

MODERNIZING THE LASER TRACKER NETWORK ADJUSTMENT WORKFLOW AN INTEGRATED SOFTWARE SUITE FOR ACCELERATOR ALIGNMENT

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Abstract

This paper presents an integrated three-component software suite developed at SLAC National Accelerator Laboratory for high-precision network measurement and adjustment in accelerator alignment. The system consists of AlignTrackPro for automated laser tracker data acquisition, a modernized version of the legacy LEGO adjustment engine, and LEGO Pipeline, which provides visualization through interactive 2D network maps and error ellipses. The suite addresses a critical limitation of commercial laser tracker software: the inability to perform gravity-compensated network adjustments. In large networks, neglecting gravity-field effects on measured height differences can introduce errors of approximately 0.2 mm over 50 m baselines, which is significant relative to the sub-millimeter tolerances required in accelerator facilities. The integrated system is now in production use for SLAC facility networks.

INTRODUCTION

Accelerator alignment requires precise geodetic networks established using gravity-based instruments like laser trackers and levels. In long terrestrial networks over tens of meters, non-parallelism of local gravity vectors and curvature reductions can introduce millimeter-level systematic effects over tens to hundreds of meters if not modeled. For facilities requiring sub-millimeter alignment tolerances, these effects cannot be neglected and must be properly modeled in the network adjustment [1, 2].

Commercial metrology software such as Spatial Analyzer (SA), which is an industry standard, performs network adjustment in Cartesian coordinate systems [3]. SA's standard approach assumes a single, global frame with uniform vertical direction. While excellent for local component measurements and small networks, this characteristic becomes important when the local vertical direction varies across extended measurement volumes.

The LEGO software, originally developed in the 1990s at SLAC, provides gravity-compensated network adjustment by working in geodetic coordinate systems where the vertical is properly defined at each point [4]. However, by 2025, LEGO had become obsolete. Last compiled in 2012, the software was not maintained and stopped working on

modern Windows systems.

This paper presents a complete modernization of the SLAC network workflow through three integrated components designed specifically for accelerator alignment networks. AlignTrackPro automates field acquisition with Leica AT-series trackers, the rebuilt LEGO engine preserves critical gravity-compensated adjustment capabilities, and LEGO Pipeline provides modern visualization and analysis tools. The system addresses operational challenges encountered in production environments and is now deployed at SLAC.

SYSTEM ARCHITECTURE

The integrated suite consists of three modular components connected through human-readable text file formats. AlignTrackPro handles field data acquisition and communicates with Leica laser trackers via the LMF.Tracker.Connection.dll API (Application Programming Interface), implemented in Python for Windows [5]. The LEGO adjustment engine, written in C/C++ and rebuilt using Visual Studio 2025, performs the core network adjustment computations. LEGO Pipeline, a Python-based GUI provides the user interface for configuration, execution, and analysis. It replaces the command-line operation and manual text file editing with an integrated graphical environment, while adding enhanced analysis capabilities beyond the original LEGO functionality.

Data flows sequentially through the system. AlignTrackPro produces observation files (.inp) containing measured horizontal angles, vertical angles, and distances, along with parameter files (.par) defining adjustment settings. LEGO Pipeline reads and edits these files, executes the LEGO adjustment engine with one-click operation, and processes the outputs. LEGO produces standard reports (.out) and adjusted coordinates (.xyz), while LEGO Pipeline extracts additional information to create enhanced statistics (.out2) and provides comprehensive visualization of all results. The system architecture is presented in figure 1.

ALIGNTRACKPRO: ACQUISITION SOFTWARE

AlignTrackPro addresses the workflow inefficiencies of using commercial software for large network campaigns.

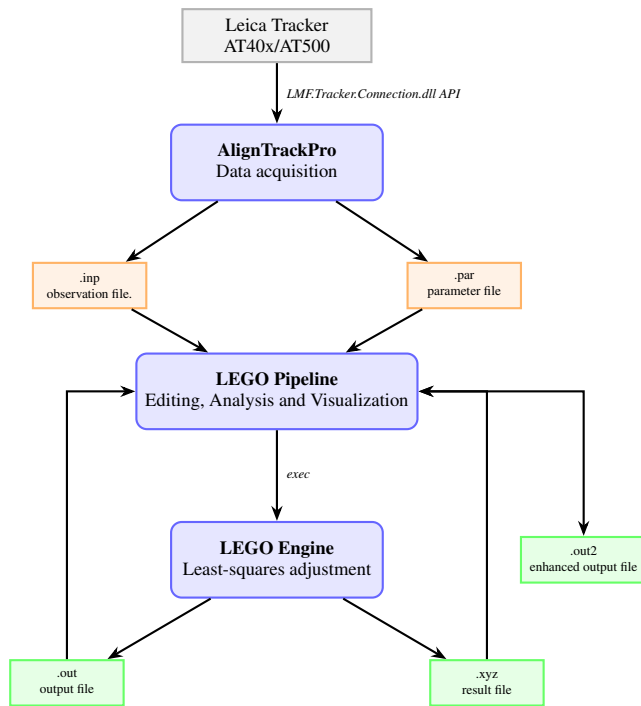


Figure 1: System architecture showing data flow through three integrated components

While SA can control laser trackers and record measurements, it is not focused on automation for tasks repeated at every station: resection to known points, systematic measurement of network points in both instrument faces, and export to formats suitable for gravity-compensated adjustment. AlignTrackPro automates these repetitive operations while maintaining full operator control when needed. It provides real-time information about measurement outliers and resection quality during field operations.

The software architecture uses a JSON-based database with a single points file per project and multiple station files, one for each instrument setup. This structure efficiently organizes projects containing hundreds of points measured from dozens of stations. The software allows loading approximate coordinates of network points from text files as well as adding new points and modifying existing ones.

The system supports Leica AT40x and AT500 series trackers, with particular emphasis on exploiting the Orient-to-Gravity (OTG) capability available on these instruments. OTG provides continuous inclinometer data during measurements, essential for subsequent gravity-compensated adjustment.

The main interface divides into three functional areas. The top panel manages projects with buttons for creating, loading, saving, importing, and exporting, as well as tracker connection and initialization controls. The left area displays measurement data in three tabs: Project Points showing the master point list with approximate coordinates, Station Points showing points measured or to

be measured from the current station with quality indicators, and Station Measurements showing all observations recorded at the current station with face information and measurement quality indicators. The right panel contains measurement controls including station management, tracker connection status, leveling information from the built-in inclinometer, and measurement action buttons. The basic software GUI (Graphical User Interface) of AlignTrackPro is presented in Fig. 2

The automated measurement workflow significantly improves field efficiency compared to manual operation. After connecting to the tracker and selecting a station, the operator measures two known points using the "Measure" function, navigating between them using the "Manual Control" function. The program automatically locks onto targets but also allows manual control over the locking process. The software immediately calculates an approximate station resection and enables the "Aim to Point" button. Clicking this button automatically drives the tracker to the third known point from the list. After measuring the third point, the system performs a full 3D resection calculation. The 3D resection can be initiated manually at any time to exclude points and recalculate the station position.

With the station properly resected, the operator can trigger batch measurement mode. The software systematically aims to each network point in the project, locks onto the target, and records the measurement in Face 1. After completing the full horizon set, the software executes a reverse set, measuring all points in Face 2. This two-face measurement protocol eliminates systematic errors and provides internal quality control through face comparison.

Measurement modes are configurable for different operational scenarios. Single-face measurement is available when speed is critical and systematic errors are less concerning. Two-face measurement, which is the default mode, provides the highest quality but requires more time. Profile settings select between standard and high-precision modes, affecting the number of samples averaged per measurement. Accuracy settings adjust targeting tolerances and lock stability criteria.

A key feature of the software is the real-time quality control provided in the measurement tab. After each observation, three columns display diagnostic information. The first column shows the face difference when measurements are performed in both faces, indicating instrument systematic errors. The second column shows the time difference between the first measurement of a given point and consecutive measurements within the station, allowing monitoring of station drift over time. The third column shows the difference between measured coordinates (based on resection and observation) and nominal coordinates loaded at the beginning of the project, enabling rapid detection of outliers, damaged monuments, and gross errors. Differences exceeding safety thresholds are color-coded in orange and red to immediately draw the operator's attention to potential problems.

The software exports observations directly to LEGO for-

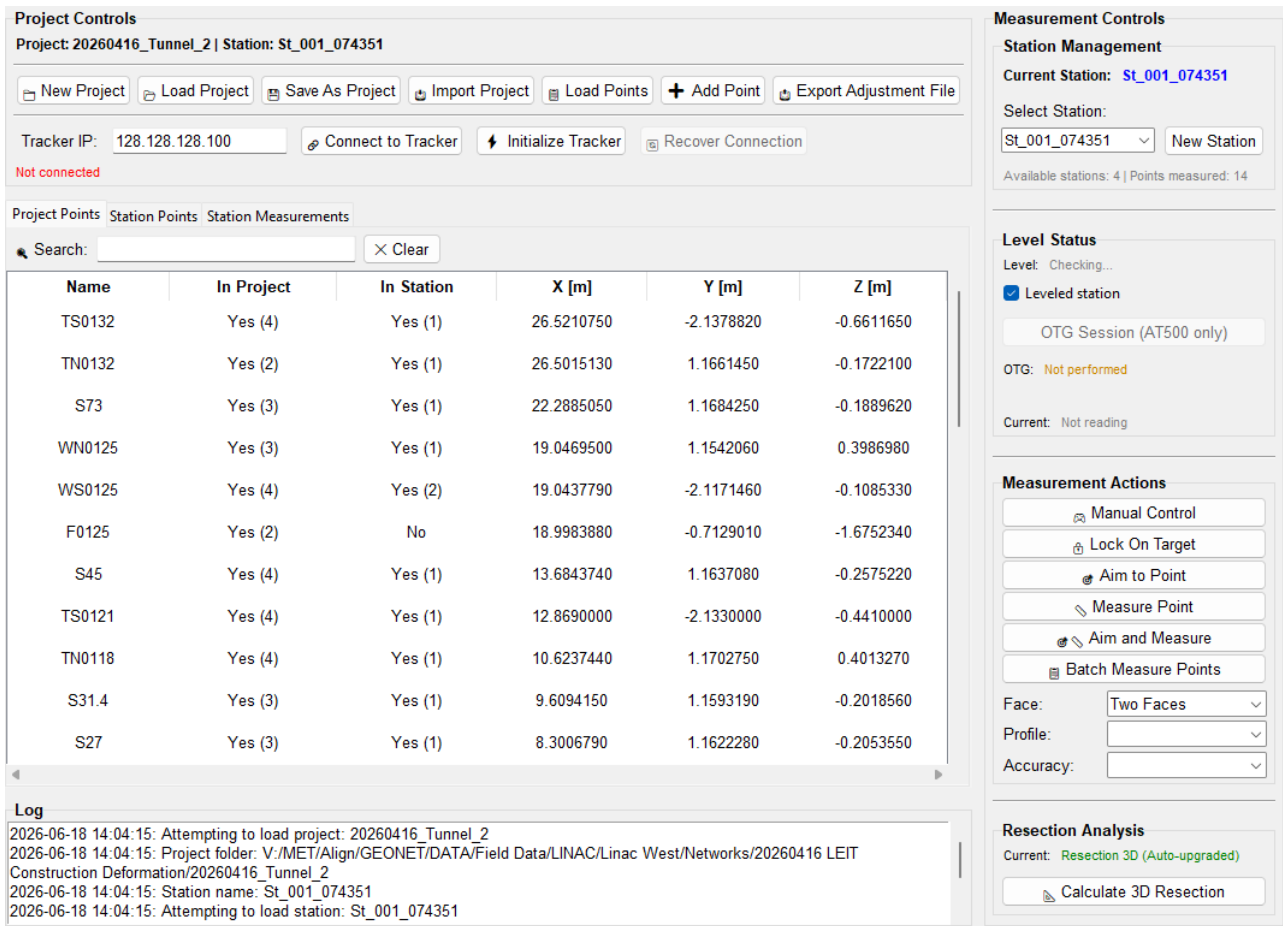


Figure 2: Main interface of AlignTrackPro showing the three functional areas: top panel with project management and tracker controls, left panel with three data tabs, and right panel with measurement controls and action buttons.

mat, writing the .inp file with measured horizontal angles, vertical angles, and slope distances. Station coordinates from the resection are included, and inclinometer data from OTG are applied according to options selected in the software. This direct export eliminates manual data transfer and associated errors. In addition, AlignTrackPro exports a simple observation file (.res) and CERN LGC adjustment software format.

LEGO ENGINE MODERNIZATION

LEGO was developed in the 1990s at SLAC for accelerator alignment network adjustment, with the last build occurring in 2012 for Windows 7. Its core capability, least-squares adjustment in geodetic coordinates with proper gravity modeling, is essential for SLAC operations but unavailable in SA. The adjustment engine handles observation networks combining polar observations, distances, orthogonal observations, leveling and GNSS.

When Windows 11 deployment began in 2021, LEGO became completely non-functional. The program crashed immediately on launch with an error preventing any execution. Investigation indicated that the legacy executable and its dependencies were not compatible with the Win-

dows 11 64-bit runtime environment, leading to an immediate crash at startup. Without LEGO, all SLAC facility networks would lose their ability to perform large-scale adjustments.

The rebuild was performed in Microsoft Visual Studio 2025, targeting Windows 11 64-bit systems. The software consists of five components that must be compiled together with matching versions: the main executable run-lego.exe and four supporting DLLs. The feedback.dll library handles user interaction and progress reporting. The input.dll library parses observation and parameter files. The lego.dll library performs the core adjustment computations including matrix operations and statistical analysis. The project.dll library manages coordinate system definitions and transformations between Cartesian and geodetic systems.

The most critical technical challenge involved memory management errors in the legacy code. Uninitialized pointer variables in adjustment computation routines caused undefined behavior that older compilers accepted but modern compilers correctly rejected. These latent bugs were systematically corrected by initializing all pointers to nullptr, adding null checks before deallocation, and

eliminating duplicate `free()` calls that caused memory corruption. Additional issues included linker conflicts from multiple `main()` functions in different source files and legacy code compatibility problems such as format string mismatches, implicit type conversions, and missing headers. A pragmatic approach was adopted: fix all compilation errors preventing building while accepting remaining warnings, as testing confirmed correct operation and aggressive warning elimination risked introducing new bugs in stable code.

While preserving the core adjustment algorithms, several practical improvements were implemented. Comment support was added using the `%` symbol as a delimiter in data files, enabling inline documentation. Point name length was extended from the original 8-character limit to 16 characters, improving readability in large networks with systematic naming conventions. Backward compatibility was maintained; all existing LEGO files from the past 25 years remain fully functional.

Validation was performed by comparing outputs against archived results from the 2012 version. Test datasets representing various network configurations were processed with both versions. Adjusted coordinates, standard deviations, correlation matrices, and statistical test values matched within numerical precision limits, confirming that the core algorithms remained unchanged. The modernized LEGO is now in production use across all SLAC facilities, processing real alignment campaigns with full confidence in result accuracy.

LEGO PIPELINE: GUI AND VISUALIZATION

The original LEGO was compatible with GEONET, a graphical user interface, but this component failed on modern Windows systems. A modern replacement was needed that could edit files and execute adjustments in an integrated environment.

LEGO Pipeline was implemented in Python with direct parsing of LEGO text file formats. The software reads `.inp` observation files, `.par` parameter files, `.out` standard output, `.xyz` coordinate files, and a custom `.out2` format containing enhanced statistics. The Matplotlib library provides two-dimensional network visualization with interactive controls. The LEGO executable is embedded and called directly, eliminating the need for command-line operation.

The GUI uses a multi-tab architecture providing access to all file types. The "Input File (`.inp`)" tab displays and edits observation data. The "Parameter File (`.par`)" tab configures adjustment settings including observation weights, convergence criteria, and output options. The "Output File (`.out`)" tab shows standard LEGO results including adjusted coordinates, standard deviations, and statistical tests. The "Coordinates (`.xyz`)" tab presents adjusted point coordinates with standard deviations. The "Output Report (`.out2`)" tab displays enhanced statistics file. The Graphical Map tab provides interactive network visualization de-

scribed in detail below.

The top control bar enables one-click operation. The "Save and Run" button writes any edited files to disk, executes the LEGO adjustment, and automatically refreshes all output tabs with new results. The adjustment type selector provides access to all LEGO modes including free network adjustment and network simulation. The "Configure LEGO Path" button allows specification of the LEGO executable location, supporting multiple LEGO versions for testing or backward compatibility. The LEGO Pipeline GUI is shown in Fig. 3

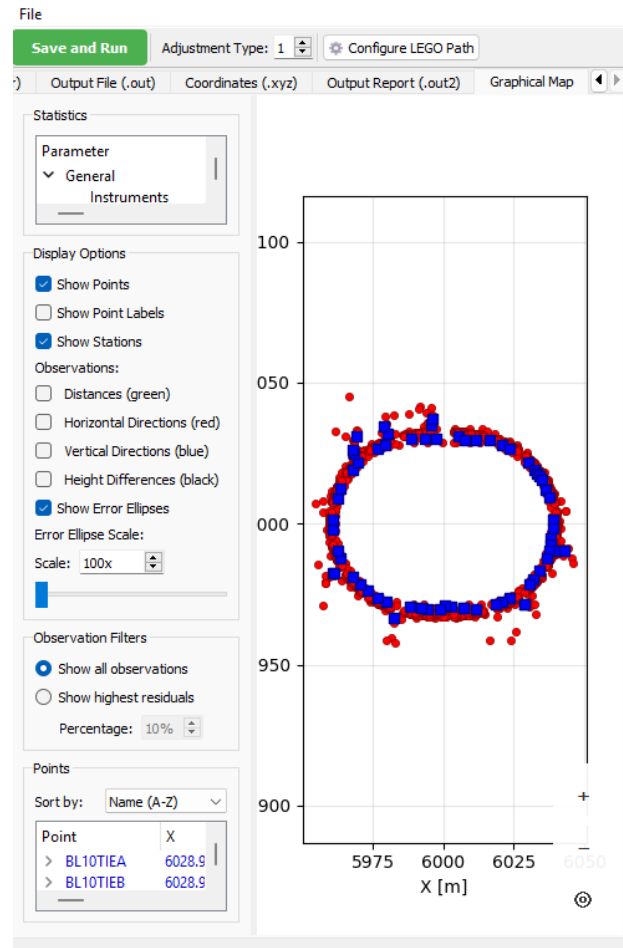


Figure 3: LEGO Pipeline GUI featuring multi-tab file editing interface and interactive network visualization with observation residual filtering and error ellipse display.

The graphical map tab provides comprehensive network visualization for quality control. The display shows network points as red circles, instrument stations as blue squares, and observations as colored lines. Distance observations appear in green, horizontal direction observations in red, vertical direction observations in blue, and height difference observations in black. Point labels can be toggled for clarity in dense networks. Error ellipses are drawn in black around each adjusted point, scaled by a user for visibility since actual ellipses at sub-millimeter scale would

be invisible.

A critical feature is the observation filter enabling display of either all observations or only the highest residuals. By setting the filter to show the top 10% of residuals, operators can immediately identify problematic measurements requiring investigation. The ability to visualize residuals spatially accelerates quality control compared to reading numerical tables.

Interactive navigation supports large networks. Pan and zoom controls allow exploration of networks containing hundreds of points. A coordinate list provides sorted access to specific points. Clicking a point in the list centers the map view on that location. This is particularly useful for accelerator ring networks where points are distributed around large circular structures, requiring zooming to different sections for detailed inspection.

The enhanced .out2 file format was created by modifying LEGO to export additional data not present in the standard output. Most significantly, the full covariance matrix is exported, enabling correlation analysis between points and advanced uncertainty propagation. This information is essential for analyzing how measurement errors at one point affect neighboring points in the network. Additional statistical measures are under development for future releases, including reliability metrics and separability analysis for blunder detection.

LEGO Pipeline supports two primary workflows. In simulation mode, operators import design coordinates, configure expected observations, and execute a priori adjustment to evaluate network precision before field deployment. Error ellipses identify areas of highest uncertainty, allowing optimization of station locations and identification of points requiring redundant measurements. In analysis mode, operators import field observations from AlignTrackPro, execute the adjustment with one click, and perform visual quality control via the graphical map. Residual filtering rapidly identifies outliers requiring remeasurement. The entire workflow from field data to final coordinates and reports can be completed in minutes, with all results ready for delivery to alignment teams and archival storage.

DISCUSSION

The presented software suite closes a practical gap between field acquisition with modern laser trackers and rigorous network adjustment required for accelerator alignment. The key technical distinction from common commercial metrology workflows is the ability to perform adjustment in a geodetic framework with a physically consistent treatment of the local vertical. For networks spanning tens of meters, the non-parallelism of vertical directions produces systematic effects that become comparable to the sub-millimeter tolerances typical for accelerator infrastructure.

AlignTrackPro and LEGO Pipeline reduce the number of manual steps that historically created opportunities for transcription errors. Automating routine sequences (resec-

tion, two-face rounds, structured export) standardizes measurement practice across operators and campaigns. In particular, providing immediate station-level diagnostics improves robustness when networks are observed over long shifts and changing environmental conditions.

The modernization strategy for LEGO intentionally prioritized algorithmic equivalence over refactoring. This choice is defensible because the dominant project risk was loss of a validated adjustment engine rather than lack of new functionality. The consequence is that some legacy design constraints remain (e.g., file-based batch execution, partial modernization of the codebase, and limited test coverage compared to contemporary software standards). From a scientific software perspective, the work highlights a recurrent tension: aggressive rewrites can improve maintainability but may degrade trust in numerical results unless extensive revalidation is feasible. Here, maintaining continuity of results was the critical requirement, and validation against archived adjustments provides strong evidence that numerical behavior was preserved.

The current system also has limitations that should be stated explicitly. First, the workflow is predominantly post-processed: observations are collected, exported, and then adjusted. This is adequate for establishing and maintaining control networks, but it is less optimal for applications requiring immediate feedback (e.g., interactive troubleshooting during measurement, or stakeout with live uncertainty estimates). Second, the text-based interfaces are transparent and durable, but they can become a bottleneck for very large datasets (e.g., photogrammetry) without stronger support for metadata, versioning, and automated checks. Third, sustainability remains a concern typical of in-house tools: without institutionalized ownership (documentation, regression tests, release procedure), long-term maintainability depends on a small number of contributors.

Overall, the suite is a production solution for gravity-sensitive alignment networks. It preserves a specialized adjustment capability while making the workflow faster, more repeatable, and easier to quality-control. It is most valuable in large facilities where networks are re-observed regularly and reference frames must remain consistent over many years.

FUTURE DEVELOPMENT

Planned enhancements focus on expanding capabilities while maintaining the core strengths of the current system. Live data presentation would enable real-time coordinate display during measurement, creating a "watch window" showing updated positions as each observation is recorded. This would support stakeout operations where components must be positioned to target coordinates, with immediate feedback on achieved accuracy. Implementation requires streaming data from AlignTrackPro to LEGO Pipeline and performing incremental adjustments as new observations arrive.

Non-verticalized coordinate systems would support advanced accelerator geometry applications. Some accel-

erator sections follow curved reference surfaces or tilted planes rather than level datums. Current LEGO assumes vertical axes align with gravity, appropriate for most applications but limiting for specialized cases. Extending the coordinate transformation framework to handle arbitrary reference surfaces would enable alignment in these geometries while maintaining proper error propagation.

Enhanced statistical output will expand the .out2 format with additional reliability measures, redundancy analysis, and automated quality metrics. Current network analysis requires manual interpretation of residuals and statistical tests. Automated flagging of potential blunders, identification of weak network areas, and recommendations for additional observations would make the software accessible to less experienced users while improving quality control even for experts.

CONCLUSIONS

This paper presented an integrated three-component software suite addressing specific operational needs of network acquisition and adjustment in accelerator alignment. AlignTrackPro automates field acquisition through automated resection and batch measurement sequences, reducing operator workload and measurement time while maintaining precision and control. The LEGO modernization preserved critical gravity-compensated adjustment capabilities unavailable in commercial software by successfully rebuilding 25-year-old code for modern Windows systems, ensuring continued operation of essential alignment workflows. LEGO Pipeline provides modern visualization with interactive network maps, error ellipse display, and residual filtering, transforming quality control from numerical table review to intuitive graphical analysis.

The system is deployed across SLAC facilities including SPEAR, LCLS, and experimental beamlines, processing routine alignment campaigns with networks of arbitrary size and complexity. The key contribution is maintaining specialized capabilities, particularly gravity compensation for large networks, while modernizing workflow efficiency and usability. The modular architecture using text interfaces ensures long-term sustainability and allows independent evolution of components as technology and requirements change.

The experience demonstrates both the value and challenges of in-house scientific software development. Commercial packages provide excellent general-purpose tools, but specialized applications with unique requirements often need custom solutions. Preserving legacy scientific code requires proactive maintenance as operating systems evolve, and modular design with standard interfaces provides the best path to long-term sustainability. The integrated workflow treats acquisition, processing, and visualization as one system instead of separate tools, improving efficiency and result quality.

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