalog (default: LEO)
-h, --help     This help
-s, --site      Site (COSPAR)
-d, --iod       IOD observations
-l, --length    Trail length [default: 60s]
-P, --planar-id planar search satellite ID
-r, --planar-alt planar search altitude
-V, --visibility-alt altitude for visibility contours
-p, --positions-file File with xyz positions
-L, --longitude manual site longitude (deg)
-B, --latitude  manual site latitude (deg)
-H, --elevation manual site elevation (m)

```

5.5 Tracking Software

The tracking software used depends upon the tracking mount.

See section 4.5, page 35 for discussion of hardware tracking mounts.

For our uses here, there are three broad categories of tracking software:

Telescopes — Controlling telescopes remotely.

Antennas — Controlling antennas remotely with hamlib.

Cameras — Controlling PTZ cameras remotely.

5.5.1 Telescope Tracking Software

Software that can be used with telescope tracking mounts:

INDI — Main client/server used by other applications.

KStars — Sky charts, INDI control.

Ekos — Application used within KStars for remote control of telescopes and related hardware via INDI.

Stellarium — Sky charts, has INDI plugin.

Other INDI — Many more applications work with INDI.

INDIGO — Positions itself as a next-generation INDI (?).

Using INDI with KStars and Ekos on a Sky-Watcher or Celestron telescope mount is a known working solution.

Celestron telescopes are widely used and available for many years. There is a variety of software written to control the mounts. The below list covers the drivers (e.g. INDI), not the software on top (e.g. KStars).

Celestron Nexstar telescope tracking mount drivers:^{1,2,3}

Celestron INDI — Celestron INDI

libnexasr INDIGO — libnexasr INDIGO.

Sky-Watcher EQ6-R Pro telescope tracking mount drivers:^{4,5,6}

EQMod Mount INDI — Drives Sky-Watcher protocol.

¹<https://www.indilib.org/telescopes/celestron.html>

²<https://github.com/indigo-astronomy/libnexasr>

³https://github.com/indigo-astronomy/indigo/blob/master/indigo_drivers/mount_nexstar/README.md

⁴<https://www.indilib.org/telescopes/skywatcher.html>

⁵<https://www.indilib.org/telescopes/skywatcher/eqmod.html>

⁶<https://www.indilib.org/telescopes/skywatcher/synscan-telescope.html>

Synscan INDI — Drives Synscan hand controller. INDI recommends using EQMod Mount over Synscan.

libnexusstar INDIGO — libnexusstar INDIGO.

5.5.2 INDI

INDI does much, KStars, etc.

One option to consider is making stvid an INDI client.

5.5.3 INDIGO

INDIGO⁷ works with libnexusstar, which supports many mounts:⁸

This library implements the serial commands supported by the Celestron NexStar hand control (HC) and SkyWatcher/Orion SynScan HC. This applies to the Celestron: NexStar GPS, NexStar GPS-SA, NexStar iSeries, NexStar SE Series, NexStar GT, CPC, SLT, Advanced-VX, Advanced-GT, CGE, CGEM etc. SkyWatcher: EQ5, HEQ5, EQ6 (Pro), AZ-EQ5 GT, AZ-EQ6 GT, EQ8 etc. and the corresponding Orion mounts.

5.5.4 Antenna Tracking Software

At present, for the SatNOGS network RF ground stations, hamlib is typically used for tracking, if directional antennas are used. Hamlib was originally created for amateur radio equipment, but has expanded to control many more devices. Hamlib can be used for some telescope mounts.

hamlib — Antenna rotator control.

5.5.5 Hamlib

I don't know of anyone prototyping a satellite tracking mount with hamlib, but it should be possible using the "leap frog" method, perhaps on the same mount as existing SatNOGS antennas. The mount may not be steady enough.

Hamlib lists support for the following tracking mounts, usually used with telescopes.⁹

1401	Celestron	NexStar	20110821.0	Untested
↪	ROT_MODEL_NEXSTAR			
1801	Meade	LX200/Autostar	20200610.0	Stable
↪	ROT_MODEL_MEADE			
1901	iOptron	iOptron	20191209.0	Alpha
↪	ROT_MODEL_IOPTRON			

⁷<https://www.indigo-astronomy.org/>

⁸<https://github.com/indigo-astronomy/libnexusstar>

⁹Output from version 4.3.1 of `rotctl -list`

5.5.6 Camera Tracking Software

There are applications for using PTZ control of cameras, such as used in “security” cameras.

motion — PTZ camera control. XXX check

I don’t know of any of these being used in satellite tracking prototypes at present.

5.6 GNSS with gpsd

GNSS is used for time synchronization and for (somewhat) accurately determining the location of the observation.

GNSS collectively includes the USA GPS, Europe’s Galileo, Russia’s Global Navigation Satellite System (GLONASS), and China’s BeiDou Navigation Satellite System (BDS), as well as other regional systems.

A basic, widely available COTS USB GNSS device with a basic (or no!) antenna plugged into the embedded system can get time and location accurate enough for the purposes here. See various U-Blox devices, for example.

In Debian GNSS service with a USB device can be provided by the `gpsd` application.

```
sudo apt install gpsd gpsd-tools
```

Edit the configuration file, `/etc/default/gpsd` like:

```
DEVICES="/dev/ttyACM0"
GPSD_OPTIONS="-Gn"
USBAUTO="false"
```

This will start a `gpsd` daemon listening on all interfaces, so it can be used by other computers on the network (such as if acquire and process are on different machines). Using the device `/dev/ttyACM0` can be problematic if there are multiple `/dev/ttyACM*` devices. Perhaps something like this could be used in that case:

```
DEVICES="/dev/serial/by-id/usb-u-blox_AG_-_www.u-blox.com_u-blox_GNSS_receiver-if00"
```

Even with `gpsd` configuration listening on all Internet Protocol Addresses (IPs), don’t think `systemd` won’t do what it likes. So you may have to do:

```
systemctl edit --full gpsd.socket
```

And create a `gpsd` configuration like this (I have Internet Protocol version 6 (IPv6) disabled, in this case):

```
[Unit]
Description=GPS (Global Positioning System) Daemon Sockets

[Socket]
ListenStream=/run/gpsd.sock
# ListenStream=[::]:2947
```

```
ListenStream=0.0.0.0:2947
SocketMode=0600
BindIPv6Only=no
```

```
[Install]
WantedBy=sockets.target
```

(Re)start:

```
sudo systemctl restart gpsd.service gpsd.socket
```

Test all is good:

```
gpsmon -n
# or
cgps -u m
```

Enable to start on boot:

```
sudo systemctl enable gpsd.service gpsd.socket
```

See below for sample output from cgps.

```

                                Seen 39/Used 28
Time:          2022-09-02T00:40:28.000Z (18) GNSS  PRN  Elev  Azim  SNR  Use
Latitude:      40.56896250 N                GP  1   1  24.0  237.0  44.0  Y
Longitude:     105.22600420 W                GP  3   3  63.0  297.0  50.0  Y
Alt (HAE, MSL): 1848.352, 1869.637 m         GP  4   4  33.0  292.0  45.0  Y
Speed:         0.05 km/h                    GP 16  16  21.0  162.0  36.0  Y
Track (true, var): 85.1, 8.2 deg            GP 21  21  13.0  218.0  40.0  Y
Climb:         0.00 m/min                   GP 22  22  40.0  77.0  18.0  Y
Status:        3D DGPS FIX (29 secs)        GP 26  26  43.0  140.0  46.0  Y
Long Err (XDOP, EPX): 0.40, +/- 1.5 m      GP 31  31  57.0  49.0  39.0  Y
Lat Err (YDOP, EPY): 0.36, +/- 1.3 m      SB131 44  42.0  198.0  44.0  Y
Alt Err (VDOP, EPV): 0.90, +/- 0.7 m      SB133 46  37.0  214.0  41.0  Y
2D Err (HDOP, CEP): 0.51, +/- 0.5 m      GL  6   70  48.0  99.0  21.0  Y
3D Err (PDOP, SEP): 1.04, +/- 5.1 m      GL  7   71  62.0  352.0  51.0  Y
Time Err (TDOP): 0.57                     GL  8   72  19.0  314.0  47.0  Y
Geo Err (GDOP): 1.18                      GL  9   73  71.0  149.0  45.0  Y
ECEF X, VX:    -1274598.340 m -0.010 m/s   GL 10  74  28.0  194.0  29.0  Y
ECEF Y, VY:    -4682900.030 m -0.010 m/s   GL 23  87  13.0  305.0  48.0  Y
ECEF Z, VZ:    4127382.070 m  0.020 m/s    GA  2  302  31.0  168.0  40.0  Y
Speed Err (EPS): +/- 0.4 km/h             GA  3  303  72.0  40.0  39.0  Y
Track Err (EPD): n/a                      GA  8  308  40.0  300.0  47.0  Y
Time offset:   -0.005160195 s             GA 13  313  22.0  285.0  43.0  Y
Grid Square:   DN70jn26                   GA 15  315  17.0  232.0  43.0  Y
More...
```

5.7 NTP

With all the above, time still needs to be configured. Configuring `gpsd` isn't enough for correct system time. The main system on the Internet used for time synchronization is NTP. In Debian there are a few options for NTP. The best is to use a hardware GNSS (GPS), with Pulse per second (PPS) for improved accuracy. The easiest is to just use NTP.

5.8. KSTARS WITH TRACKING MOUNT

All systems in the pipeline need to have the correct time and location. It is best if they all pull from the same NTP server, or even better than best if they all run GNSS hardware with PPS enabled.

Some quick and dirty time synchronization commands. The `ntpd` daemon can have slow startup synchronization sometimes. If so, perhaps run like this:

```
# Get the daemon out of the way.
sudo systemctl stop ntp

# Get time from someone, MIT in this case:
sudo ntpdate time.mit.edu

# OR

# Get time from local server, such as router (made up IP):
sudo ntpdate 192.168.1.1

# If above complains, to do an initial sync at boot (force ntpdate):
sudo ntpdate -b 192.168.1.1

# Restart daemon
sudo systemctl start ntp
```

Go through each of the systems used in the toolchain and make sure they all have accurate time or processing will be off.

5.8 KStars with Tracking Mount

KStars is an application that has been used for years in the astronomy community. It is well established, well supported, and included in Debian.

KStars has multiple uses for imaging satellites. One main use is to control a telescope tracking mount, such as the hardware described in section 4.7, page 40.

For the purposes here, described below will be using KStars with a Sky-Watcher tracking mount with INDI and Ekos. See figure 2.3, page 25 for a photo of the setup used with KStars below.

The telescope mount will be used in sidereal tracking mode, where the stars will appear as “points”, and the satellites will appear as trails. The mount is not used in a satellite tracking mode. Sidereal is the “standard” tracking mode of telescopes.

KStars is the “main” application, but it depends on other key parts. INDI is the protocol that KStars uses for telescope control. INDI itself is a collection of applications. While KStars has the main sky chart and Ekos is launched within it, the actual mount control is done with the Ekos application. While it may sound complex, all of this is set up pretty easily in Debian.

```
# Quick and dirty from memory, something like:
sudo apt update
sudo apt install kstars indi-bin indi-eqmod indi-gpsd
```

KStars has a sky chart, as can be see in figure 5.3, page 58. When mount control is functioning, a location on the sky chart, such as a star, can be clicked on and the mount will GoTo that location and optionally track it. Using this, a telescope mount can be used to easily

point the camera at a location and track it to observe satellites. It should also provide a superior FITS file for extracting data than using a static mount with star trails (XXX made up).

To use a telescope tracking mount for use with `stvid`, the following steps need to be performed in roughly this order, assuming everything has been configured. An overview of steps:

1. Physically mount all hardware.
2. Plug in and power everything up.
3. Confirm all hardware looks ok (e.g. `lsusb`).
4. Confirm GNSS time and location are ok (e.g. `cgps -u m`). See section 5.6, page 53.
5. Confirm time is correct on all systems in the toolchain (e.g. `date`). See section 5.7, page 54, for information about NTP.
6. Run camera configuration script (e.g. `v4l2-ctl` commands).
7. Start `indiserver` on the embedded system, using scripts to include a camera (such as `indi_v4l2_ccd`).
8. Start KStars on the workstation.
9. Launch Ekos within KStars, under Tools.
10. In Ekos, select a configuration with the EQ Mount for the Sky-Watcher, and V4L2 for the CCD, which will work with The Imaging Source camera used in this example. Alternatively, the ZWO ASI could be used with a similar configuration.
11. The Ekos configuration should also be set to use the remote `indiserver` IP address of the embedded system USB connected to the Sky-Watcher mount.
12. Hit the start button to start Ekos/INDI.
13. On the screen that pops up, confirm all the tabs are good.
14. Check the last configuration tab for the camera, it often resets the size.
15. Hit close on the screen with the INDI devices.
16. Click the mount icon, and start tracking.
17. Perhaps do some focusing... XXX
18. Click the solver icon.
19. Click the Sync radio button.
20. Click Capture and Solve. XXX what is it.

5.8. KSTARS WITH TRACKING MOUNT

21. If everything is tracking happily, good.
22. If not, do all the alignment steps.
23. When alignment is good and tracking is accurate, stop Ekos and close it.
24. Stop the `indiserver` running on the embedded system.
25. Start the `indiserver` on the embedded system, but without using a camera (e.g. remove `indi_v412_ccd`).
26. Select the INDI configuration with a remote `indiserver`, the EQ Mount, and the Simulated CCD.
27. Hit start in Ekos to get INDI connections going.
28. Confirm all is ok in hardware tabs, then hit close.
29. Now in the KStars sky chart window there is control of the mount without interfering with the camera.
30. Start `stvid`. See XXX for more info.
31. When done capturing that part of the sky with `stvid`, stop `stvid`
32. Go to the KStars sky chart and right-click on the new location, and slew to it.
33. Start `stvid` again, pointing at the new location.
34. Repeat the last few steps each time a new sky location is desired.

If the camera and mount are connected to the embedded system OK, it will look like below, in this case with The Imaging Source camera and Sky-Watcher mount:

```
jebba@odroid-01:~$ lsusb
Bus 002 Device 003: ID 199e:9004 The Imaging Source Europe GmbH DMK 33UX174
Bus 002 Device 002: ID 05e3:0620 Genesys Logic, Inc. GL3523 Hub
Bus 002 Device 001: ID 1d6b:0003 Linux Foundation 3.0 root hub
Bus 001 Device 003: ID 067b:23d3 Prolific Technology, Inc. USB-Serial Controller
Bus 001 Device 002: ID 05e3:0610 Genesys Logic, Inc. Hub
Bus 001 Device 001: ID 1d6b:0002 Linux Foundation 2.0 root hub
```

Note the The Imaging Source Europe GmbH DMK 33UX174 device is the camera and the Prolific Technology, Inc. USB-Serial Controller is the Sky-Watcher telescope mount. Other views of the devices:

```
jebba@odroid-01:~$ ls -l /dev/bus/usb/002/003 /dev/bus/usb/001/003 /dev/video* /dev/ttyUSB0
crw-rw---- 1 root plugdev 189, 2 Sep 1 20:08 /dev/bus/usb/001/003
crw-rw-rw- 1 root video 189, 130 Sep 1 20:08 /dev/bus/usb/002/003
crw-rw---- 1 root dialout 188, 0 Sep 1 20:08 /dev/ttyUSB0
crw-rw---- 1 root video 81, 0 Sep 1 20:08 /dev/video0
crw-rw---- 1 root video 81, 1 Sep 1 20:08 /dev/video1
crw-rw---- 1 root video 81, 2 Sep 1 20:08 /dev/video2
```

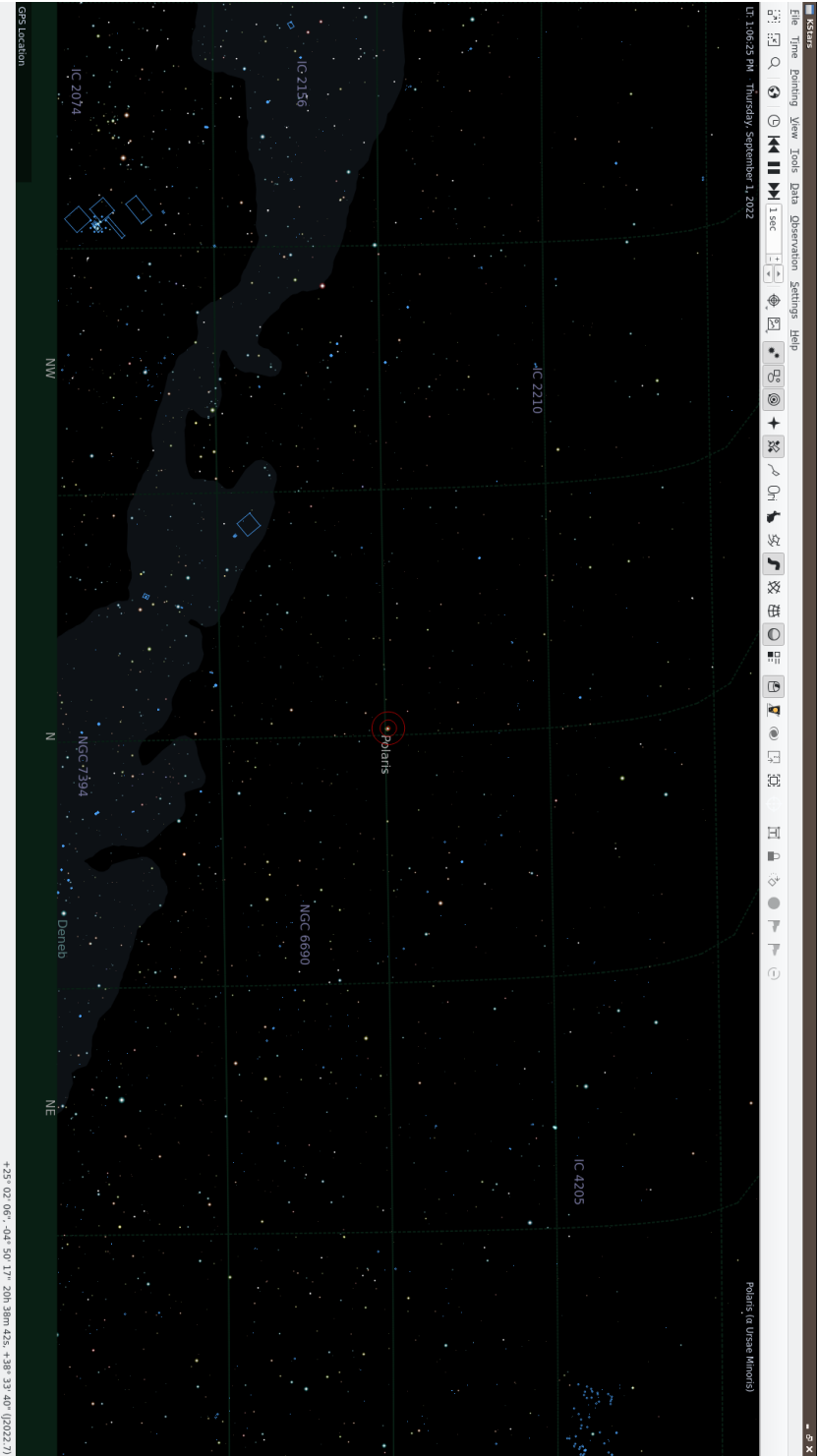


Figure 5.3: , example screenshot.

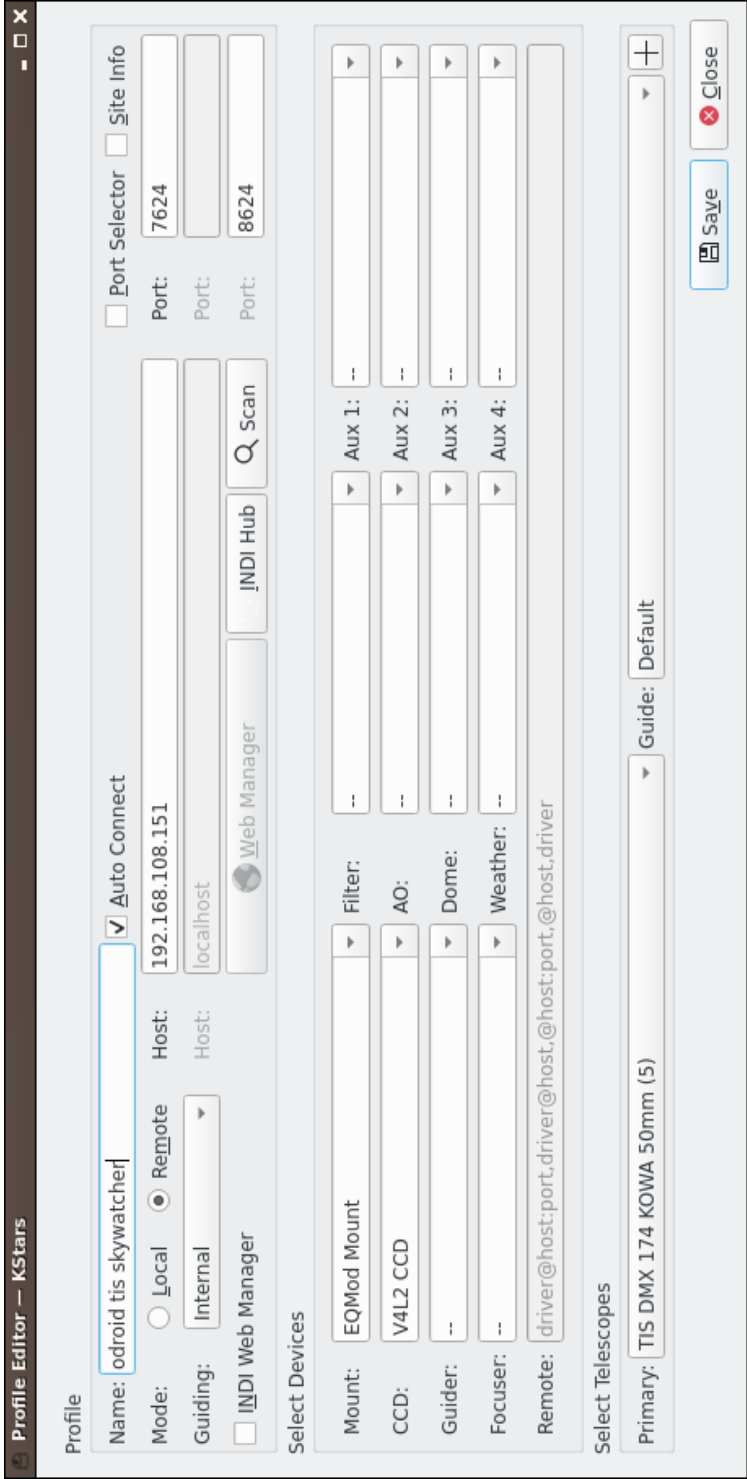


Figure 5.4: using V4L2, example screenshot.

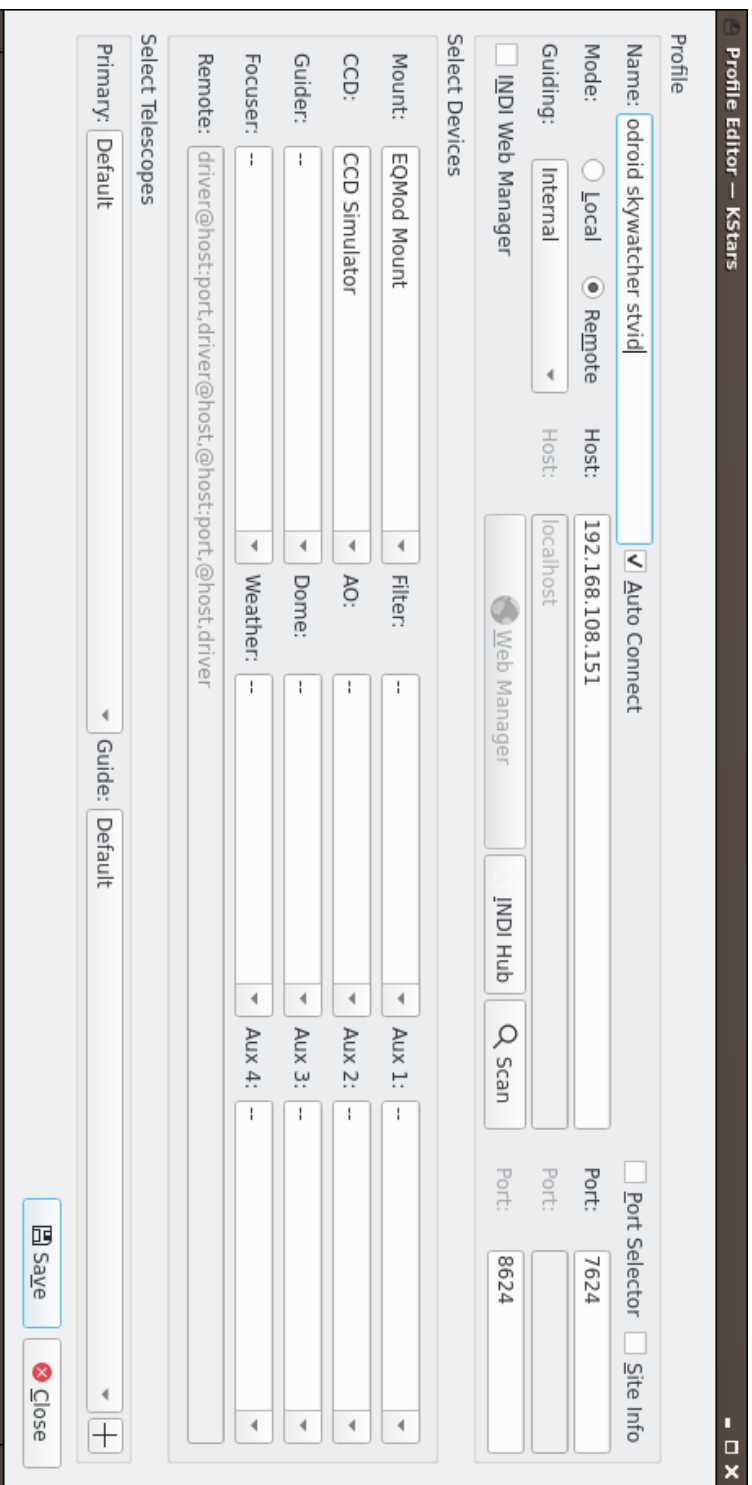


Figure 5.5: using simulated CCD, example screenshot.

5.9. STVID WITH DOCKER

Side note: you need to be in the `plugdev`, `video`, `dialout` groups. Side note: on the Odroid N2, there is another `/dev/video` device, so three devices are appearing. The The Imaging Source camera appears as two `/dev/video` devices.

5.9 stvid with Docker

Daniel Ekman has created a Docker setup for easier installation and configuration.

The Docker source code repo is available here:

* <https://github.com/kng/stvid-docker>

The Docker itself is here:

* <https://hub.docker.com/repository/docker/knegge/stvid>

Acquire Data
Twinkle, Twinkle, Little Starlink

6.1 Overview of Operation

Below shows how to run a SatNOGS Optical ground station, after it has been set up and configured.

6.2 Setup with stvid

Acquire data with `acquire.py` from `stvid`. Enter `virtualenv`, if used:

```
cd stvid/
source env/bin/activate
```

Get the latest TLEs:

```
./update_tle.py
```

Acquire live data from camera.

```
cd stvid/
./acquire.py
```

6.3 `acquire.py` Output

Example output while running `acquire.py`.

```
2022-09-01 22:33:09,495 [MainThread ] [INFO ] Using config: configuration.ini
2022-09-01 22:33:09,495 [MainThread ] [INFO ] Test mode: True
2022-09-01 22:33:09,495 [MainThread ] [INFO ] Test duration: 3600s
2022-09-01 22:33:09,496 [MainThread ] [INFO ] Live mode: False
2022-09-01 22:33:09,517 [MainThread ] [INFO ] Starting data acquisition
2022-09-01 22:33:09,518 [MainThread ] [INFO ] Acquisition will end after
↳ 2022-09-02T05:33:09.496
2022-09-01 22:33:09,620 [MainThread ] [INFO ] Storing files in
↳ /home/jebba/devel/spacecruf/stvid/data/obs/20220902_1/043309
2022-09-01 22:33:20,086 [MainThread ] [DEBUG] Captured z1
2022-09-01 22:33:20,086 [MainThread ] [DEBUG] Processing buffer 1
2022-09-01 22:33:21,842 [MainThread ] [INFO ] Compressed 2022-09-02T04:33:09.871.fits in
↳ 1.75 sec
2022-09-01 22:33:21,842 [MainThread ] [DEBUG] Processed buffer 1
2022-09-01 22:33:30,171 [MainThread ] [DEBUG] Captured z2
2022-09-01 22:33:30,172 [MainThread ] [DEBUG] Processing buffer 2
2022-09-01 22:33:31,930 [MainThread ] [INFO ] Compressed 2022-09-02T04:33:20.136.fits in
↳ 1.76 sec
```



Figure 6.1: Satellite images acquired by stvid.

Plate Solvers
Place from Pixels

7.1 Plate Solver

A “plate solver” will take an image of stars and detect the time and place of the picture. There are two main steps:

1. Extract stars from an image, such as a FITS file generated by `stvid`.
2. “Solve” the image of the stars in the image against vast databases in a star catalogue.

See below for a list of software tools that detect/extract stars from images (e.g. FITS).

- Source Extractor.
- KStars with Ekos adds `Internal SEP`.
- KStars with Ekos adds `Builtin method for solver`.

See below for a list of plate solvers that can be used.

- `astrometry.net` locally.
- `astrometry.net` Internet.
- `astap`.
- `Watney`.

7.2 Source Extractor

Source Extractor, formerly SExtractor and some other names, is an application to extract stars from images. The software has been widely used for many years.

<https://www.astromatic.net/software/sextractor>

7.3 astrometry.net

Astrometry.net is a website and software that can be run locally to solve a plate of stars that has been extracted from Source Extractor. XXX

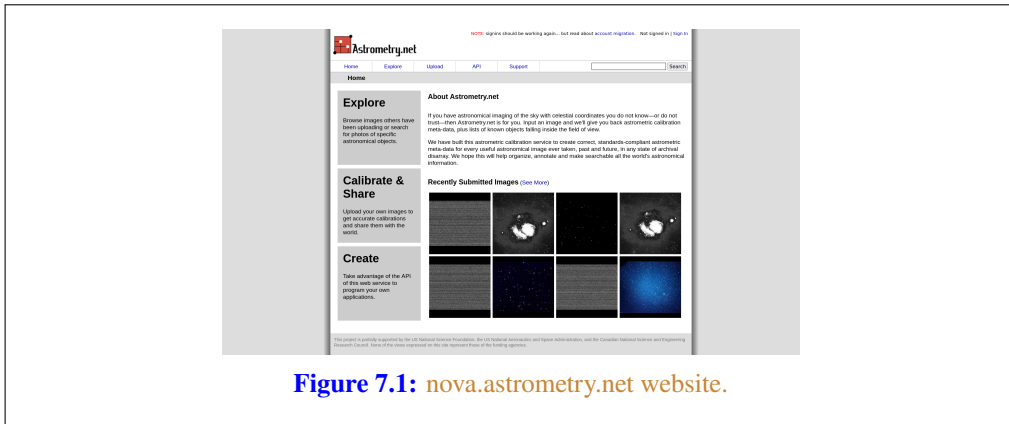
NOTICE:

Using `astrometry.net` online requires an account with non-libre services. The `astrometry.net` software can be installed locally to avoid this.

7.4 Star Catalogues

To use a plate solver, you will need star catalogues. They can get large. The `stvid` application includes a basic star catalogue. XXX The 4200 index series is also recommended.

7.5. WORLD COORDINATE SYSTEM



7.5 World Coordinate System

World Coordinate System (WCS) info. XXX

7.6 SIP

Simple Imaging Polynomial (SIP) info. XXX

7.7 Plate Solving with stvid

Use the process.py scripts described in section 7.1, page 68, to solve plates with stvid.

Detect
Find Satellites

8.1 Satellite Detection with stvid

This is a description of satellite detection processes. To detect satellite in a FITS file using the stvid toolchain, run `process.py` or, if it exists, the `process_new.py` Python script.

Note the stvid application's `process.py` and `process_new.py` will perform both the detection and identification steps.

8.1.1 process_new.py Usage

This assumes you have installed stvid as shown in section 6.2, page 64. Adjust the dated directory used in this example to the actual directory name.

```
cd stvid/
# Maybe you need to update TLE
./update_tle.py
# Process directory
./process_new.py -c config_new.ini -d data/obs/20220825_1/020502/
```

8.1.2 process.py Usage

If there is no `process_new.py` it has likely been merged into `process.py`. Or perhaps, to use the “older” script it would be run as shown below. Note, the old and new configuration files are different and should be used with the correct corresponding Python script.

```
cd stvid/
./process.py -c configuration.ini -d data/obs/20220825_1/020502/
```

8.1.3 process_new.py Example Output

```
Computing astrometric calibration for
↪ /srv/obs/odroid-01/obs/20220902_1/043309/2022-09-02T04:33:09.871.fits
2022-09-02T04:33:09.871.fits 216.814874 31.756777 199/ 342 10.6 13.9 16.53 +- 0.69
48144 21 027BE 9999 G 20220902043314699 17 25 1431290+312311 37 S
51636 22 012Q 9999 G 20220902043314094 17 25 1413930+340692 37 S
File queue empty, waiting for new files...
2022-09-02T04:33:20.136.fits 216.815061 31.756834 198/ 345 10.8 13.2 16.53 +- 0.70
2022-09-02T04:33:30.223.fits 216.815420 31.756810 202/ 338 10.5 13.9 16.53 +- 0.70
90000 22 500A 9999 G 20220902043336020 17 25 1433368+375908 37 S
2022-09-02T04:33:40.315.fits 216.815570 31.756676 206/ 342 10.1 13.1 16.54 +- 0.70
```

8.2 AstroImageJ

Analyze data with applications, such as AstroImageJ.

FITS files are commonly used in astronomy.¹ AstroImageJ can read FITS format files. See 8.1, page 73, for a screenshot displaying a FITS file generated by stvid.

¹Wikipedia contributors. *FITS* — Wikipedia, The Free Encyclopedia. <https://en.wikipedia.org/w/index.php?title=FITS&oldid=1091431488>. [Online; accessed 28-August-2022]. 2022

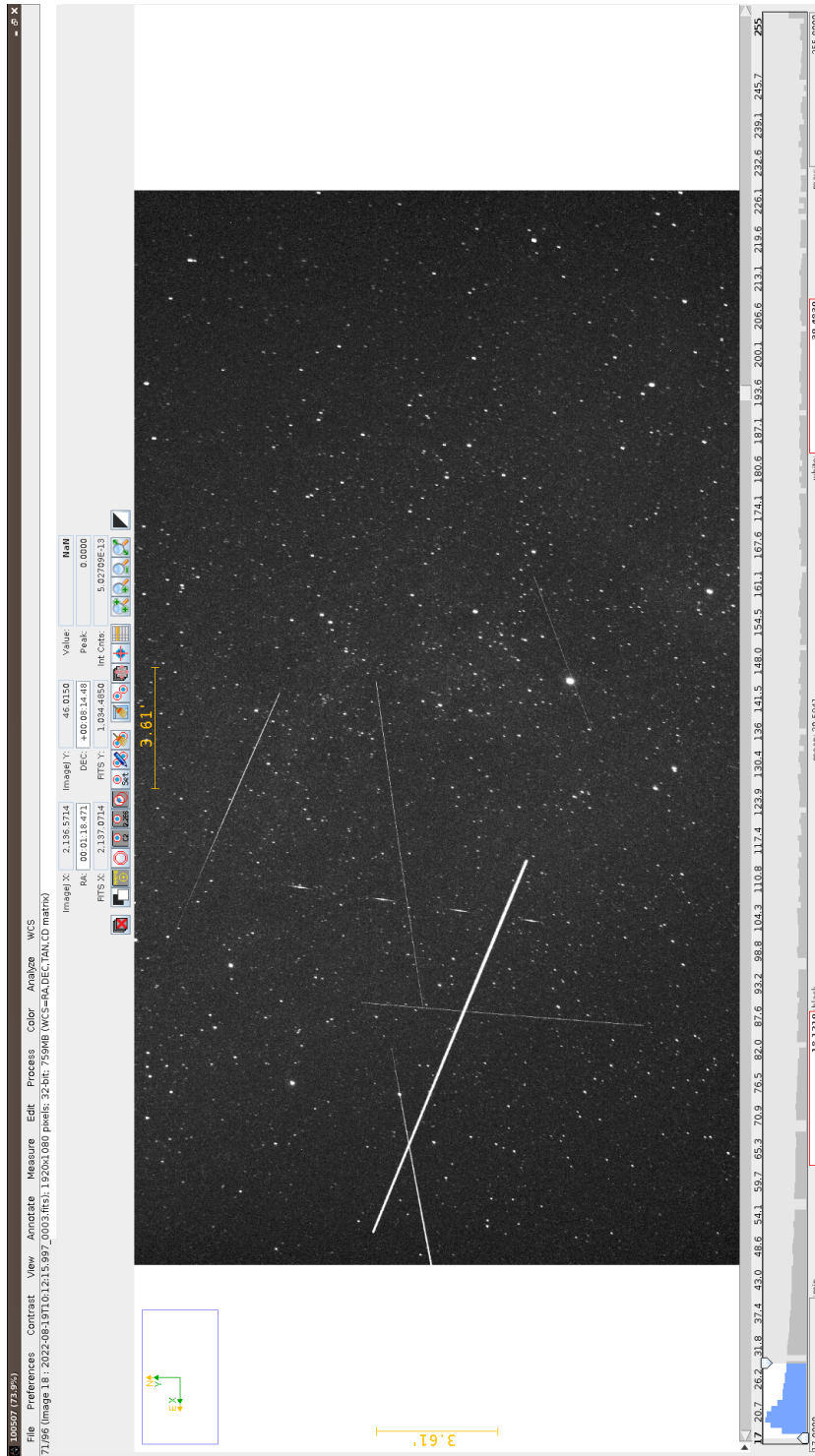


Figure 8.1: AstrometryJ screenshot viewing FITS file.

Identify
More Than Just Old Rocket Bodies

9.1 Overview of Satellite Identification

The LSF is developing a project called Spacecraft Identification and Localization (SIDLOC), for satellite identification and localization. With the addition of many more satellites in orbit there is a growing need for Space Situational Awareness (SSA).

9.2 `stvid`'s `process.py` for Identification

The best tool for identifying satellites from FITS files is the `process.py` script from `stvid`, available here:

* <https://github.com/cbassa/stvid>

My fork is here:

* <https://spacecraft.org/spacecraft/stvid>

9.3 Identifying Satellites with `satid`

The deprecated C application, `satid` from the `sattools` package can help identify satellites. See figure 9.1, page 77 for output from my Giza port of `satid`.¹

* <https://github.com/cbassa/sattools>

My fork is here:

* <https://spacecraft.org/spacecraft/sattools>

9.4 Identification with `stvid`

See section 8.1, page 72 for details on identification with `stvid`. The detection and identification steps are both done in one script.

See figure 9.2, page 78 for an example of from `stvid` automated processing of an input FITS file. The output image is in Portable Network Graphics (PNG) format. `stvid` will also output other files with results, such as Comma Separated Value (CSV) files.

9.5 Review of Images

See the following subsections for example output from `stvid`.

9.5.1 Unidentified Satellites

When `stvid` runs the `process.py` (or `new`) script and it encounters a satellite it cannot identify, it gives it the North American Aerospace Defense Catalog Number (NORAD ID) 90000. If more unidentified satellites are detected in the same image, each detection is incremented by one.

See figure 9.3, page 79, for an example image, with three unidentified satellites. One is on the left, the other two on the right, next to each other.

See figures 9.4, 9.5, and 9.6, pages 80, 81, and 82, to see an example of `stvid` labelling three identified satellites with NORAD IDs 90000, 90001, 90002.

¹<https://spacecraft.org/spacecraft/sattools/media/branch/spacecraft/img/satid-giza-3.png>

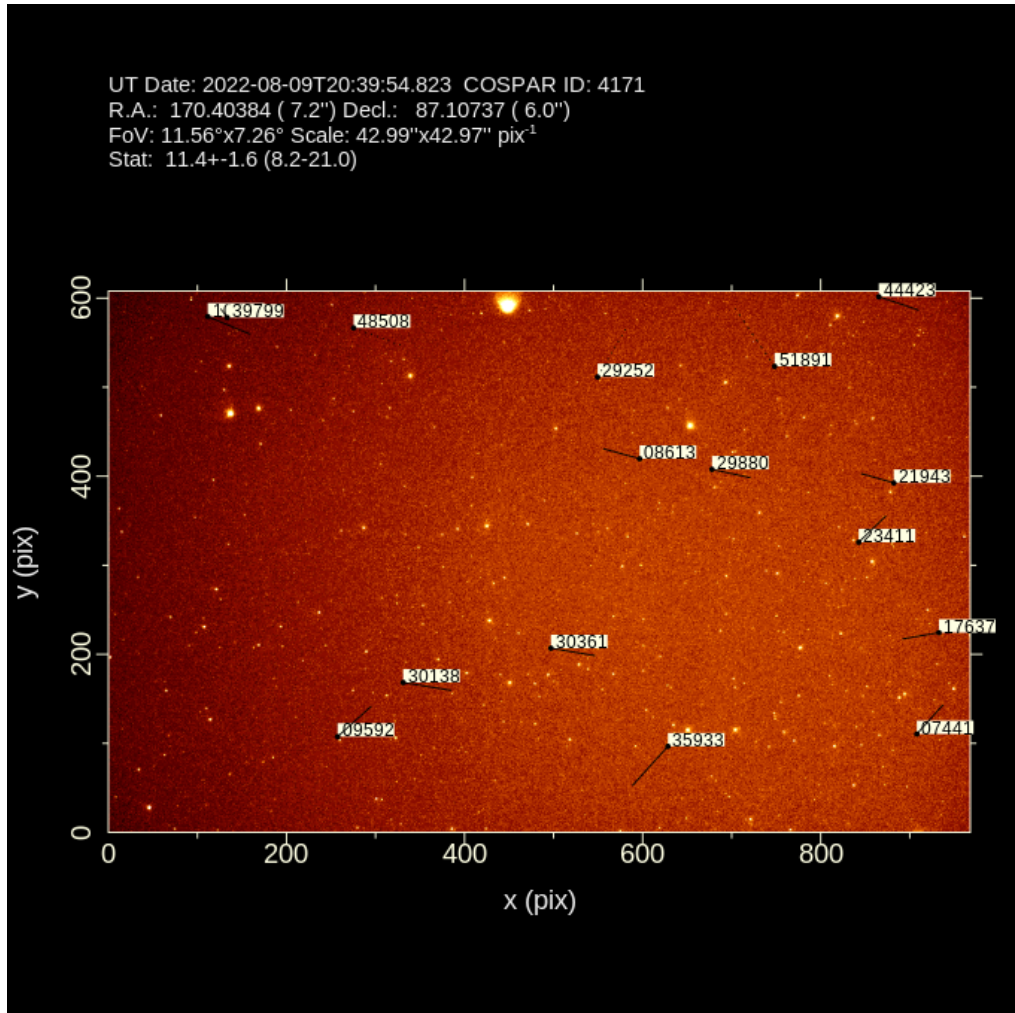


Figure 9.1: satid example.

UT Date: 2022-08-23T11:21:34.290 COSPAR ID: 9999
R.A.: 343.290526 (61.4") Decl.: 41.561853 (73.7")
FOV: 40.53° x 22.77° Scale: 75.99" x 75.89" pix⁻¹

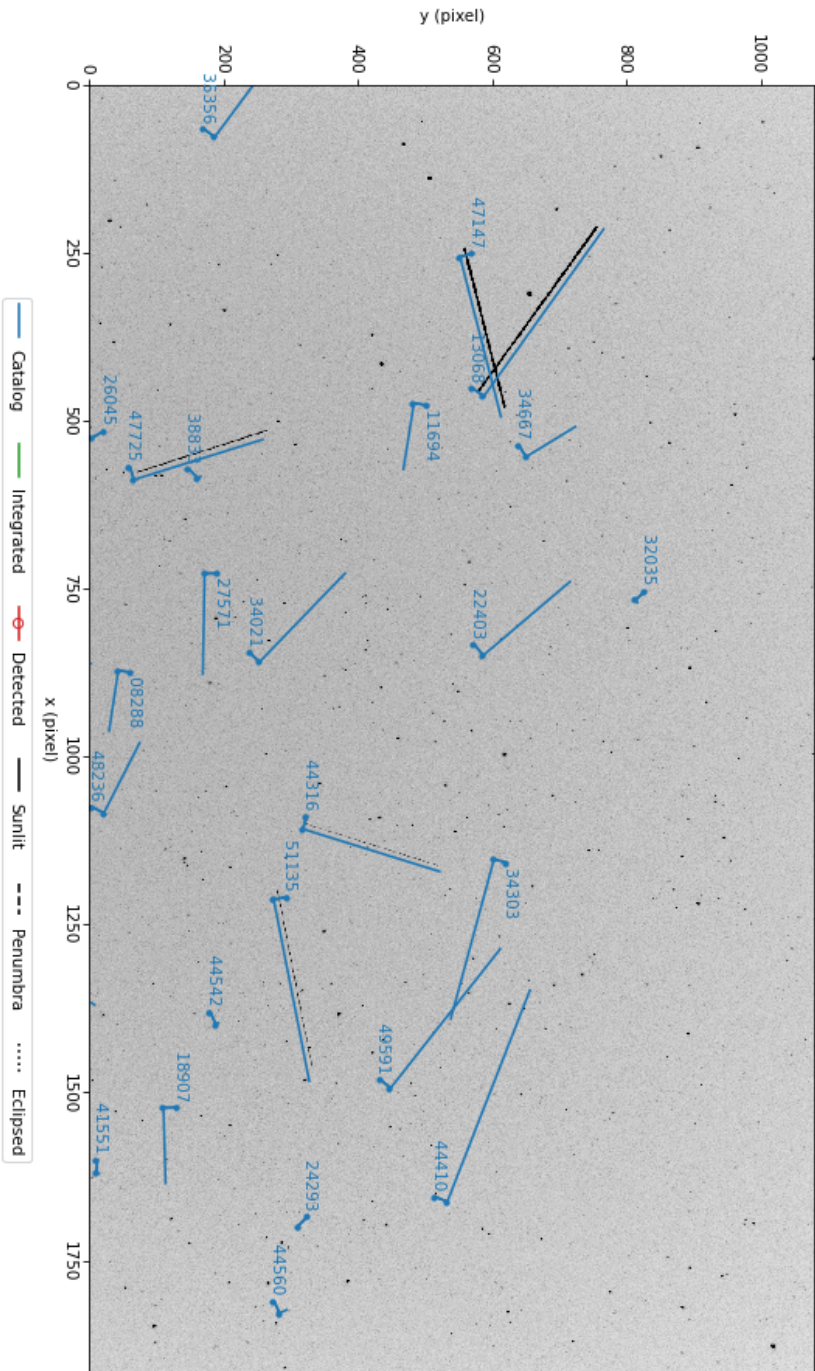


Figure 9.2: Example satellite image processed by stvid.

UT Date: 2022-08-23T11:18:12.531 COSPAR ID: 9999
 R.A.: 342.449488 (59.5") Decl.: 41.563068 (71.6")
 FOV: 40.52° x 22.76° Scale: 75.97"x75.88" pix⁻¹

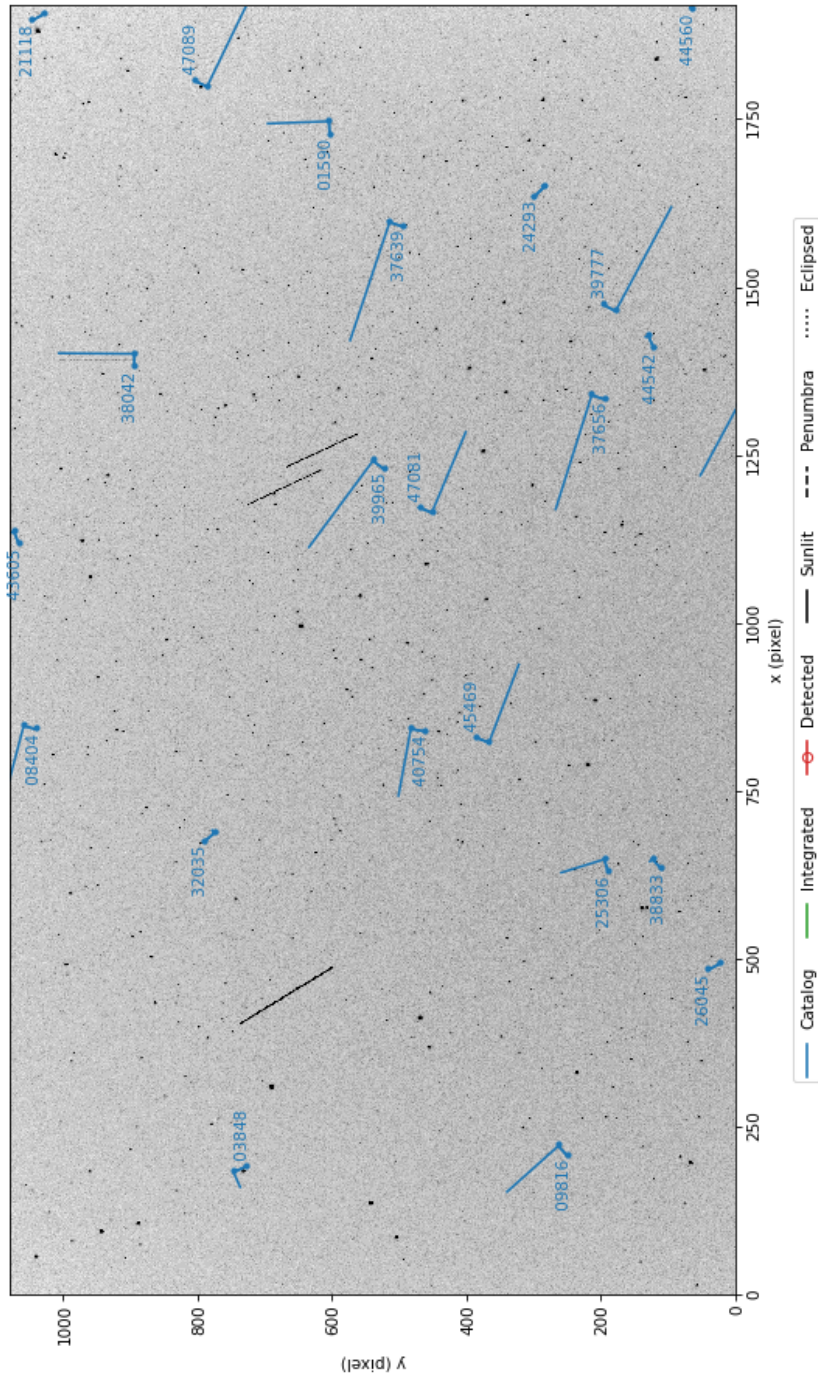


Figure 9.3: stvid processed image, with three unidentified satellites.

UT Date: 2022-08-23T11:18:12.531 COSPAR ID: 9999
 R.A.: 342.449488 (59.5") Decl.: 41.563068 (71.6")
 FOV: 40.52° x 22.76° Scale: 75.97" x 75.88" pix⁻¹

90000 22 500A 9999 G 20220823111817523 17 25 2301981+305036 37 S

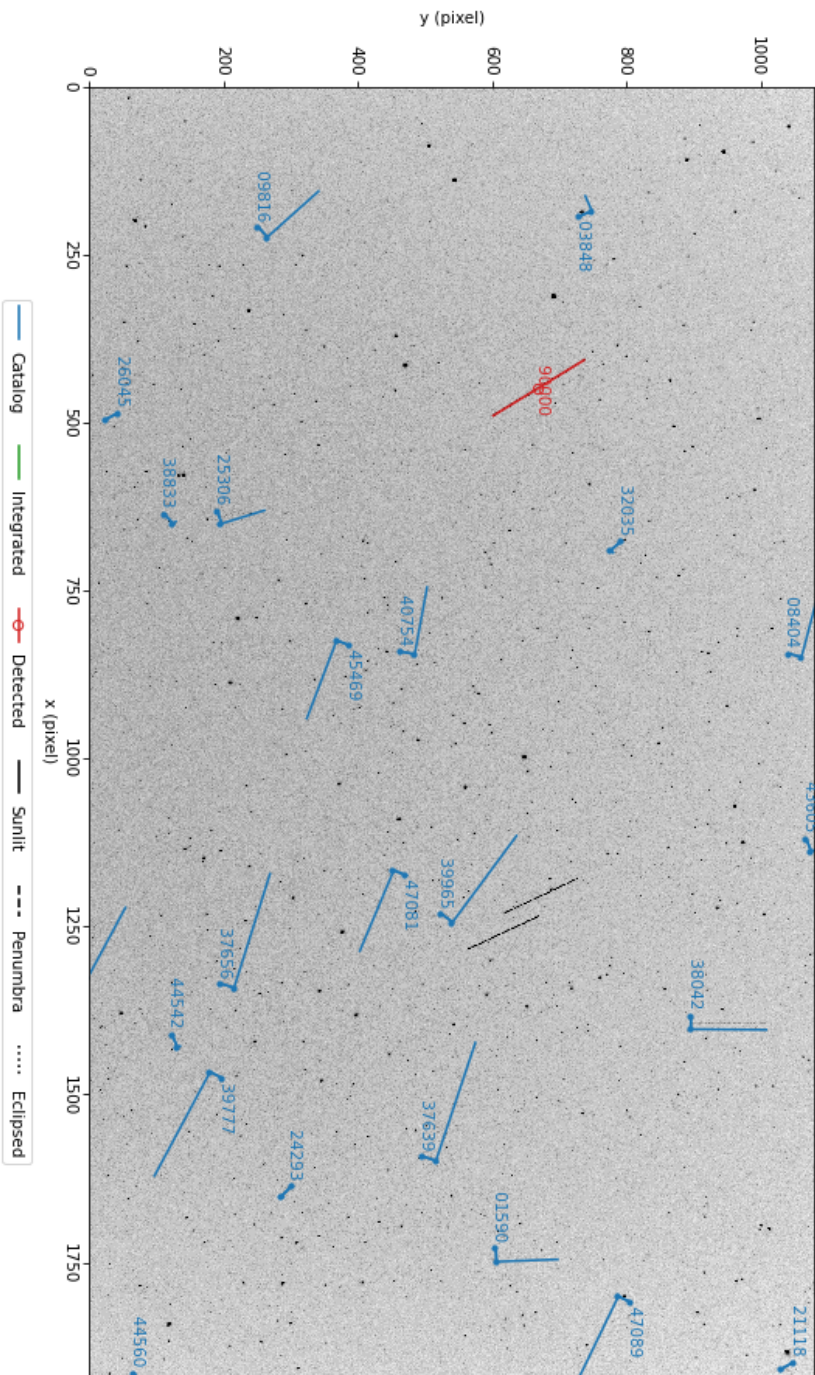


Figure 9.4: stivid processed image, with three unidentified satellites, the first labeled with NORAD ID 90000.

UT Date: 2022-08-23T11:18:12.531 COSPAR ID: 9999
 R.A.: 342.449488 (59.5") Decl.: 41.563068 (71.6")
 FOV: 40.52° x 22.76° Scale: 75.97" x 75.88" pix⁻¹

90001 22 500A 9999 G 20220823111817523 17 25 2258940+475019 37 S

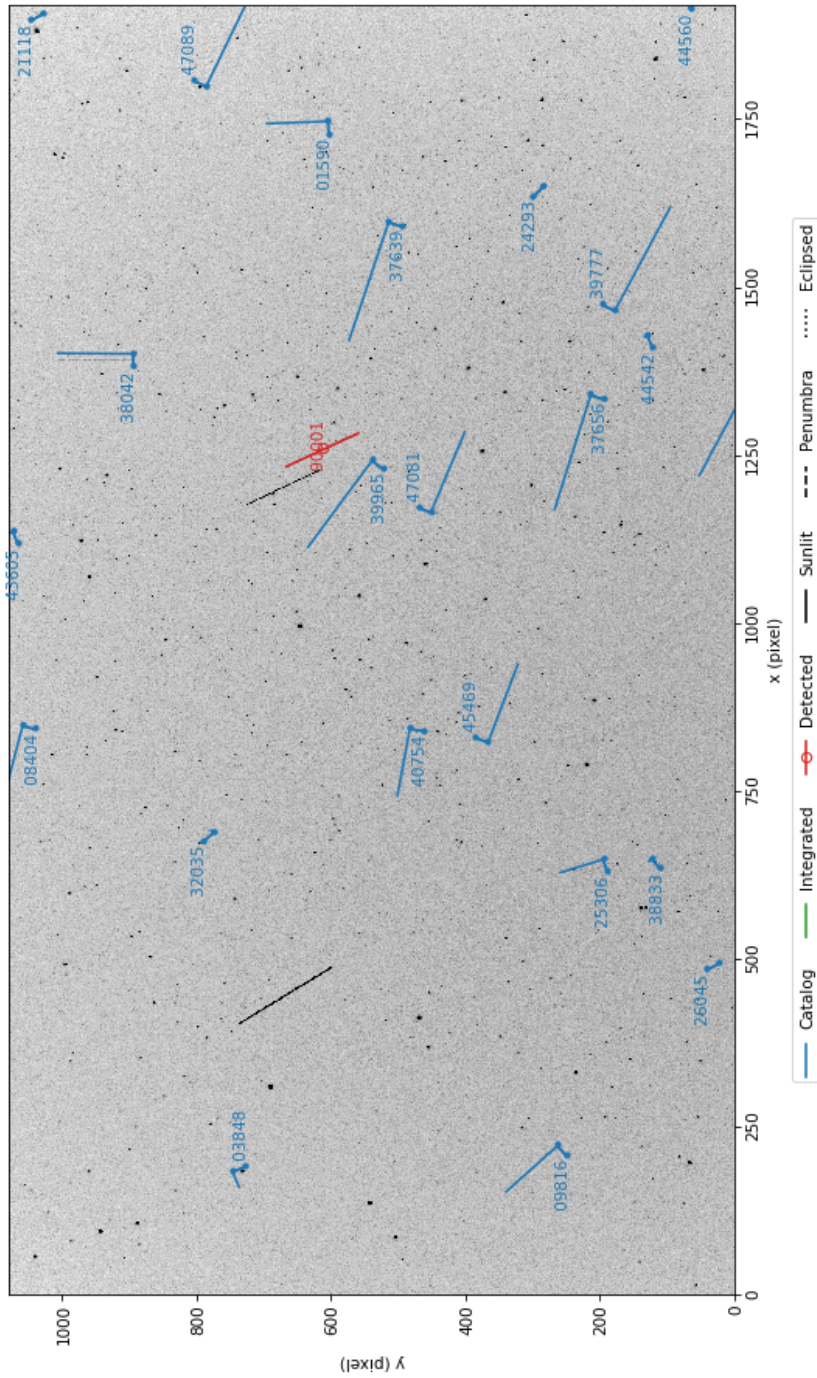


Figure 9.5: stvid processed image, with three unidentified satellites, the second labeled with NORAD ID 90001.

UT Date: 2022-08-23T11:18:12.531 COSPAR ID: 9999
 R.A.: 342.449488 (59.5") Decl.: 41.563068 (71.6")
 FOV: 40.52° x 22.76° Scale: 75.97" x 75.88" pix⁻¹

90002 22 500A 9999 G 20220823111817523 17 25 2305759+463788 37 S

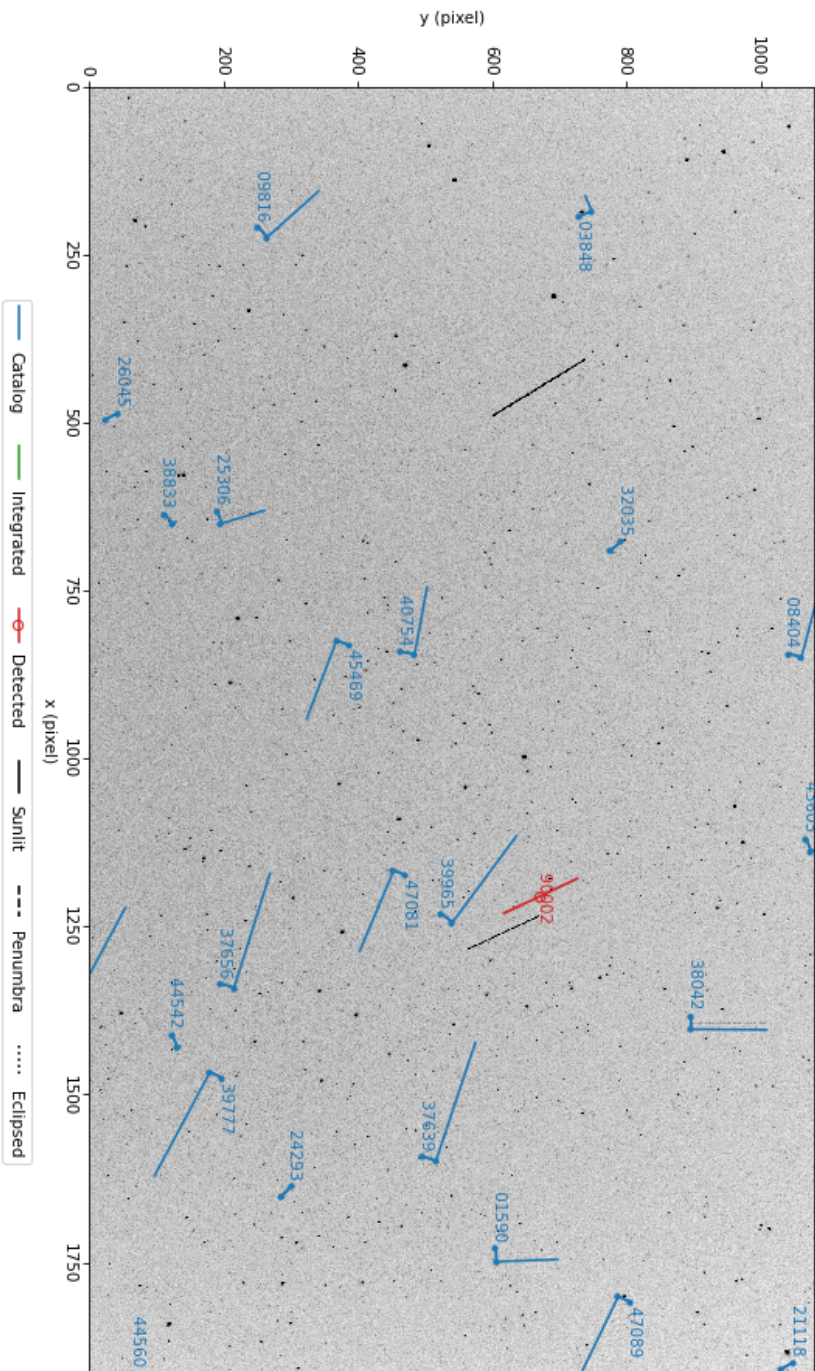


Figure 9.6: stvid processed image, with three unidentified satellites, the third labeled with NORAD ID 90002.

9.5.2 Airplanes

Airplanes are noise in the data.

Airplanes will appear not infrequently in images. See figure 9.7, page 84 for an example with an airplane in the left side, forming two parallel trails from the aircrafts' lights.

In figure 9.8, page 85, is shown an example image with an airplane with a very distinct blinking light.

In figure 9.9, page 86, airplane solid parallel trails can be seen with blinking lights.

9.5.3 Configuration and Setup Errors in Images

See figure 9.10, page 87, for an example of an image processed by a mis-configured system. As can be seen, the plotted lines are offset from the actual images of satellites. This, and similar issues, can be addressed by checking:

- Recent TLEs on both the processing workstation and the embedded system.
- Correct, NTP (or better) synchronized time on on the processing workstation and the embedded system.
- Correct latitude, longitude, and altitude are set in configuration files, typically based on GNSS readings.

9.5.4 Image Processed with Bad TLE

In figure 9.11, page 88, can be seen a FITS file that has been processed by `stvid`, but with TLEs that are around two days old. As can be seen, the satellites don't quite line up where they should.

9.5.5 Image Acquired During Slew

See figured 9.12, page 89, for an example image that is bad due to slewing during acquisition.

9.5.6 Light Outside FoV Artifact

See figured 9.13, page 90, for an example of an artifact, visible crossing the left and center, generated by light outside the FoV, in this case the moon!² This is also an example image that detects classified satellites. This is how the main upstream `stvid` works.

²Pierros in SatNOGS Optical Matrix

UT Date: 2022-08-23T04:17:27.161 COSPAR ID: 9999
 R.A.: 237.032058 (51.4") Decl.: 41.748434 (59.8")
 FOV: 40.48° x 22.75° Scale: 75.90" x 75.83" pix⁻¹

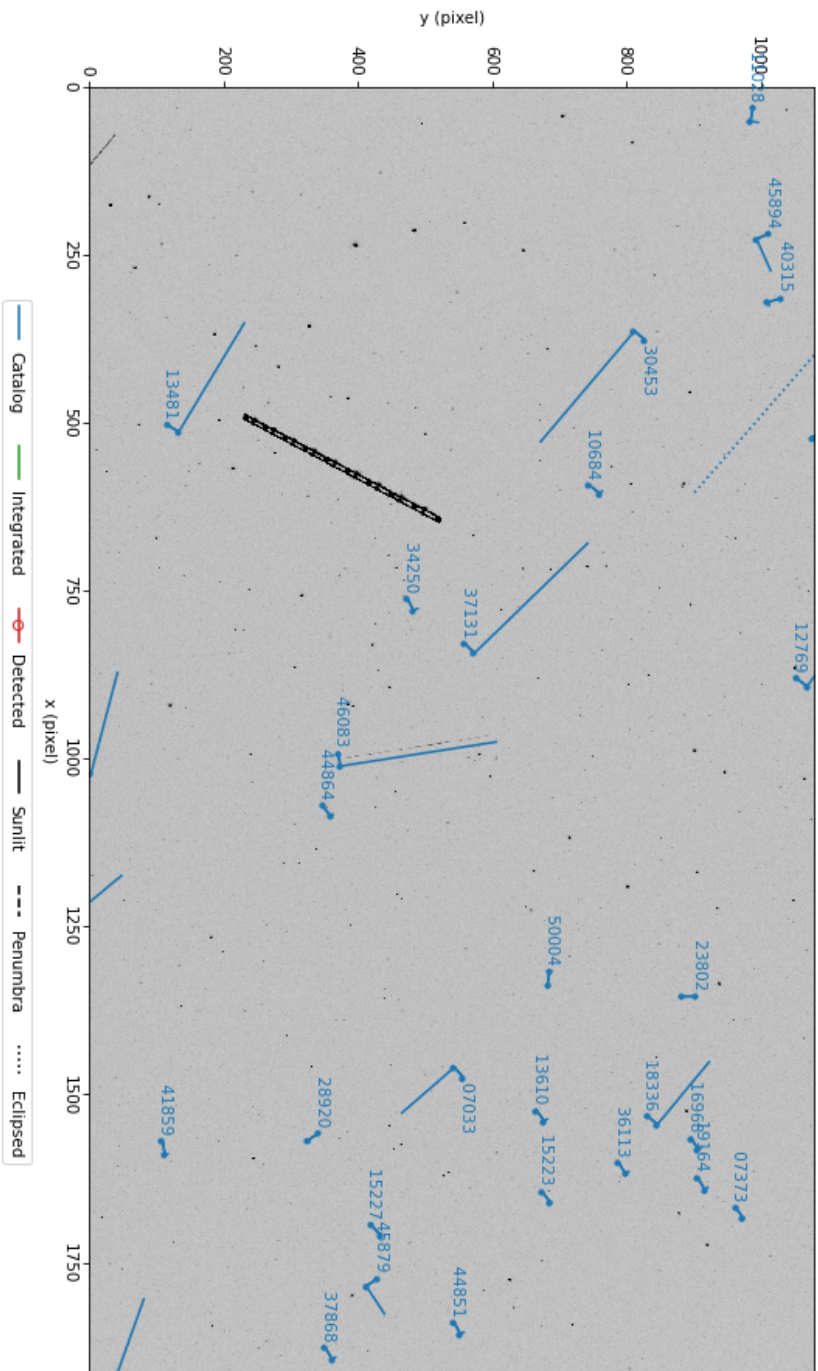


Figure 9.7: Airplane, bold left side, in stvid processed image.

UT Date: 2022-08-24T03:05:30.370 COSPAR ID: 9999
 R.A.: 314.764111 (12.5") Decl.: -28.905790 (12.6")
 FOV: 12.83° x 7.26° Scale: 24.05"x24.21" pix⁻¹

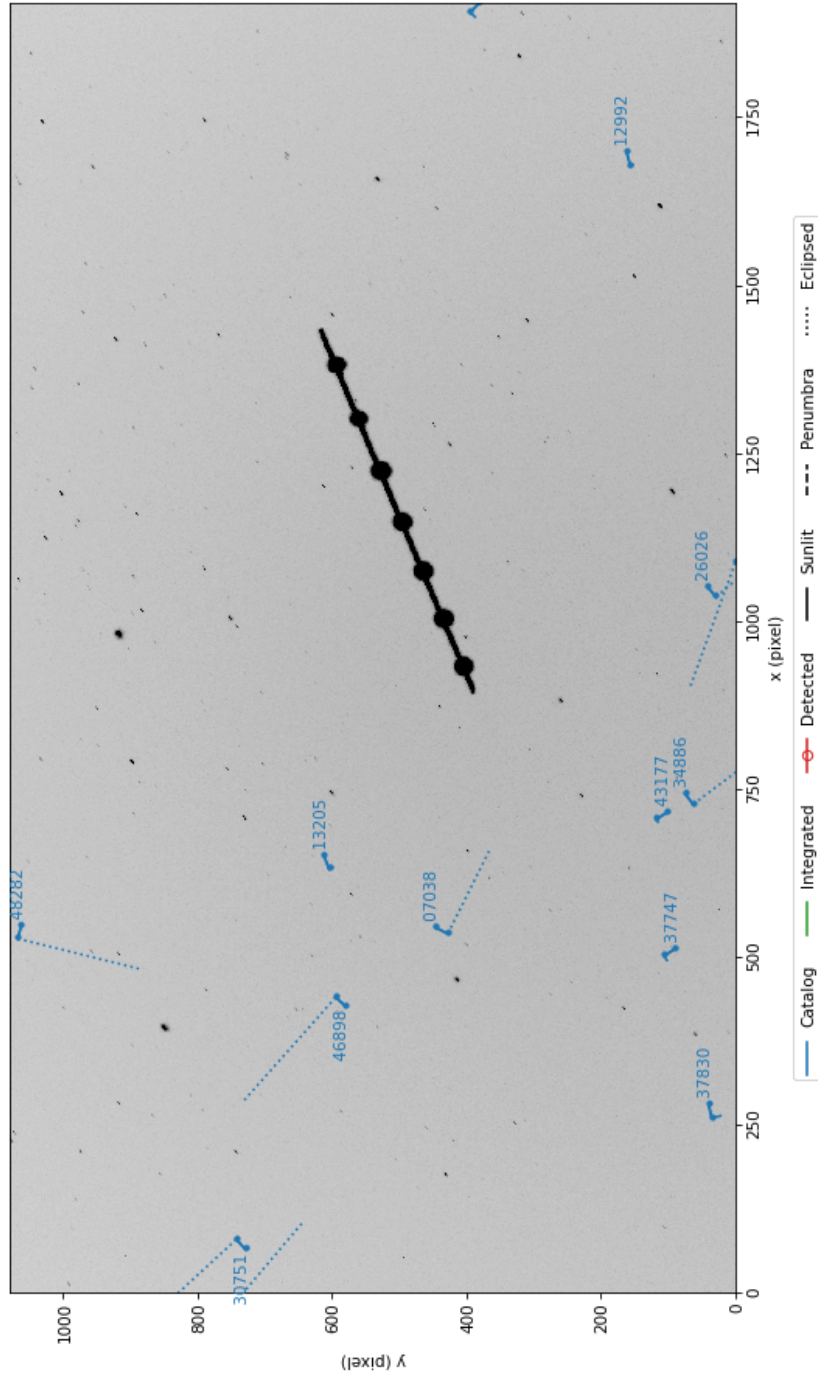


Figure 9.8: Airplane, blinking, in stvid processed image.

UT Date: 2022-08-24T09:18:02.277 COSPAR ID: 9999
R.A.: 290.900475 (9.7") Decl.: 30.043184 (11.6")
FOV: 12.83° x 7.22° Scale: 24.05" x 24.08" pix⁻¹

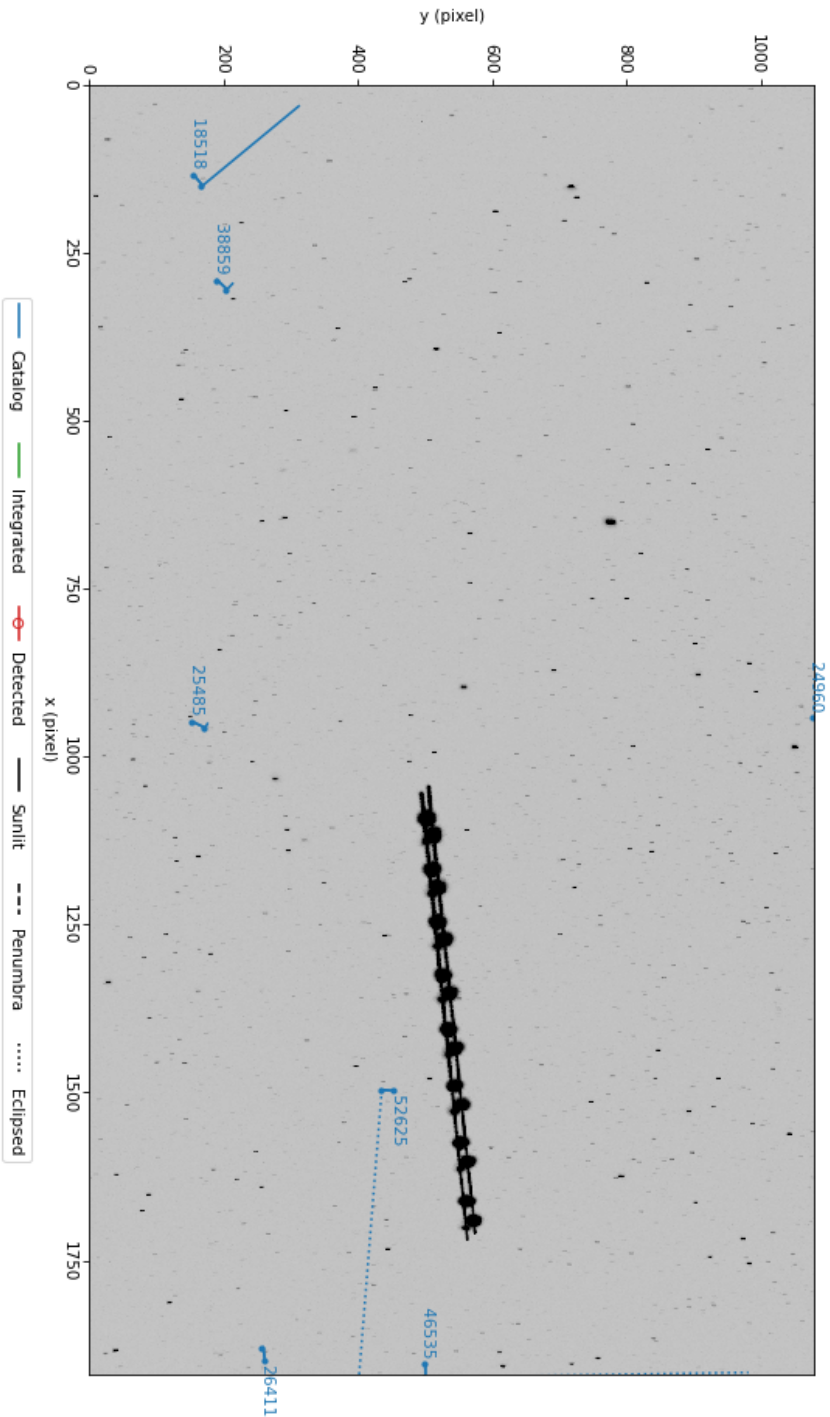


Figure 9.9: Airplane, two solid lights plus blinking, in stvid processed image.

UT Date: 2022-08-25T03:40:03.853 COSPAR ID: 9999
 R.A.: 175.070637 (257.6") Decl.: 43.619880 (226.0")
 FOV: 12.83 ° x 7.22 ° Scale: 48.12"x48.11" pix⁻¹

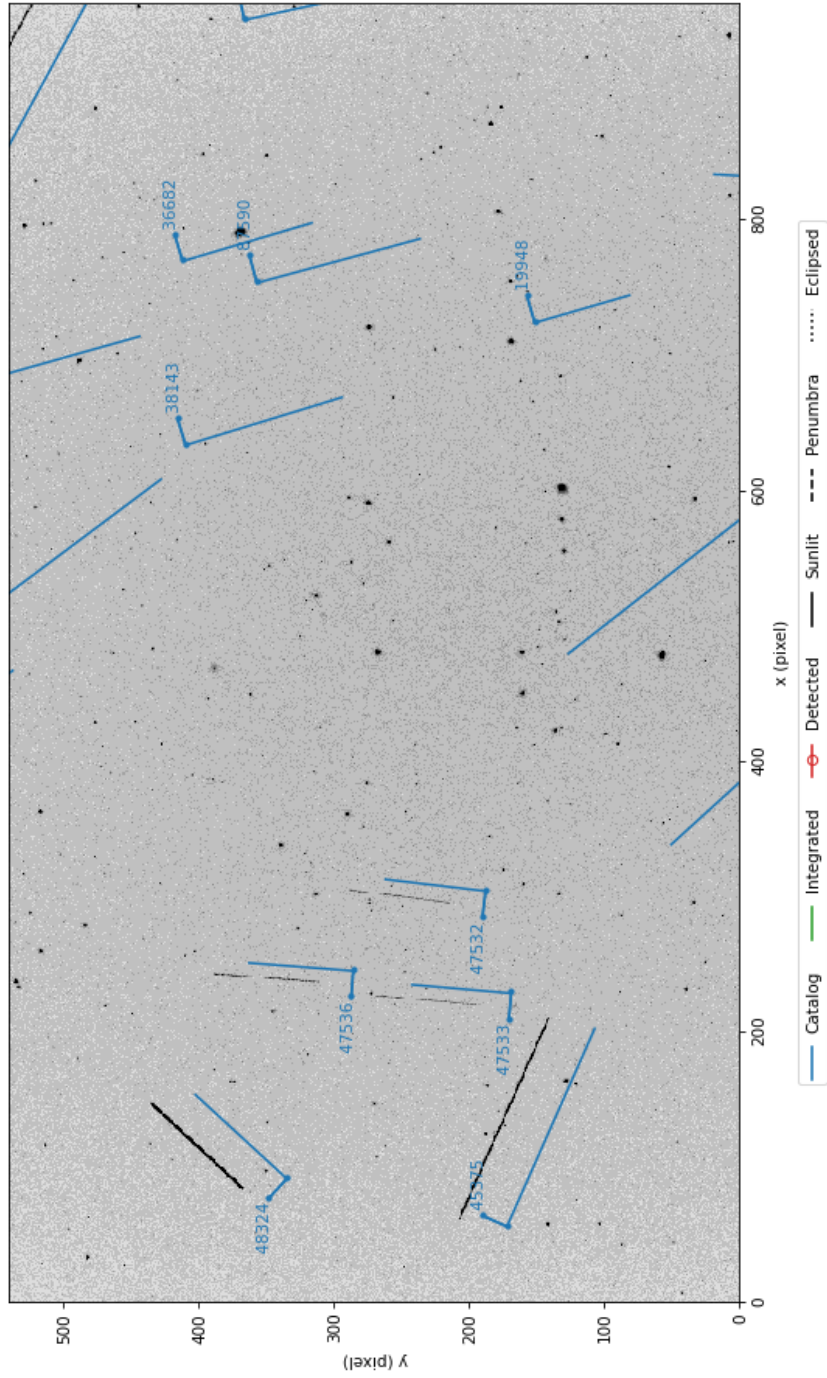


Figure 9.10: stvid processed image, showing mis-configured/setup system.

UT Date: 2022-09-04T03:40:07.923 COSPAR ID: 9999
 R.A.: 174.257271 (9.7") Decl.: 48.751617 (12.2")
 FOV: 12.84° x 7.23° Scale: 48.17"x48.21" pix⁻¹

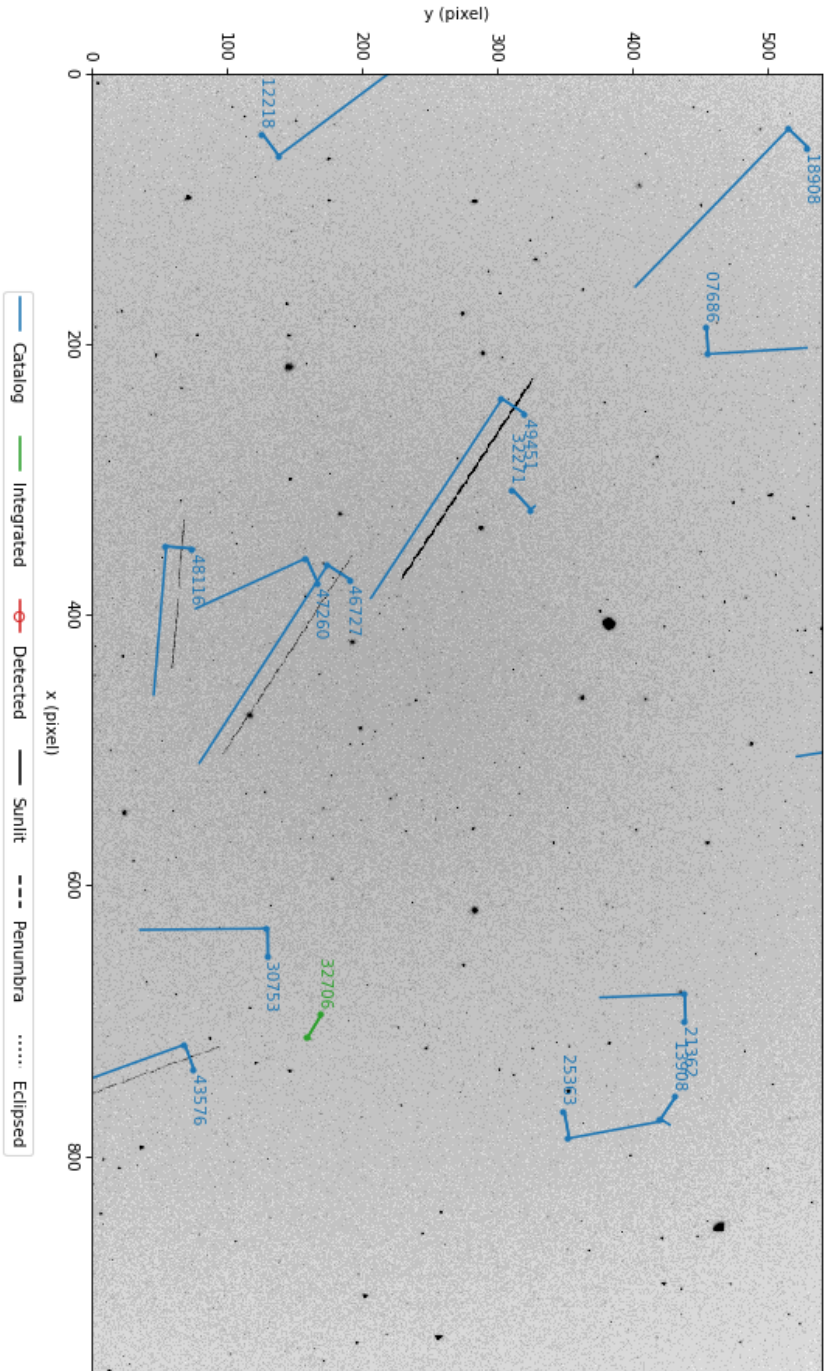


Figure 9.11: stvid processed image, alignment off due to use of old TLE.

UT Date: 2022-09-04T04:56:37.072 COSPAR ID: 9999
 R.A.: 212.056788 (193.8") Decl.: 40.503090 (279.9")
 FOV: 12.80 ° x 7.16 ° Scale: 48.00"x47.75" pix⁻¹

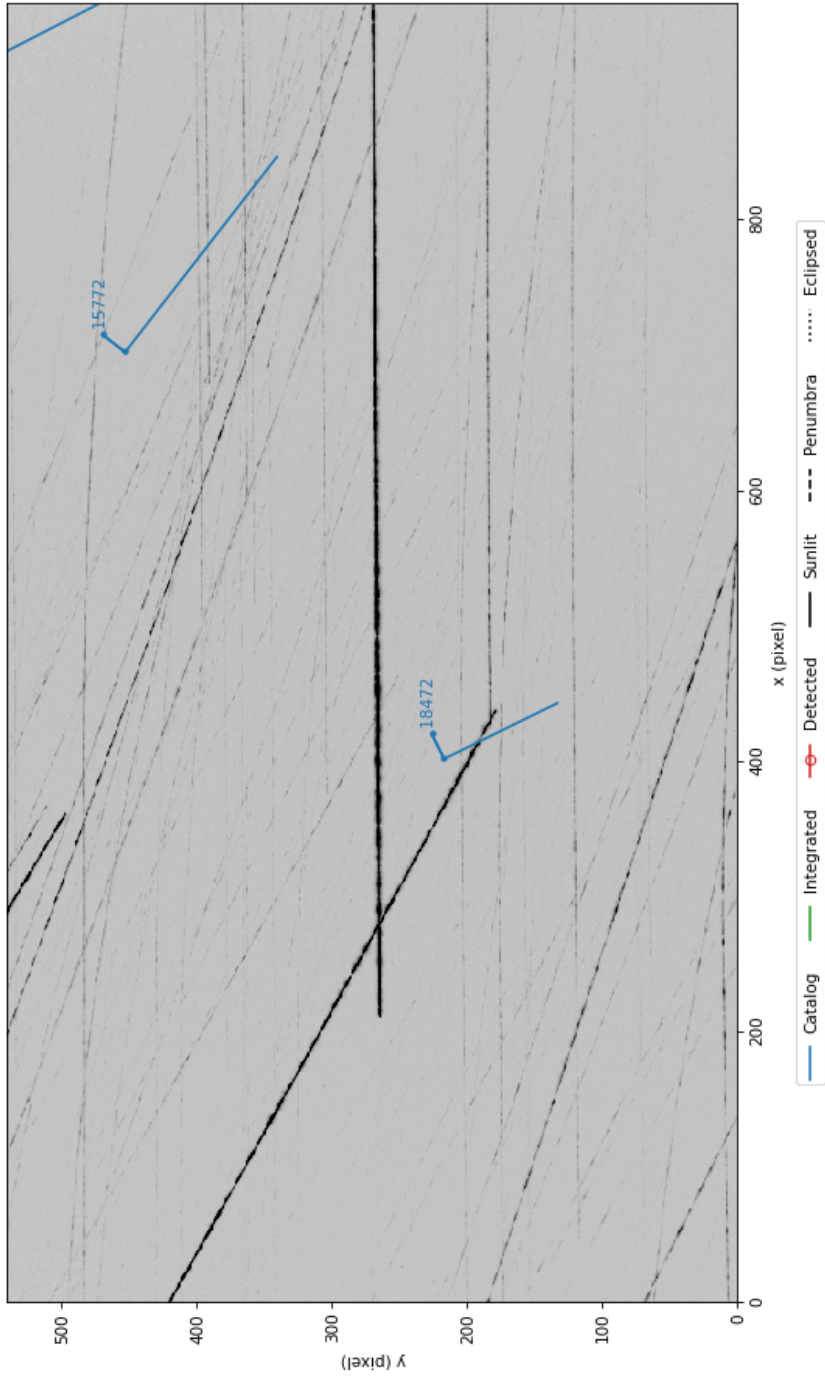


Figure 9.12: stvid processed image, trails due to slewing during acquire.

UT Date: 2022-09-07T18:38:45.042 COSPAR ID: 797
 R.A.: 315.145637 (6.4") Decl.: -11.501175 (4.9")
 FOV: 12.61" x 7.92" Scale: 46.88" x 46.90" pix⁻¹

13386 82 073J 0797 G 202220907183849994 17 25 2108454-111083 37 S

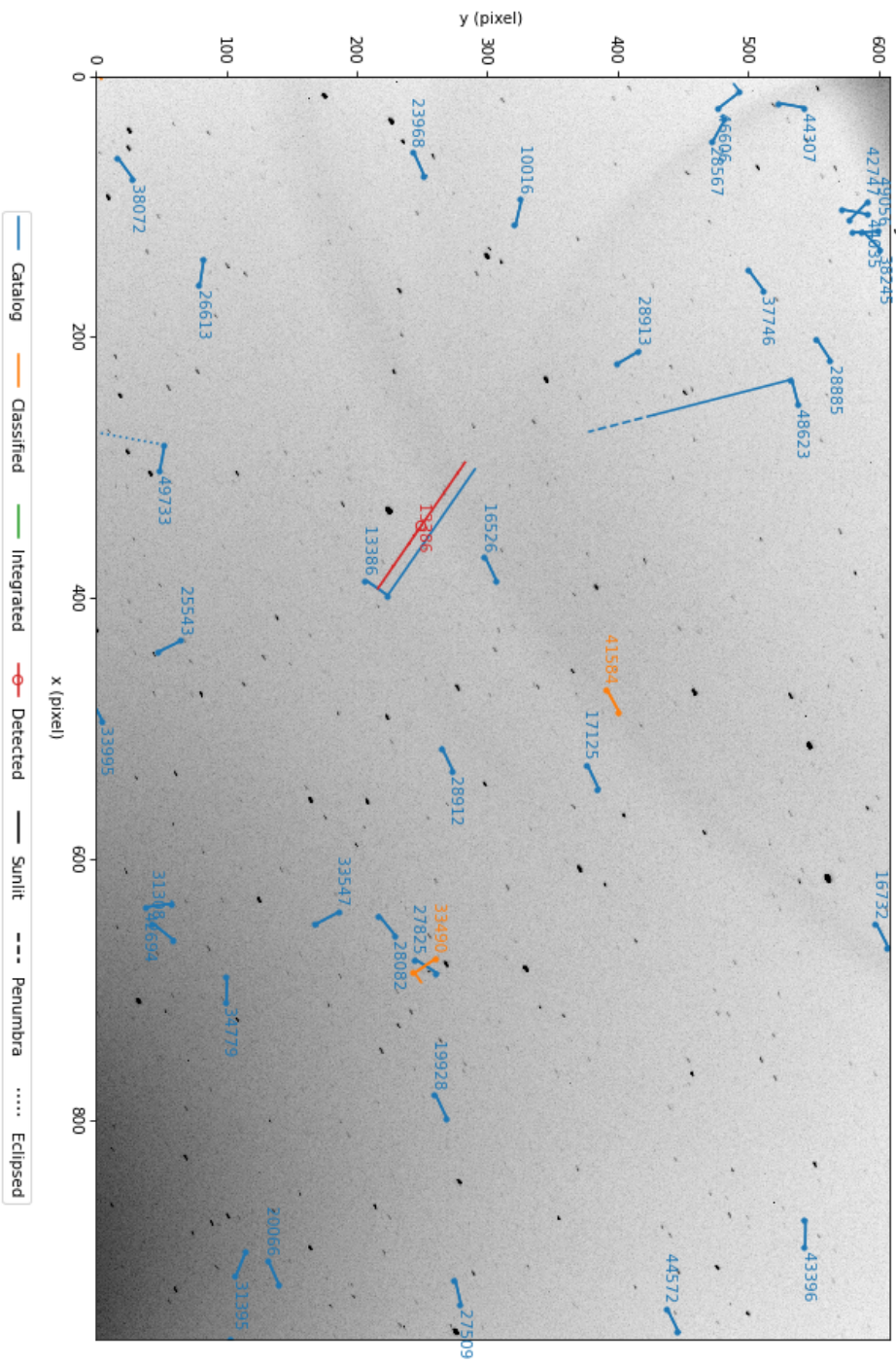


Figure 9.13: stvid processed image, with classified satellites and light artifact.

Upload & Share

Send Data to the SatNOGS Network

10.1 Push Data Upstream

The SatNOGS network isn't ready for optical data yet. So there is nothing that can be uploaded. This is under development.

10.2 File Extensions

The following file extensions are in use:

```
.cal — Cal  
.cat — Cat  
.csv — CSV  
.dat — Data.  
.fits — FITS.  
.png — PNG.
```

10.3 Data Files

After the `stvid` acquisition and processing steps have been run, files such as below will be generated:

```
2022-08-23T04:16:26.633.fits  
2022-08-23T04:16:26.633.fits.cal  
2022-08-23T04:16:26.633.fits.cat  
2022-08-23T04:16:26.633.fits.png  
2022-08-23T04:16:26.633_48473_catalog.dat  
2022-08-23T04:16:26.633_48473_catalog.png  
2022-08-23T04:16:26.633_52718_catalog.dat  
2022-08-23T04:16:26.633_52718_catalog.png  
2022-08-23T04:16:26.633_90000_unid.dat  
2022-08-23T04:16:26.633_90000_unid.png  
2022-08-23T04:16:26.633_hough.csv  
2022-08-23T04:16:26.633_predict.csv  
2022-08-23T04:16:26.633_threshold.csv
```

10.3.1 .fits FITS Files

FITS files are the main files created during acquisition and are the main files used in processing. It has the data of the actual image taken with the camera. FITS files will be significantly larger than the other files, at around 8 to 35 megabytes each, depending on sample rate, frame size, and binning.

The `stvid` program creates its customized FITS format file, which is a stack up of multiple images. I'll leave explanation of the `stvid` FITS file structure to the program's author, Cees Bassa:

10.3. DATA FILES

With `stvid`, I typically store 10 seconds worth of video frames, 100 frames at 10 hertz (Hz) frame rate or 250 frames at 25 Hz frame rate into a so-called “four frame”. Here, for each pixel of the initial 100 or 250 frames, the mean, standard deviation, maximum and argmax are stored, each as its own frame. Objects that move will stand out because they will have a high $(\text{max} - \text{mean}) / \text{standard deviation}$, which allows me to detect trails. Once a trail is detected, the argmax frame tells me the frame number and hence the motion of the trail, and using the timestamps of the individual 100 or 250 frames, I can reconstruct the pixel position as a function of time during the 10 second exposure, using only 4 frames instead of the 100 or 250 individual video frames.

10.3.2 .cal CAL Files

Example .cal filename:

```
2022-08-23T04:16:26.633.fits.cal
```

Sample data from .cal file, just the top select lines of a 577 line file:

```
1172.876  11.776  7.1775  221.117561  45.185979  6.761
786.524   1.817  6.0213  222.623526  37.272049  5.590
838.954  21.772  8.0430  222.941344  38.403949  7.653
872.352  25.919  8.3855  222.909215  39.103246  7.884
692.542  37.123  8.2615  223.889916  35.455924  8.718
738.829  47.126  8.2037  223.973142  36.430116  7.777
691.964  52.656  7.7910  224.278547  35.490201  7.411
951.962  53.159  8.0072  223.315748  40.816697  7.844
1209.704 60.030  6.0799  222.327791  46.116208  5.811
893.057  66.086  7.1867  223.943996  39.648460  8.039
...
```

10.3.3 .cat CAT Files

`stvid` generates .cat files, generated from FITS files, such as:

```
2022-08-23T04:16:26.633.fits.cat
```

Sample data from .cat file, just the top select lines of a 1,033 line file:

```
# 1 X_IMAGE           Object position along x           [pixel]
# 2 Y_IMAGE           Object position along y           [pixel]
# 3 MAG_BEST           Best of MAG_AUTO and MAG_ISOCOR   [mag]
# 4 FLUX_BEST          Best of FLUX_AUTO and FLUX_ISOCOR [count]
# 5 FLUX_MAX           Peak flux above background        [count]
# 6 BACKGROUND         Background at centroid position    [count]
1172.8755  11.7756  7.1775  33.80787  11.09625  16.06616
28.8250    11.4696  6.7443  50.38253  5.008112  15.81194
1347.4933  10.4887  8.3649  11.32553  2.619246  16.04644
269.9134   9.8019   8.4220  10.74506  1.56768   15.97937
468.9823   7.9780   8.8072  7.535751  5.987358  16.02673
1475.9681  6.6672  8.6115  9.024131  2.281431  16.03049
847.0105   5.9795   8.1992  13.19223  14.31796  16.08833
181.5139   5.5141   7.9473  16.63711  2.278276  15.95168
460.1482   5.1577   8.5318  9.711239  2.795708  16.02688
1559.9583  2.9245   7.5915  23.08835  6.981803  15.9909
```

786.5237 1.8174 6.0213 98.05751 27.88283 16.09418
 ...

10.3.4 .fits.png FITS PNG Files

The `stvid` application can generate multiple PNG files, depending how many satellites it finds. In every case it creates at least one PNG file, with a name like:

2022-08-23T04:16:26.633.fits.png

In this image, as can be see in figure 10.1, page 94, no detected satellites are indicated. The blue lines are from the “Catalog”, which in this case means TLEs. The blue lines are drawn whether no, a few, or many satellites are detected. They are generated by taking data from the plate solver about where the picture FoV is, and overlaying satellite orbits that are calculated from TLEs.

The main blue line is slightly offset from where the satellite is calculated to appear. The blue line forms a small L shape. The smaller segment indicates the area where the satellite may pass. Next to the small segment line is the NORAD ID for the satellite. If it is unknown, it will be given the number 90000 or larger.

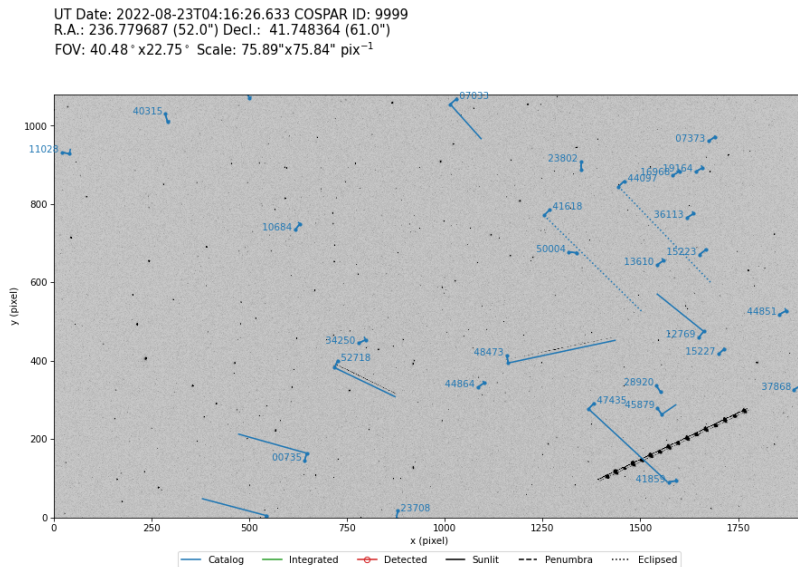


Figure 10.1: PNG.

10.3.5 catalog.png catalog PNG Files

When `stvid` identifies a satellite, it creates a new PNG file for each satellite detected in the image. A file name example follows, with satellite NORAD ID 48473 identified, also shown in figure 10.2, page 95.

10.3. DATA FILES

2022-08-23T04:16:26.633_48473_catalog.png

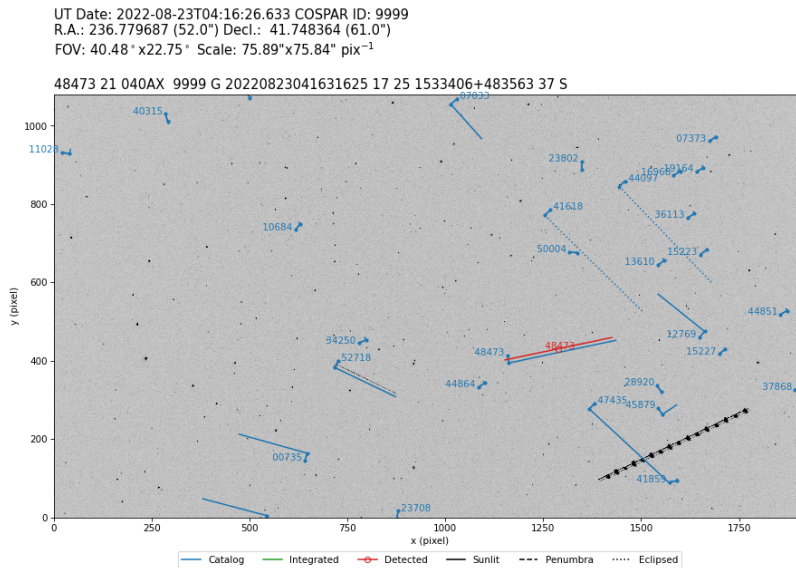


Figure 10.2: PNG of the satellite trail of NORAD ID 48473 identified in red.

If multiple satellites are detected in the image, they will each get a PNG file. For the example image, a satellite with NORAD ID 52718 was also identified. The file name is:

2022-08-23T04:16:26.633_52718_catalog.png

10.3.6 unid.png Unidentified PNG Files

As shown previously, *stvid* will create a new PNG with a red line when it identifies a satellite. When *stvid* finds a trail it can't identify in the TLE catalogs, it gives it a NORAD ID starting with 90000, incrementing by one. See figure 10.4, page 97, for an example of *stvid* marking an unidentified trail red. In this case, the trail was created by an airplane, but *stvid* would do the same with an unidentified satellite trail.

10.3.7 .dat Data Files

For each trail detected as shown in previous sections, such as for which a PNG file was created, *stvid* will output a .dat file. The .dat filenames corresponding to the figures at 10.2, 10.3, and 10.4 are:

```
2022-08-23T04:16:26.633_48473_catalog.dat
2022-08-23T04:16:26.633_52718_catalog.dat
2022-08-23T04:16:26.633_90000_unid.dat
```

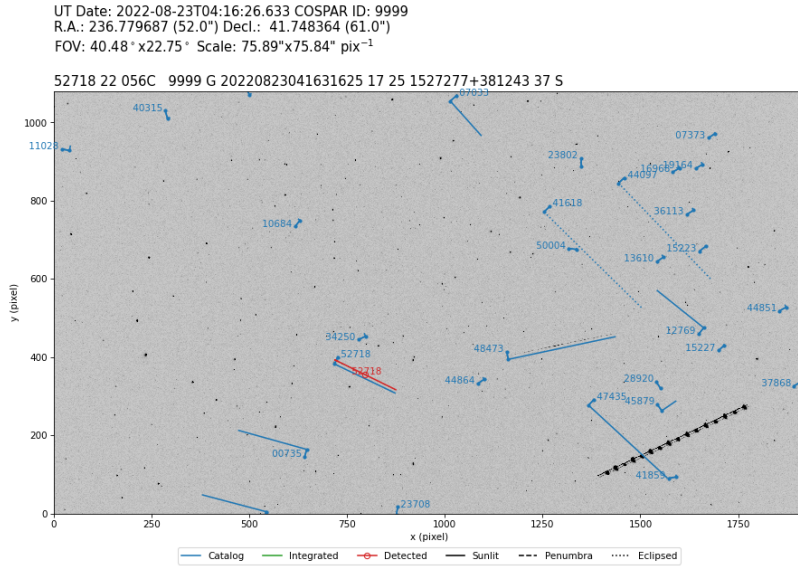


Figure 10.3: PNG of the satellite trail of NORAD ID 52718 identified in red.

Note, there is no .dat file created corresponding to the 2022-08-23T04:16:26.633.fits.png file, since it doesn't show detected trails.

The .dat file contents look like this, for NORAD ID 48473:

```
48473 21 040AX 9999 G 20220823041631625 17 25 1533406+483563 37 S
```

XXX This is the IOD ? XXX The first field is the NORAD ID. The fourth field looks like COSPAR. XXX Large number starting with 2022 is date and time stamp.

The .dat file contents look like this, for NORAD ID 52718:

```
52718 22 056C 9999 G 20220823041631625 17 25 1527277+381243 37 S
```

The .dat file contents look like this, for the unidentified trail (the airplane):

```
90000 22 500A 9999 G 20220823041631625 17 25 1457613+535844 37 S
```

10.3.8 stvid .csv Files

During processing, stvid generates (at least!) three CSV files. For the observation discussed above, starting with figure 10.1, the following CSV files are generated:

10.3. DATA FILES

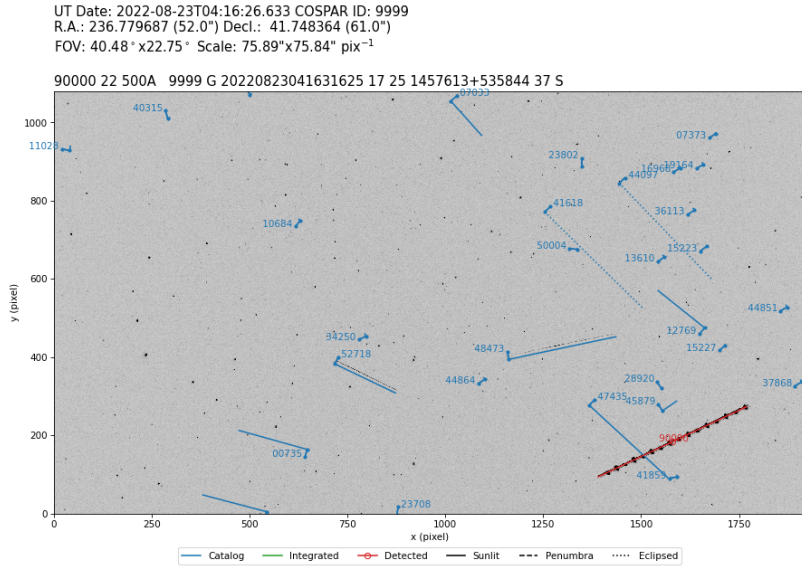


Figure 10.4: PNG of an unidentified trail in red.

```
2022-08-23T04:16:26.633_hough.csv
2022-08-23T04:16:26.633_predict.csv
2022-08-23T04:16:26.633_threshold.csv
```

stvid hough.csv Files

Full contents of the 2022-08-23T04:16:26.633_hough.csv file:

```
ax, ay, az, bx, by, bz, n
1585.699766,186.468458,51.073014,0.879795,0.416052,0.229917,3424
794.849123,355.614035,48.596491,0.780147,-0.382158,0.495304,285
1297.660777,432.469965,52.989399,0.923059,0.193205,0.332617,283
```

stvid predict.csv Files

The 2022-08-23T04:16:26.633_predict.csv is 3,764 lines long. Below is an extract of the lines. I shortened the path, which included the full path to my home directory, for clarity:

```
satno, cospar, mjd, ra, dec, state, tlefile, age
00134, 61015U ,59814.17808603,182.367480,+37.582914,sunlit,/data/tle/catalog.tle,0.441
00134, 61015U ,59814.17809887,182.231429,+37.736730,sunlit,/data/tle/catalog.tle,0.441
00134, 61015U ,59814.17811171,182.094454,+37.890457,sunlit,/data/tle/catalog.tle,0.441
00134, 61015U ,59814.17812455,181.956550,+38.044091,sunlit,/data/tle/catalog.tle,0.441
...
00735, 64002C ,59814.17808603,227.004270,+34.763570,sunlit,/data/tle/catalog.tle,0.027
```

```
00735,64002C ,59814.17809887,227.192764,+34.379114,sunlit,/data/tle/catalog.tle,0.027
00735,64002C ,59814.17811171,227.378969,+33.994697,sunlit,/data/tle/catalog.tle,0.027
...
46083,20055BJ ,59814.17808603,204.492490,+40.972573,sunlit,/data/tle/catalog.tle,0.022
46083,20055BJ ,59814.17809887,204.840813,+41.039396,sunlit,/data/tle/catalog.tle,0.022
46083,20055BJ ,59814.17811171,205.193715,+41.105756,sunlit,/data/tle/catalog.tle,0.022
...
32706,08010A ,59814.17808603,169.555855,+50.073199,sunlit,/data/tle/inttles.tle,0.624
32706,08010A ,59814.17809887,169.560127,+50.075268,sunlit,/data/tle/inttles.tle,0.624
32706,08010A ,59814.17811171,169.564400,+50.077336,sunlit,/data/tle/inttles.tle,0.624
...
```

stvid threshold.csv Files

stvid creates a threshold.csv file with a filename like:

2022-08-23T04:16:26.633_threshold.csv

The above file has 5,293 lines. Here are a few of them:

```
58.000000,0.000000,38.000000
69.000000,1.000000,59.000000
1832.000000,1.000000,52.000000
418.000000,2.000000,11.000000
1183.000000,2.000000,71.000000
...
1276.000000,1078.000000,1.000000
11.000000,1079.000000,38.000000
1500.000000,1079.000000,45.000000
```

**Support
Help!**

11.1 Support

How to get help.

- `#satnogs-optical` channel in Matrix — `#satnogs-optical:matrix.org`
- LSF Community Forum — <https://community.libre.space>

Contact

Email, Chat, Forum

12.1 Contact

Jeff Moe

Username: jebba

Email: moe@spacecraft.org

List of Abbreviations

V Volt

Acronyms

API application programming interface

BDS BeiDou Navigation Satellite System

BIOS Basic Input/Output System

BSD Berkeley Software Distribution

CCD charge-coupled device

CMOS Complementary metal–oxide–semiconductor

COTS Commodity off the shelf

CPU central processing unit

CSV Comma Separated Value

DC Direct current

DCS distributed control system

DFSG Debian Free Software Guidelines

DSLR digital single-lens reflex

EQ equatorial

FITS Flexible Image Transport System

FLIR Forward-looking infrared

FLOSS Free/libre and open-source software

FOSH Free open-source hardware

FOSS free and open-source software

FoV Field of View

GHz gigahertz

ACRONYMS

GLONASS Global Navigation Satellite System

GNSS Global Navigation Satellite System

GNU GNU's Not Unix!

GPL GNU General Public License

GPS Global Positioning System

HDL Hardware description language

Hz hertz

INDI Instrument Neutral Distributed Interface

IP Internet Protocol Address

IP67 Ingress Protection code 67

IPv6 Internet Protocol version 6

ISS International Space Station

ITU International Telecommunication Union

kHz kilohertz

LSF Libre Space Foundation

MHz megahertz

MIPI Mobile Industry Processor Interface

NASA National Aeronautics and Space Administration

NGC New General Catalogue of Nebulae and Clusters of Stars

NORAD North American Aerospace Defense Command

NORAD ID North American Aerospace Defense Catalog Number

NTP Network Time Protocol

NUC Next Unit of Computing

OS Operating System

OSAT open-source appropriate technology

OSH open-source hardware

OSS open-source software

PaaS Platform as a Service

ACRONYMS

PC	Personal Computer
PCB	Printed Circuit Board
PIP	Package Installer for Python
PNG	Portable Network Graphics
PoE	Power over Ethernet
PPS	Pulse per second
PTZ	Pan-tilt-zoom
RAM	Random-access memory
RASA	Rowe-Ackermann Schmidt Astrograph
RF	radio frequency
SBC	Single board computer
SDK	Software development kit
SDP	Simplified Deep Space Perturbations
SDR	Software-defined radio
SDS	Space Defense Squadron
SGP	Simplified General Perturbations
SIDLOC	Spacecraft Identification and Localization
SIP	Simple Imaging Polynomial
SSA	Space Situational Awareness
TLE	two-line element set
UHF	Ultra High Frequency
USB	Universal Serial Bus
USM	Ultrasonic motor
USSPACECOM	United States Space Command
UVC	USB video device class
V4L2	Video for Linux v2
VHF	Very High Frequency
WCS	World Coordinate System

Glossary

altazimuth mount a simple two-axis mount for supporting and rotating an instrument about two perpendicular axes — one vertical and the other horizontal. Rotation about the vertical axis varies the azimuth (compass bearing) of the pointing direction of the instrument. Rotation about the horizontal axis varies the altitude angle (angle of elevation) of the pointing direction. These mounts are used, for example, with telescopes, cameras, and radio antennas.¹

amateur radio is the use of the radio frequency spectrum for purposes of non-commercial exchange of messages, wireless experimentation, self-training, private recreation, radiosport, contesting, and emergency communications.²

antenna the interface between radio waves propagating through space and electric currents moving in metal conductors, used with a transmitter or receiver.³

appropriate technology is a movement (and its manifestations) encompassing technological choice and application that is small-scale, affordable by locals, decentralized, labor-intensive, energy-efficient, environmentally sustainable, and locally autonomous. Appropriate technology has been used to address issues in a wide range of fields. Today appropriate technology is often developed using Open Source principles, which have led to open-source appropriate technology (OSAT) and thus many of the plans of the technology can be freely found on the Internet.⁴

astrograph is a telescope designed for the sole purpose of astrophotography. Astrographs are mostly used in wide-field astronomical surveys of the sky and for detection of objects such as asteroids, meteors, and comets.⁵

AstroImageJ Application for astronomy and satellite image analysis.⁶

astronomical catalogue is a list or tabulation of astronomical objects, typically grouped together because they share a common type, morphology, origin, means of detection, or method of discovery. The oldest and largest are star catalogues. Hundreds have been published,

¹Wikipedia contributors. *Altazimuth mount* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Altazimuth_mount&oldid=1056074953. [Online; accessed 28-August-2022]. 2021

²Wikipedia contributors. *Amateur radio* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Amateur_radio&oldid=1106068703. [Online; accessed 2-September-2022]. 2022

³Wikipedia contributors. *Antenna (radio)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=Antenna_\(radio\)&oldid=1104603350](https://en.wikipedia.org/w/index.php?title=Antenna_(radio)&oldid=1104603350). [Online; accessed 28-August-2022]. 2022

⁴Wikipedia contributors. *Appropriate technology* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Appropriate_technology&oldid=1104787534. [Online; accessed 2-September-2022]. 2022

⁵Wikipedia contributors. *Astrograph* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Astrograph&oldid=1106095357>. [Online; accessed 30-August-2022]. 2022

⁶<https://www.astro.louisville.edu/software/astroimagej/>

including general ones and special ones for such items as infrared stars, variable stars, giant stars, multiple star systems, and star clusters. Since the late 20th century catalogs are increasingly often compiled by computers from an automated survey, and published as computer files rather than on paper.⁷

binning is the process of combining adjacent pixels throughout an image, by summing or averaging their values, during or after readout. Charge from adjacent pixels in CCD image sensors and some other image sensors can be combined during readout, increasing the line rate or frame rate. In the context of image processing, binning is the procedure of combining clusters of adjacent pixels, throughout an image, into single pixels. For example, in 2x2 binning, an array of 4 pixels becomes a single larger pixel, reducing the number of pixels to 1/4 and halving the image resolution in each dimension. The result can be the sum, average, median, minimum, or maximum value of the cluster. This aggregation, although associated with loss of information, reduces the amount of data to be processed, facilitating analysis. The binned image has lower resolution, but the relative noise level in each pixel is generally reduced. Also called pixel binning.⁸

C is a general-purpose computer programming language. It was created in the 1970s by Dennis Ritchie, and remains very widely used and influential. By design, C's features cleanly reflect the capabilities of the targeted central processing units (CPUs). It has found lasting use in Operating Systems (OSs), device drivers, protocol stacks, though decreasingly for application software. C is commonly used on computer architectures that range from the largest supercomputers to the smallest microcontrollers and embedded systems. C is used in the sattools suite of applications.⁹

Celestron is an American company based in Torrance, California, United States, that manufactures telescopes and distributes telescopes, binoculars, spotting scopes, microscopes, and accessories.¹⁰

CubeSat is a class of miniaturized satellite based around a form factor consisting of 10 cm (3.9 in) cubes. CubeSats have a mass of no more than 2 kg per unit, and often use COTS components for their electronics and structure. CubeSats are put into orbit by deployers on the ISS, or launched as secondary payloads on a launch vehicle. More than a thousand CubeSats have been launched.¹¹

daemon a service in a Unix OS.¹²

Debian a GNU/Linux distribution composed of free and open-source software, developed by the community-supported Debian Project, which was established by Ian Murdock on August 16, 1993. Debian is the basis for many other distributions, notably Ubuntu. Debian is one of the oldest operating systems based on the Linux kernel.¹³

⁷Wikipedia contributors. *Astronomical catalog* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Astronomical_catalog&oldid=1035999452. [Online; accessed 2-September-2022]. 2021

⁸Wikipedia contributors. *Pixel binning* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Pixel_binning&oldid=1085651660. [Online; accessed 4-September-2022]. 2022

⁹Wikipedia contributors. *C (programming language)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=C_\(programming_language\)&oldid=1106686212](https://en.wikipedia.org/w/index.php?title=C_(programming_language)&oldid=1106686212). [Online; accessed 30-August-2022]. 2022

¹⁰Wikipedia contributors. *Celestron* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Celestron&oldid=1091418493>. [Online; accessed 2-September-2022]. 2022

¹¹Wikipedia contributors. *CubeSat* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=CubeSat&oldid=1106408835>. [Online; accessed 30-August-2022]. 2022

¹²Wikipedia contributors. *Daimon (disambiguation)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=Daimon_\(disambiguation\)&oldid=1069803376](https://en.wikipedia.org/w/index.php?title=Daimon_(disambiguation)&oldid=1069803376). [Online; accessed 3-September-2022]. 2022

¹³Wikipedia contributors. *Debian* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Debian&oldid=1105900486>. [Online; accessed 28-August-2022]. 2022

Docker is a set of Platform as a Service (PaaS) products that use OS-level virtualization to deliver software in packages called containers.¹⁴

embedded system is a computer system—a combination of a computer processor, computer memory, and input/output peripheral devices—that has a dedicated function within a larger mechanical or electronic system. It is embedded as part of a complete device often including electrical or electronic hardware and mechanical parts. Because an embedded system typically controls physical operations of the machine that it is embedded within, it often has real-time computing constraints. embedded systems control many devices in common use today. it was estimated that ninety-eight percent of all microprocessors manufactured were used in embedded systems.¹⁵

firmware firmware is a specific class of computer software that provides the low-level control for a device’s specific hardware. Firmware, such as the Basic Input/Output System (BIOS) of a Personal Computer (PC), may contain basic functions of a device, and may provide hardware abstraction services to higher-level software such as OSs. For less complex devices, firmware may act as the device’s complete OS, performing all control, monitoring and data manipulation functions. Typical examples of devices containing firmware are embedded systems (running embedded software), home and personal-use appliances, computers, and computer peripherals.¹⁶

Free Software or libre software, is computer software distributed under terms that allow users to run the software for any purpose as well as to study, change, and distribute it and any adapted versions. Free software is a matter of liberty, not price; all users are legally free to do what they want with their copies of a free software (including profiting from them) regardless of how much is paid to obtain the program. Computer programs are deemed “free” if they give end-users (not just the developer) ultimate control over the software and, subsequently, over their devices.¹⁷

GoTo In amateur astronomy, “GoTo” refers to a type of telescope mount and related software that can automatically point a telescope at astronomical objects that the user selects. Both axes of a GoTo mount are driven by a motor and controlled by a computer. It may be either a microprocessor-based integrated controller or an external PC. This differs from the single-axis semi-automated tracking of a traditional clock-drive equatorial mount. The user can command the mount to point the telescope to the celestial coordinates that the user inputs, or to objects in a pre-programmed database including ones from the Messier catalogue, the New General Catalogue of Nebulae and Clusters of Stars (NGC), and even major Solar System bodies (the Sun, Moon, and planets). Like a standard EQ mount, EQ GoTo mounts can track the night sky by driving the right ascension axis. Since both axes are computer controlled, GoTo technology also allows telescope manufacturers to add EQ tracking to mechanically simpler altazimuth mounts.¹⁸

¹⁴Wikipedia contributors. *Docker (software)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=Docker_\(software\)&oldid=1108127182](https://en.wikipedia.org/w/index.php?title=Docker_(software)&oldid=1108127182). [Online; accessed 4-September-2022]. 2022

¹⁵Wikipedia contributors. *Embedded system* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Embedded_system&oldid=1106874216. [Online; accessed 2-September-2022]. 2022

¹⁶Wikipedia contributors. *Firmware* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Firmware&oldid=1099439511>. [Online; accessed 2-September-2022]. 2022

¹⁷Wikipedia contributors. *Free software* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Free_software&oldid=1106538260. [Online; accessed 28-August-2022]. 2022

¹⁸Wikipedia contributors. *GoTo (telescopes)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=GoTo_\(telescopes\)&oldid=841595201](https://en.wikipedia.org/w/index.php?title=GoTo_(telescopes)&oldid=841595201). [Online; accessed 2-September-2022]. 2018

- gPhoto** is a set of software applications and libraries for use in digital photography. gPhoto supports not just retrieving of images from camera devices, but also upload and remote controlled configuration and capture, depending on whether the camera supports those features. gPhoto supports more than 2500 cameras.¹⁹
- gpsd** is a computer software program that collects data from a GPS receiver and provides the data via a network to potentially multiple client applications in a server-client application architecture. Gpsd may be run as a daemon to operate transparently as a background task of the server. The network interface provides a standardized data format for multiple concurrent client applications.²⁰
- Grafana** is a multi-platform Open Source analytics and interactive visualization web application. It provides charts, graphs, and alerts for the web when connected to supported data sources. Users can create complex monitoring dashboards using interactive query builders. It is used by the SatNOGS project to visualize satellite telemetry.²¹
- ground station** a setup of equipment such as computers, cameras, SDRs, antennas, and receivers, located on Earth, observing space.
- hough3d-code** is a software application for Iterative Hough Transform for Line Detection in 3D Point Clouds.²²
- KStars** is a planetarium program. It provides an accurate graphical representation of the night sky, from any location on Earth, at any date and time. The display includes up to 100 million stars (with additional addons), 13,000 deep sky objects, constellations from different cultures, all 8 planets, the Sun and Moon, and thousands of comets, asteroids, satellites, and supernovae. It has features to appeal to users of all levels, from informative hypertext articles about astronomy, to robust control of telescopes and CCD cameras, and logging of observations of specific objects.²³
- Lagrange point** are points of equilibrium for small-mass objects under the influence of two massive orbiting bodies. At the Lagrange points, the gravitational forces of the two large bodies and the centrifugal force balance each other. This can make Lagrange points an excellent location for satellites, as few orbit corrections are needed to maintain the desired orbit. Small objects placed in orbit at Lagrange points are in equilibrium in at least two directions relative to the center of mass of the large bodies.²⁴
- libre** The English adjective free is commonly used in one of two meanings: “at no monetary cost” (gratis) and “with little or no restriction” (libre). This ambiguity of free can cause issues where the distinction is important, as it often is in dealing with laws concerning the use of information, such as copyright and patents. The terms gratis and libre may be used to categorise computer programs, according to the licenses and legal restrictions that cover them, in the Free Software and Open Source communities, as well as the broader free culture movement. For example, they are used to distinguish freeware

¹⁹Wikipedia contributors. *GPhoto* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=GPhoto&oldid=1097546275>. [Online; accessed 2-September-2022]. 2022

²⁰Wikipedia contributors. *Gpsd* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Gpsd&oldid=1076207218>. [Online; accessed 2-September-2022]. 2022

²¹Wikipedia contributors. *Grafana* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Grafana&oldid=1104046322>. [Online; accessed 30-August-2022]. 2022

²²<https://gitlab.com/pierros/hough3d-code>

²³Wikipedia contributors. *KStars* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=KStars&oldid=1076667045>. [Online; accessed 2-September-2022]. 2022

²⁴Wikipedia contributors. *Lagrange point* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Lagrange_point&oldid=1102894784. [Online; accessed 2-September-2022]. 2022

(software gratis) from Free Software (software libre). “Think free as in free speech, not free beer.” – Richard Stallman.²⁵

Linux is a free and open-source, monolithic, modular, multitasking, Unix-like operating system kernel. It was originally authored in 1991 by Linus Torvalds for his i386-based PC, and it was soon adopted as the kernel for the GNU OS, which was written to be a free (libre) replacement for Unix.²⁶

mast typically tall structures designed to support antennas for telecommunications and broadcasting.²⁷

Matrix an open standard and communication protocol for real-time communication.²⁸

Open Source is source code that is made freely available for possible modification and redistribution. Products include permission to use the source code, design documents, or content of the product. The open-source model is a decentralized software development model that encourages open collaboration. A main principle of open-source software development is peer production, with products such as source code, blueprints, and documentation freely available to the public. The open-source movement in software began as a response to the limitations of proprietary code. The model is used for projects such as in open-source appropriate technology.²⁹

OpenCV Open Source Computer Vision Library is a library of programming functions mainly aimed at real-time computer vision.³⁰

optical ground station a ground station using optical equipment (cameras) instead of antennas.

orbit is the curved trajectory of an object such as the trajectory of a planet around a star, or of a natural satellite around a planet, or of an artificial satellite around an object or position in space such as a planet, moon, asteroid, or Lagrange point. Normally, orbit refers to a regularly repeating trajectory, although it may also refer to a non-repeating trajectory. To a close approximation, planets and satellites follow elliptic orbits, with the center of mass being orbited at a focal point of the ellipse, as described by Kepler’s laws of planetary motion. For most situations, orbital motion is adequately approximated by Newtonian mechanics, which explains gravity as a force obeying an inverse-square law. However, Albert Einstein’s general theory of relativity, which accounts for gravity as due to curvature of spacetime, with orbits following geodesics, provides a more accurate calculation and understanding of the exact mechanics of orbital motion.³¹

perturbation is the complex motion of a massive body subjected to forces other than the gravitational attraction of a single other massive body. The other forces can include

²⁵Wikipedia contributors. *Gratis versus libre* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Gratis_versus_libre&oldid=1085552810. [Online; accessed 30-August-2022]. 2022

²⁶Wikipedia contributors. *Linux kernel* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Linux_kernel&oldid=1105840074. [Online; accessed 28-August-2022]. 2022

²⁷Wikipedia contributors. *Radio masts and towers* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Radio_masts_and_towers&oldid=1103964392. [Online; accessed 28-August-2022]. 2022

²⁸Wikipedia contributors. *Matrix (protocol)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=Matrix_\(protocol\)&oldid=1106244486](https://en.wikipedia.org/w/index.php?title=Matrix_(protocol)&oldid=1106244486). [Online; accessed 28-August-2022]. 2022

²⁹Wikipedia contributors. *Open source* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Open_source&oldid=1103126225. [Online; accessed 28-August-2022]. 2022

³⁰Wikipedia contributors. *OpenCV* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=OpenCV&oldid=1106133881>. [Online; accessed 2-September-2022]. 2022

³¹Wikipedia contributors. *Orbit* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Orbit&oldid=1106406646>. [Online; accessed 30-August-2022]. 2022

a third (fourth, fifth, etc.) body, resistance, as from an atmosphere, and the off-center attraction of an oblate or otherwise misshapen body.³²

photon is an elementary particle that is a quantum of the electromagnetic field, including electromagnetic radiation such as light and radio waves, and the force carrier for the electromagnetic force. Photons are massless, so they always move at the speed of light in vacuum, 299,792,458 meters/second.³³

pipeline is a set of data processing elements connected in series, where the output of one element is the input of the next one. The elements of a pipeline are often executed in parallel or in time-sliced fashion.³⁴

plate solver is software implementing a technique used in astronomy and applied on celestial images. Solving an image is finding match between the imaged stars and a star catalogue. The solution is a math model describing the corresponding astronomical position of each image pixel. The position of reference catalogue stars has to be known to a high accuracy so an astrometric reference catalogue is used. The image solution contains a reference point, often the image centre, image scale, image orientation and in some cases an image distortion model. With the astrometric solution it is possible to: 1) Calculate the celestial coordinates of any object on the image. 2) Synchronize the telescope mount or satellite pointing position to the center of the image taken. Astrometric solving programs extract the star x,y positions from the celestial image, groups them in three-star triangles or four-star quads. Then it calculates for each group a geometric hash code based on the distance and/or angles between the stars in the group. It then compares the resulting hash codes with the hash codes created from catalogue stars to find a match. If it finds sufficient statistically reliable matches, it can calculate transformation factors. There are several conventions to model the transformation from image pixel location to the corresponding celestial coordinates. The simplest linear model is called the WCS. A more advanced convention is SIP describing the transformation in polynomials to cope with non-linear geometric distortion in the celestial image, mainly caused by the optics.³⁵

Python is a high-level, interpreted, general-purpose programming language. Its design philosophy emphasizes code readability. It is often described as a “batteries included” language due to its comprehensive standard library. Python consistently ranks as one of the most popular programming languages. It is one of the main languages of the SatNOGS project and stvid.³⁶

Raspberry Pi is a series of small Single board computers (SBCs). It is typically used by computer and electronic hobbyists as an embedded system.³⁷

³²Wikipedia contributors. *Perturbation (astronomy)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=Perturbation_\(astronomy\)&oldid=1105431363](https://en.wikipedia.org/w/index.php?title=Perturbation_(astronomy)&oldid=1105431363). [Online; accessed 30-August-2022]. 2022

³³Wikipedia contributors. *Photon* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Photon&oldid=1104709214>. [Online; accessed 2-September-2022]. 2022

³⁴Wikipedia contributors. *Pipeline (computing)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=Pipeline_\(computing\)&oldid=1096885455](https://en.wikipedia.org/w/index.php?title=Pipeline_(computing)&oldid=1096885455). [Online; accessed 2-September-2022]. 2022

³⁵Wikipedia contributors. *Astrometric solving* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Astrometric_solving&oldid=1099832612. [Online; accessed 30-August-2022]. 2022

³⁶Wikipedia contributors. *Python (programming language)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=Python_\(programming_language\)&oldid=1107007073](https://en.wikipedia.org/w/index.php?title=Python_(programming_language)&oldid=1107007073). [Online; accessed 30-August-2022]. 2022

³⁷Wikipedia contributors. *Raspberry Pi* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Raspberry_Pi&oldid=1107949674. [Online; accessed 2-September-2022]. 2022

rotator a device used to change the orientation, within the horizontal plane, of a directional antenna. Most antenna rotators have two parts, the rotator unit and the controller. The controller is normally placed near the equipment which the antenna is connected to, while the rotator is mounted on the antenna mast directly below the antenna. Rotators are commonly used in amateur radio.³⁸

satellite is an object intentionally placed into orbit in outer space. Except for passive satellites, most satellites have an electricity generation system for equipment on board. Most satellites also have a method of communication to ground stations, called transponders. Many satellites use a standardized bus to save cost and work, the most popular of which is small CubeSats. Similar satellites can work together as a group, forming constellations.³⁹

satid is part of sattools.⁴⁰

SatNOGS Open Source global network of satellite ground stations.⁴¹

SatNOGS DB is an effort to create an hollistic, unified, global database for all artificial objects in space (satellites and spacecrafts). Users can view and export the data, contribute to it, or connect applications using an application programming interface (API). It is part of the SatNOGS project.⁴²

SatNOGS Optical is a project by the LSF to add optical ground stations to the SatNOGS network.⁴³

satpredict is a software application to compute satellite predictions. It is used by stvid.⁴⁴

sattools Satellite Tracking Toolkit. The main `sattools` applications are being ported to stvid and other related Python applications.⁴⁵

sky chart or star chart or star map, also called or sky map, is a map of the night sky. Astronomers divide these into grids to use them more easily. They are used to identify and locate constellations and astronomical objects such as stars, nebulae, and galaxies. They have been used for human navigation since time immemorial. Note that a sky chart differs from an astronomical catalogue, which is a listing or tabulation of astronomical objects for a particular purpose.⁴⁶

skymap is part of sattools. Visualize satellites on a map of the sky.⁴⁷

slew The process of rotating a telescope to observe a different region of the sky.⁴⁸

software repository or repo for short, is a storage location for software packages. Often a table of contents is also stored, along with metadata. A software repository is

³⁸Wikipedia contributors. *Antenna rotator* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Antenna_rotator&oldid=1064620974. [Online; accessed 28-August-2022]. 2022

³⁹Wikipedia contributors. *Satellite* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Satellite&oldid=1106286374>. [Online; accessed 30-August-2022]. 2022

⁴⁰<https://github.com/cbassa/sattools/blob/master/satid.c>

⁴¹<https://satnogs.org/>

⁴²<https://db.satnogs.org/>

⁴³<https://satnogs.org/>

⁴⁴<https://github.com/cbassa/satpredict>

⁴⁵<https://github.com/cbassa/sattools>

⁴⁶Wikipedia contributors. *Star chart* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Star_chart&oldid=1106250278. [Online; accessed 2-September-2022]. 2022

⁴⁷<https://github.com/cbassa/sattools/blob/master/skymap.c>

⁴⁸Wikipedia contributors. *Slewing* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Slewing&oldid=1061997651>. [Online; accessed 2-September-2022]. 2021

typically managed by source control or repository managers. Package managers allow automatically installing and updating repositories (sometimes called “packages”).⁴⁹

star catalogue is an astronomical catalogue that lists stars. In astronomy, many stars are referred to simply by catalogue numbers. There are a great many different star catalogues which have been produced for different purposes over the years. Most modern catalogues are available in electronic format and can be freely downloaded from space agencies’ data centres. The largest is being compiled from the spacecraft Gaia and thus far has over a billion stars. Completeness and accuracy are described by the faintest limiting magnitude and the accuracy of the positions.⁵⁰

star trail is a type of photograph that uses long exposure times to capture diurnal circles, the apparent motion of stars in the night sky due to Earth’s rotation. A star-trail photograph shows individual stars as streaks across the image, with longer exposures yielding longer arcs.⁵¹

stvid Satellite tools video application for acquiring and processing sky images.⁵²

Teledyne FLIR a subsidiary of Teledyne Technologies, specializes in the design and production of thermal imaging cameras and sensors. The name is based on the acronym Forward-looking infrared (FLIR).⁵³

telemetry is the in situ collection of measurements or other data at remote points and their automatic transmission to receiving equipment (telecommunication) for monitoring. The word is derived from the Greek roots tele, “remote”, and metron, “measure”. Although the term commonly refers to wireless data transfer mechanisms (e.g., using radio, ultrasonic, or infrared systems), it also encompasses data transferred over other media such as a telephone or computer network, optical link or other wired communications like power line carriers.⁵⁴

telescope is an optical instrument using lenses, curved mirrors, or a combination of both to observe distant objects, or various devices used to observe distant objects by their emission, absorption, or reflection of electromagnetic radiation. The word telescope now refers to a wide range of instruments capable of detecting different regions of the electromagnetic spectrum, and in some cases other types of detectors.⁵⁵

toolchain is a set of programming tools that is used to perform a complex software development task or to create a software product, which is typically another computer program or a set of related programs.⁵⁶

⁴⁹Wikipedia contributors. *Software repository* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Software_repository&oldid=1081326130. [Online; accessed 2-September-2022]. 2022

⁵⁰Wikipedia contributors. *Star catalogue* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Star_catalogue&oldid=1107326057. [Online; accessed 2-September-2022]. 2022

⁵¹Wikipedia contributors. *Star trail* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Star_trail&oldid=1075094531. [Online; accessed 2-September-2022]. 2022

⁵²<https://github.com/cbassa/stvid>

⁵³Wikipedia contributors. *Teledyne FLIR* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Teledyne_FLIR&oldid=1102704879. [Online; accessed 3-September-2022]. 2022

⁵⁴Wikipedia contributors. *Telemetry* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Telemetry&oldid=1080706265>. [Online; accessed 30-August-2022]. 2022

⁵⁵Wikipedia contributors. *Telescope* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Telescope&oldid=1106167988>. [Online; accessed 30-August-2022]. 2022

⁵⁶Wikipedia contributors. *Toolchain* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Toolchain&oldid=1094527160>. [Online; accessed 2-September-2022]. 2022

- Unix** is a family of multitasking, multiuser computer OSs that derive from the original AT&T Unix, whose development started in 1969 at the Bell Labs research center by Ken Thompson, Dennis Ritchie, and others.⁵⁷
- upstream** refers to a direction toward the original authors or maintainers of software that is distributed as source code, and is a qualification of either a version (released by the original authors, based on their upstream source code), a bug or a patch.⁵⁸
- application programming interface (API)** application programming interface.
- Basic Input/Output System (BIOS)** Basic Input/Output System.
- BeiDou Navigation Satellite System (BDS)** BeiDou Navigation Satellite System.
- Berkeley Software Distribution (BSD)** Berkeley Software Distribution.
- central processing unit (CPU)** central processing unit.
- charge-coupled device (CCD)** charge-coupled device.
- Comma Separated Value (CSV)** Comma Separated Value.
- Commodity off the shelf (COTS)** Commodity off the shelf.
- Complementary metal–oxide–semiconductor (CMOS)** Complementary metal-oxide-semiconductor (pronounced “see-moss”).
- Debian Free Software Guidelines (DFSG)** Debian Free Software Guidelines is a set of guidelines that the Debian Project uses to determine whether a software license is a Free Software license, which in turn is used to determine whether a piece of software can be included in Debian. The DFSG is part of the Debian Social Contract.⁵⁹
- digital single-lens reflex (DSLR)** digital single-lens reflex.
- Direct current (DC)** Direct current.
- distributed control system (DCS)** distributed control system.
- equatorial (EQ)** Equatorial.
- Field of View (FoV)** Field of view.
- Flexible Image Transport System (FITS)** Flexible Image Transport System is an open standard defining a digital file format useful for storage, transmission and processing of data: formatted as multi-dimensional arrays (for example a 2D image), or tables. FITS is the most commonly used digital file format in astronomy. The FITS standard was designed specifically for astronomical data, and includes provisions such as describing photometric and spatial calibration information, together with image origin metadata.⁶⁰
- Forward-looking infrared (FLIR)** Forward-looking infrared.
- free and open-source software (FOSS)** free and Open Source software is a term used to refer to groups of software consisting of both Free Software and OSS where anyone is freely licensed to use, copy, study, and change the software in any way, and the source code is openly shared so that people are encouraged to voluntarily improve the design of the software. This is in contrast to proprietary software, where the software is under restrictive copyright licensing and the source code is usually hidden

⁵⁷Wikipedia contributors. *Unix* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=Unix&oldid=1105826457>. [Online; accessed 2-September-2022]. 2022

⁵⁸Wikipedia contributors. *Upstream (software development)* — *Wikipedia, The Free Encyclopedia*. [https://en.wikipedia.org/w/index.php?title=Upstream_\(software_development\)&oldid=1066370459](https://en.wikipedia.org/w/index.php?title=Upstream_(software_development)&oldid=1066370459). [Online; accessed 3-September-2022]. 2022

⁵⁹Wikipedia contributors. *Debian Free Software Guidelines* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Debian_Free_Software_Guidelines&oldid=1086423235. [Online; accessed 31-August-2022]. 2022

⁶⁰Wikipedia contributors, *FITS* — *Wikipedia, The Free Encyclopedia*

from the users. FOSS maintains the software user's civil liberty rights. Other benefits of using FOSS can include decreased software costs, increased security and stability (especially in regard to malware), protecting privacy, education, and giving users more control over their own hardware. Free and open-source operating systems such as Linux and descendants of Berkeley Software Distribution (BSD) are widely utilized today, powering millions of servers, desktops, smartphones (e.g., Android), and other devices. Free-software licenses and Open Source licenses are used by many software packages. The free software movement and the Open Source software movement are online social movements behind widespread production and adoption of FOSS, with the former preferring to use the terms Free/libre and open-source software (FLOSS) or free/libre.⁶¹

Free open-source hardware (FOSH) Free open-source hardware. See also: OSH.

Free/libre and open-source software (FLOSS) Free/libre and open-source software. See also: free and open-source software (FOSS).

gigahertz (GHz) gigahertz.

Global Navigation Satellite System (GLONASS) Global Navigation Satellite System.

Global Navigation Satellite System (GNSS) Global Navigation Satellite System.

Global Positioning System (GPS) Global Positioning System.

GNU General Public License (GPL) GNU General Public License is a series of widely used Free Software licenses that guarantee end users the four freedoms to run, study, share, and modify the software. The license was the first copyleft for general use. Historically, the GPL license family has been one of the most popular software licenses in the FLOSS software domain.⁶²

GNU's Not Unix! (GNU) "GNU's Not Unix!" is an extensive collection of Free Software, which can be used as an OS or can be used in parts with other OSs. The use of the completed GNU tools led to the family of operating systems popularly known as Linux. Most of GNU is licensed under the GNU Project's own GNU General Public License (GPL). GNU is also the project within which the Free Software concept originated.⁶³

Hardware description language (HDL) Hardware description language.

hertz (Hz) hertz.

Ingress Protection code 67 (IP67) Ingress Protection code 67.

Instrument Neutral Distributed Interface (INDI) Instrument Neutral Distributed Interface is a distributed control system (DCS) protocol to enable control, data acquisition and exchange among hardware devices and software front ends, emphasizing astronomical instrumentation.⁶⁴

International Space Station (ISS) International Space Station.

⁶¹Wikipedia contributors. *Free and open-source software* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Free_and_open-source_software&oldid=1106343648. [Online; accessed 30-August-2022]. 2022

⁶²Wikipedia contributors. *GNU General Public License* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=GNU_General_Public_License&oldid=1106596497. [Online; accessed 28-August-2022]. 2022

⁶³Wikipedia contributors. *GNU* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=GNU&oldid=1103488294>. [Online; accessed 28-August-2022]. 2022

⁶⁴Wikipedia contributors. *Instrument Neutral Distributed Interface* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Instrument_Neutral_Distributed_Interface&oldid=1062506145. [Online; accessed 31-August-2022]. 2021

International Telecommunication Union (ITU) The International Telecommunication Union is a specialized agency of the United Nations responsible for many matters related to information and communication technologies.⁶⁵

Internet Protocol Address (IP) Internet Protocol Address.

Internet Protocol version 6 (IPv6) Internet Protocol version 6.

kilohertz (kHz) kilohertz.

Libre Space Foundation (LSF) Libre Space Foundation is a non-profit foundation registered since 2015 in Greece and the creators of the SatNOGS project.⁶⁶

megahertz (MHz) megahertz.

Mobile Industry Processor Interface (MIPI) Mobile Industry Processor Interface.

National Aeronautics and Space Administration (NASA) is an independent agency of the US federal government responsible for the civil space program, aeronautics research, and space research.⁶⁷

Network Time Protocol (NTP) Network Time Protocol.

New General Catalogue of Nebulae and Clusters of Stars (NGC) New General Catalogue of Nebulae and Clusters of Stars.

Next Unit of Computing (NUC) Next Unit of Computing.

North American Aerospace Defense Catalog Number (NORAD ID) is a sequential nine-digit number assigned by the United States Space Command (USSPACECOM) in the order of launch or discovery to all artificial objects in the orbits of Earth and those that left Earth's orbits. Space Command shares the catalog via space-track.org, which is maintained by the 18th Space Defense Squadron (SDS). NORAD ID is also known as a satellite catalog number.⁶⁸

North American Aerospace Defense Command (NORAD) North American Aerospace Defense Command is a combined organization of the United States and Canada that provides aerospace warning, air sovereignty, and protection for Canada and the continental United States.⁶⁹

open-source appropriate technology (OSAT) open-source appropriate technology.

open-source hardware (OSH) open-source hardware consists of physical artifacts of technology designed and offered by the open-design movement. Both FOSS and open-source hardware are created by the open-source culture movement and apply a like concept to a variety of components. It is sometimes, thus, referred to as Free open-source hardware (FOSH). The term usually means that information about the hardware is easily discerned so that others can make it—coupling it closely to the maker movement. Hardware design (i.e. mechanical drawings, schematics, bills of material, Printed Circuit Board (PCB) layout data, Hardware description language (HDL) source code and integrated circuit layout data), in addition to the software that drives the hardware, are all released under free/libre terms. The original sharer gains feedback and potentially

⁶⁵Wikipedia contributors. *International Telecommunication Union* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=International_Telecommunication_Union&oldid=1105915792. [Online; accessed 28-August-2022]. 2022

⁶⁶<https://libre.space/about-us/>

⁶⁷Wikipedia contributors. *NASA* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=NASA&oldid=1107567899>. [Online; accessed 30-August-2022]. 2022

⁶⁸Wikipedia contributors. *Satellite Catalog Number* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Satellite_Catalog_Number&oldid=1100318368. [Online; accessed 4-September-2022]. 2022

⁶⁹Wikipedia contributors. *NORAD* — *Wikipedia, The Free Encyclopedia*. <https://en.wikipedia.org/w/index.php?title=NORAD&oldid=1105457081>. [Online; accessed 30-August-2022]. 2022

improvements on the design from the FOSH community. There is now significant evidence that such sharing can drive a high return on investment for the scientific community. It is not enough to merely use an Open Source license; an Open Source product or project will follow Open Source principles, such as modular design and community collaboration.⁷⁰

open-source software (OSS) open-source software is computer software that is released under a license in which the copyright holder grants users the rights to use, study, change, and distribute the software and its source code to anyone and for any purpose. Open-source software may be developed in a collaborative public manner. Open-source software is a prominent example of open collaboration, meaning any capable user is able to participate online in development, making the number of possible contributors indefinite. The ability to examine the code facilitates public trust in the software. Open source code can be used for studying and allows capable end users to adapt software to their personal needs in a similar way user scripts and custom style sheets allow for web sites, and eventually publish the modification as a fork for users with similar preference.⁷¹

Operating System (OS) An operating system is system software that manages computer hardware, software resources, and provides common services for computer programs.⁷²

Package Installer for Python (PIP) Package Installer for Python.

Pan-tilt-zoom (PTZ) Pan-tilt-zoom.

Personal Computer (PC) Personal Computer.

Platform as a Service (PaaS) Platform as a Service.

Portable Network Graphics (PNG) Portable Network Graphics.

Power over Ethernet (PoE) Power over Ethernet.

Printed Circuit Board (PCB) Printed circuit board.

Pulse per second (PPS) Pulse per second.

radio frequency (RF) Radio frequency is the oscillation rate of an alternating electric current or voltage or of a magnetic, electric or electromagnetic field or mechanical system in the frequency range from around 20 kilohertz (kHz) to around 300 gigahertz (GHz). This is roughly between the upper limit of audio frequencies and the lower limit of infrared frequencies; these are the frequencies at which energy from an oscillating current can radiate off a conductor into space as radio waves.⁷³

Random-access memory (RAM) Random-access memory.

Rowe-Ackermann Schmidt Astrograph (RASA) Rowe-Ackermann Schmidt Astrograph.

Simple Imaging Polynomial (SIP) Simple Imaging Polynomial.

⁷⁰Wikipedia contributors. *Open-source hardware* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Open-source_hardware&oldid=1105615869. [Online; accessed 30-August-2022]. 2022

⁷¹Wikipedia contributors. *Open-source software* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Open-source_software&oldid=1104440334. [Online; accessed 30-August-2022]. 2022

⁷²Wikipedia contributors. *Operating system* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Operating_system&oldid=1104687084. [Online; accessed 3-September-2022]. 2022

⁷³Wikipedia contributors. *Radio frequency* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Radio_frequency&oldid=1104615064. [Online; accessed 28-August-2022]. 2022

Simplified Deep Space Perturbations (SDP) Simplified Deep Space Perturbations models apply to objects with an orbital period greater than 225 minutes, which corresponds to an altitude of 5,877.5 km, assuming a circular orbit. See also: SGP.⁷⁴

Simplified General Perturbations (SGP) Simplified General Perturbations models apply to near earth objects with an orbital period of less than 225 minutes. Simplified perturbations models are a set of five mathematical models (SGP, SGP4, SDP4, SGP8 and SDP8) used to calculate orbital state vectors of satellites and space debris relative to the Earth-centered inertial coordinate system. This set of models is often referred to collectively as SGP4 due to the frequency of use of that model particularly with TLE sets produced by North American Aerospace Defense Command (NORAD) and National Aeronautics and Space Administration (NASA). These models predict the effect of perturbations caused by the Earth's shape, drag, radiation, and gravitation effects from other bodies such as the sun and moon. See also: SDP.⁷⁵

Single board computer (SBC) Single board computer.

Software development kit (SDK) Software development kit.

Software-defined radio (SDR) Software-defined radio is a radio communication system where components that have been traditionally implemented in analog hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a PC or embedded system. SDRs are used in SatNOGS ground stations.⁷⁶

Space Defense Squadron (SDS) Space Defense Squadron.

Space Situational Awareness (SSA) Space Situational Awareness.

Spacecraft Identification and Localization (SIDLOC) Spacecraft Identification and Localization.

two-line element set (TLE) two-line element set is a data format encoding a list of orbital elements of an Earth-orbiting object for a given point in time, the epoch. Using a suitable prediction formula, the state (position and velocity) at any point in the past or future can be estimated to some accuracy. TLEs can describe the trajectories only of Earth-orbiting objects. TLEs are widely used as input for projecting the future orbital tracks of space debris for purposes of characterizing “future debris events to support risk analysis, close approach analysis, collision avoidance maneuvering” and forensic analysis. The format was originally intended for punched cards, encoding a set of elements on two standard 80-column cards.⁷⁷

Ultra High Frequency (UHF) Ultra High Frequency is the International Telecommunication Union (ITU) designation for radio frequencies in the range between 300 megahertz (MHz) and 3 GHz, also known as the decimetre band as the wavelengths range from one meter to one tenth of a meter (one decimeter). Lower frequency signals fall into the VHF or lower bands.⁷⁸

⁷⁴Wikipedia contributors. *Simplified perturbations models* — Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Simplified_perturbations_models&oldid=983925578. [Online; accessed 30-August-2022]. 2020

⁷⁵Wikipedia contributors. *Simplified perturbations models* — Wikipedia, The Free Encyclopedia

⁷⁶Wikipedia contributors. *Software-defined radio* — Wikipedia, The Free Encyclopedia

⁷⁷Wikipedia contributors. *Two-line element set* — Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Two-line_element_set&oldid=1104028347. [Online; accessed 28-August-2022]. 2022

⁷⁸Wikipedia contributors. *Ultra high frequency* — Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Ultra_high_frequency&oldid=1096417717. [Online; accessed 28-August-2022]. 2022

Ultrasonic motor (USM) is a type of piezoelectric motor powered by the ultrasonic vibration of a component, the stator, placed against another component, the rotor or slider depending on the scheme of operation (rotation or linear translation). One common application of ultrasonic motors is in camera lenses where they are used to move lens elements as part of the auto-focus system.⁷⁹

United States Space Command (USSPACECOM) United States Space Command.

Universal Serial Bus (USB) Universal Serial Bus.

USB video device class (UVC) USB video device class.

Very High Frequency (VHF) Very High Frequency is the ITU designation for the range of radio frequency electromagnetic waves (radio waves) from 30 to 300 MHz, with corresponding wavelengths of ten meters to one meter. Frequencies immediately below VHF are denoted high frequency (HF), and the next higher frequencies are known as UHF.⁸⁰

Video for Linux v2 (V4L2) Video for Linux v2.

World Coordinate System (WCS) World Coordinate System.

Volt (V) Volt.

⁷⁹Wikipedia contributors. *Ultrasonic motor* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Ultrasonic_motor&oldid=1099892445. [Online; accessed 4-September-2022]. 2022

⁸⁰Wikipedia contributors. *Very high frequency* — *Wikipedia, The Free Encyclopedia*. https://en.wikipedia.org/w/index.php?title=Very_high_frequency&oldid=1105564543. [Online; accessed 28-August-2022]. 2022

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