
Introduction

FRED is an advanced, surface-based optical engineering software program capable of simulating the propagation of radiation through virtually any optical/mechanical system.

FRED can be applied to a very broad range of applications including but not limited to: illumination systems, lightpipes, reflectors, imaging systems, projection systems, scanners, thermal imaging systems, stray light analyses, laser and interferometric systems, ghost analyses, coherent beam propagation, prototype and experimental system layout, diagnostic analyses, and virtual prototyping.

FRED is intended for everyone from the infrequent user to the experienced engineer who faces challenging real-world optical engineering problems.

FRED's real-time visualization/editing and advanced user interface produce photo-realistic renderings of optical/mechanical systems with immediate user feedback.

FRED can accurately simulate virtually any light source including lasers, arc lamps, LEDs, ideal emitters, point sources, bulbs, user defined raysets, etc.

The user can define as many surfaces, curves, aspheric/polynomial terms, materials, coatings, wavelengths, sources, rays as the user's computer resources will allow.

FRED can position any assembly, subassembly, element, surface, curve or source in the coordinate system of any other assembly, subassembly, element, surface, curve, or source. Furthermore, FRED can transform any entity's coordinate system into any other coordinate system in order to help facilitate model setup and element alignments.

FRED's Optimum Edition multi-threads on up to 127 threads and has a hybrid optimization algorithm. Choose from built-in or user-defined merit functions, and define any number of variables and/or target surfaces; all to drive your system toward optimum performance. FRED Standard Edition efficiently utilizes up to 17 threads for raytracing and analyses.

FRED's MPC Edition leverages NVIDIA GPU technology to perform raytracing and analyses directly on massively parallelized graphics processing units (GPUs), allowing calculations to be performed orders of magnitude faster than traditional CPU raytracing.

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FRED™

System Requirements

Recommended Configuration:

- Up to 17 threads for FRED Regular and up to 127 threads for FRED Optimum, with clock speeds at 3+ GHz or higher
- 16+ GB of RAM
- SSD hard disk
- NVIDIA graphics card with 4+ GB of memory (for 3D rendering)
- NVIDIA graphics card with compute capability 6.0+ and 8+GB of VRAM (for use with FRED^{MPC})

OLE Automation

Automation Client:

The scripting language enables **FRED** to function as an OLE automation client. This allows **FRED** to directly manipulate, and communicate with, other applications such as Microsoft Excel® or Matlab®.

Automation Server:

FRED can function as an OLE automation server capable of being run remotely from any other application (such as Matlab®) that can serve as an automation client. Thus, **FRED** can function as a remote raytracing computational “engine” for performing calculations difficult or impossible to do in non-optical applications. This capability is tightly coupled to **FRED**’s scripting language.

Import/Export Capabilities

Import from Optical Design Software:

- **CODEV®** (proprietary product of Optical Research Associates)
- **OSLO®** (proprietary product of Lambda Research)
- **ZEMAX®** (proprietary product of Zemax Development Corporation)

Import options include:

- **Render transmitting surfaces as transparent**
- **Creating edges/bevels on lens elements**
- **Creating default sequential path**
- **Showing dummy surfaces**
- **Computing unassigned apertures from paraxial raytrace**
- **Resetting minimum thickness/separation**
- **Setting cement thickness** (If selected, **FRED** will try to identify those surfaces that are part of lenses and represent them as such. Cemented lens groups are represented as individual elements that are cemented together.)

Import/Export from/to most CAD software:

- **Import:** Import via the STEP and IGES standards. These two formats are supported by almost all CAD software. OBJ/STL files may also be imported.
- **Export:** Export via the STEP and IGES standards. It offers export of most **FRED** surfaces as well as ray trajectories (which offers mechanical designers a convenient means to set baffle clearances).

Import from Commercial Lens Catalogs:

FRED has an up-to-date database of commercially available lenses and prisms from the following major US suppliers:

- | | |
|-----------------|----------------|
| • Edmund Optics | • Esco |
| • JML Optics | • Melles-Griot |
| • Newport | • OptoSigma |
| • Oriel | • Rolyn |
| • Archer | • Ealing |
| • Ross | • ThorLabs |

Project/Document Control

Multiple versions of **FRED** document and script files can be stored in a single repository. This allows multiple team members to coordinate work on a **FRED** project. It also provides a convenient mechanism for tracking changes to **FRED** models as they are developed.

32/64 Bit Versions

FRED is available in either 32 bit or 64 bit versions. The 32 bit version will execute on both 32 bit and 64 bit operating systems. The 64 bit version is available to all **FRED** license types.

Output Window

FRED's output window is an Excel-compatible spreadsheet with built-in "formula engine". The spreadsheet may be "cut and pasted" into Excel while preserving equations, etc. Output text coloring is under user-control. All floating point numbers can be viewed to full double precision accuracy.

FRED Optimum Edition

System Requirements

Recommended Configuration:

- Up to 127 CPU threads with clock speeds at 3+ GHz or higher
- 32+ GB of RAM
- SSD hard disk
- NVIDIA graphics card with 4+ GB of memory

Distributed Computing

FRED Optimum licenses can distribute calculations to an arbitrary number of Windows networked computers, dramatically reducing the time required for analyses due to the parallel nature of distributed processes.

Optimization

FRED has a general optimization feature designed to address a wide range of applications. Performance criteria are specified through user-defined or built-in merit functions and applied with Simplex (multi-variable) or 1-D (single variable) methods.

Variable Specifications:

- Position/orientation parameter for any system object
- Surface curvature
- Surface conic constant
- Surface aspheric coefficients
- NURB control point positions
- NURB control point weight
- Lens element bending parameter
- Lens element thickness
- Surface aperture size
- Element primitive parameter value
- Source power
- Super-Gaussians Surface parameters
- User-defined script (allows custom non-default variables)

Merit Function Aberration Specifications:

- RMS spot size
- Encircled spot radius
- Total maximized power on the surface
- Total minimized power on the surface
- RMS and Encircled spot sizes

- Spot centroid location
- RMS and Encircled ray direction spread
- Ray direction centroid
- P-V and RMS Irradiance/Illuminance
- P-V and RMS Intensity
- RMS color chromaticity variation
- Encircled color chromaticity variation
- Centroid color chromaticity
- User-defined script (allows custom non-default merit function aberrations)

Optimization Method Specifications:

- 1-D minimization
- Simplex
- 1-D minimization with multiple restarts
- Simplex with multiple restarts
- Simplex with simulated annealing

Parameter Pickups (Optimum Edition only)

FRED's parameter pickups allow multiple entity variables to be dynamically and automatically linked together through built-in and user-definable parameterization. This feature adds a lot of power and flexibility in building models which can be reliably and efficiently manipulated and optimized.

Configurations (Optimum Edition only)

The System(s) Configuration Manager allows a model's geometry to be defined in a multiplicity of states. Rather than having multiple versions of a single model corresponding to unique configurations, a single model can be managed with the configuration data built in. A classic example of configurations would be specifying lens group locations for multiple zoom positions.

FRED^{MPC} Edition

System Requirements

Recommended Configuration:

- Up to 127 CPU threads with clock speeds at 3+ GHz or higher
- 32+ GB of RAM
- SSD hard disk
- NVIDIA graphics card with 8+ GB of memory and compute capability 6.0 or newer

The FRED^{MPC} capability allows raytracing and analyses to be performed directly on GPUs, with calculations being performed orders of magnitude faster than traditional CPU raytracing. GPU calculations and analyses can be performed in both single and double float precision.

Geometry

The user has many options for geometry definition ranging from direct user input of **FRED** primitives (lenses, mirrors, prisms, vendor elements, and surfaces/curves incorporated into user-defined custom elements), import from a CAD program, and direct import of prescription files from many lens design programs.

Since **FRED** has a multiple document user interface, components may be cut, copied, and pasted among documents. Entities may be logically arranged into hierarchies of assemblies, subassemblies, and elements that correspond to the physical layout of the system. Each can be located relative to any arbitrary coordinate system. Any surface may be trimmed (sliced) by any implicit surface, or by an aperture collection curve, which is defined below.

Element Primitives

Commonly used geometry solids can be easily defined as Element Primitive objects. A minimal set of parameters completely specifies the geometry without the need for user management of the base surfaces constructing the object.

Available Element Primitives:

- Plane
- Paraboloid
- Parabolic Trough
- Sphere
- Ellipsoid
- Cube
- Block
- Rod
- Frustum
- CPC
- N-Sided Extruded Solid
- N-Sided Pipe
- N-Sided Pyramid Solid
- Beveled Wedge
- Multimode Fiber Optic
- Pipe
- Circular Pyramid
- Hemisphere Solid
- Hemisphere Shell
- Hemisphere Surface
- Torus
- Coil
- Wedge
- Truncated Ellipsoid
- Cylinder Lens
- N-Sided Extruded Surface
- N-Sided Plane
- N-Sided Plane with N-Sided Hole
- Ideal Lens

Element Composites

Element primitives and element composites can be combined together using Boolean operations to form complex solids. The resultant solids are dynamic, meaning that the solid is updated as its component elements are modified. Element composites are exportable to CAD from within FRED.

Lens Types

A lens (singlet) may be specified by radii, curvatures, or focal length/bending factor. Apertures can be circular, elliptical, or rectangular. **FRED** can add edges and flats as needed. By default, surfaces are spherical but may be updated to any other surface type.

Mirror Types

A mirror may be specified by radii, curvatures, or focal length, central thickness, material, with circular, elliptical, or rectangular outer boundary and optional central hole. By default, surfaces are spherical/conic but may be updated to any other surface type.

Prism Types

A prism is specified by its dimensions and material. The following prism types are supported:

- Abbe
- Amici
- Dove
- Equilateral
- Fresnel Rhomb
- Leman
- Pechan
- Penta
- Porro
- Reversion
- Right Angle
- Schmidt
- Corner Cube (refractive)

- **Wedge** (circular w/user-defined angle)
- **General** (user-defined angles)
- **Cube Beamsplitter** (may be dichroic, polarization, or amplitude depending upon user specification)

Rectilinear Arrays

Any surface, element, subassembly, or source may be replicated in a rectilinear array. Various drawing attributes of the array may be specified.

Traceable/Not Traceable

Every subassembly, element, surface, curve, and source can be designated as being “traceable” or “not traceable”. Any object designated as “traceable” will be rendered and included in the raytrace. Conversely, any object designated as “not traceable” is neither rendered nor included in the raytrace, although it continues to exist in the model. This feature is particularly useful for evaluating multiple configurations and performing diagnostic analyses.

Detector Entities

Spatial, incoherent analyses can be performed using Detector Entity cones, planes, spheres and cylinders. Detector Entities are capable of dynamically collecting ray information during the raytrace, after the raytrace or upon user request and will create an accompanying analysis results node which stores the results of the calculation.

Voxels

The 3D Box type detector entity is used to track absorption, power in-flux, and power out-flux through voxels within the 3D Box volume. The results can be dynamically displayed within FRED’s 3D viewer and exported to a variety of formats supported by open-source data visualization software.

Analysis Results Nodes

Analyses results can optionally be stored as nodes on FRED’s object tree in the Analysis Results folder. Analysis Results Nodes (ARNs) allow users to easily keep track of and compare analyses created during the document session. ARN’s contain all information regarding the configuration of the analysis and the accompanying data. These results can be displayed in the chart view, the 3D view, or written to file.

Surfaces and Curves

Surface types fall into two categories: implicit and explicit. Implicit functions define a surface through the equation $f(x,y,z)=0$ where all (x, y, z) points which satisfy the equation lie on the surface. Explicit functions define a surface parametrically in the form $(x(u,v), y(u,v), z(u,v))$ where (u,v) are the parameter values. Several explicit functions are based upon curve types described below.

Implicit Surface Types

- **Plane** (flat surface)
- **Conicoid** (spheroid, ellipsoid, hyperboloid, etc. – the classic optical surface)
- **Standard sphere** (conicoid plus polynomial in even powers of radial distance)
- **General sphere** (conicoid plus polynomial in even and odd powers of radial distance)
- **Cylinder** (tube/cone)
- **Ellipsoid/Hyperboloid** (specified by two foci locations)
- **Toroidal sphere** (anamorphic aspheric “potato chip” surface with non-symmetric aspheric warping)
- **XY Toroidal sphere** (X or Y toroid with even/odd polynomial aspheric terms)
- **Polynomial sphere** (conicoid plus XY polynomial aspheric terms)
- **Polynomial surface** (general 3D polynomial in x, y, z)
- **Forbes QCon and QBsf** (axially symmetric aspheres represented by Forbes polynomials)
- **Super-Gaussians Superposition** (formed from a superposition of offset and rotated super-gaussians)

- **Zernike surface** (the first 66 Zernike polynomial terms plus a base conic and standard aspheric terms)
- **User-defined surface** (BASIC script)
- **Sampled Mesh surface** (Rectilinear mesh of sampled sag values with bicubic interpolation between sample points. Surface data may be imported from a bitmap file or a common ASCII "INT" file format)

Auxiliary Data

Each surface can have any number of associated auxiliary data items. Each item consists of a name and value, and is completely user-defined and arbitrary.

Surface Deformations

Any implicit surface type can serve as a base surface that can be deformed according to another implicit surface of the form $z = f(x, y)$.

Gratings/Holographic/DOE

Any surface can become a grating. Assign these properties directly from the Surface dialog.

- **Linear grating**
- **Two-point hologram** w/optional aspheric phase terms
- **User-recorded 2-point HOE** for modeling non-idealized recording setups
- **Unlimited diffraction orders and efficiencies** (efficiencies may be pre-computed for blazed, kinoform, binary(step), and sinusoidal grating line shapes)
- **Continuous, modulo 2π , or None** phase additions across grating line pairs
- **Diffraction efficiency dependence on wavelength, incident polar and azimuth angles, polarization state with cross-coupling, as well as distinction between reflection and transmission efficiencies**
- **Volume hologram efficiency calculation with polarization**

Explicit Surface Types

- **Tabulated cylinder** (straight line extruded curve)
- **Spline** (collection of parametric polynomial patches)
- **Ruled surface** (two curves connected together)
- **Surface of revolution** (curve revolved around an arbitrary axis)
- **NURBS surface** (Non-Uniform Rational Basis-Spline surface)
- **Trimmed parametric** (explicit surface trimmed by curves in parametric space)
- **Coil** (explicitly parameterized by coil radius, cross section radius, coil pitch and the number of turns)
- **Lens Modules** (perfect lenses; spherical surface, finite conjugate, infinite conjugate, afocal)
- **Ideal Lens** (perfect lens surface with f-theta, f-tan, and f-sin mapping functions)
- **Faceted Surface** (defined by a collection vertex positions and surface normals)

Curve Types

- **Circular arc** (segment of a circle – or the complete circle)
- **Conic arc** (segment of a circle, ellipse, hyperbola, etc.)
- **Line segment** (single linear segment)
- **NURBS** (Non-Uniform Rational Basis-Spline curve)
- **Spline** (polynomial segments)
- **Segmented lines** (set of connected line segments user-defined, digitized or FRED-generated)
- **Racetrack curve** (rectangle with rounded corners)
- **Composite curve** (set of connected curve segments of arbitrary type)
- **Aperture collection curve** (a special collection of closed curves that may be used for surface bounding, clear aperture/edge/hole/obscuration specification, and linear extrusion)

Sources

Sources are rayset definitions with specific properties selected by the user to simulate the emission characteristics of physical phenomena or devices. Source properties determined by random number generation

can be set to generate a new set of random numbers prior to each ray trace. Source power can be specified in photometric, radiometric or arbitrary units.

Source Properties

- **Immersion material**
- **Ray position specification** (more details below)
- **Ray direction specification** (more details below)
- **Total power**
- **Position apodization function** (more details below)
- **Direction apodization function** (more details below)
- **Coherence state** (incoherent or coherent)
- **Polarization state** (unpolarized or polarized with specific properties)
- **Multiple wavelengths** (more details below)
- **Post-construction propagation**
- **Post-construction constant phase shift**
- **Replication over a rectilinear array of positions**
- **Acceptance Filter**

Coherent Source Primitives

- **Plane Wave (coherent)**
- **Point Source (coherent)**
- **Laser Beam (00 mode)**
- **Astigmatic Gaussian Beam**
- **Laser Diode Beam (coherent)**
- **M-Squared Laser Beam (coherent)**

Incoherent Source Primitives

- **Point Source (incoherent)**
- **Plane Wave (incoherent)**
- **Lambertian Plane**
- **Lambertian Surface**
- **Rayfile Source**
- **Random Volume into a sphere**
- **Ray Fan**
- **Solar Source (simple)**
- **Laser Diode (incoherent)**
- **LED (far-field)**
- **Bitmap**

Ray Position Specifications

- **Planar array of points arranged in a rectilinear grid**
- **Planar array of points arranged in hexagonal pattern**
- **Planar set of points at random positions**
- **Set of points randomly placed inside a volume**
- **Random points arranged as character or string**
- **Random points on a surface** (surface emitter)
- **Points determined by a bitmap image** (the colors of the bitmap pixels are used to set source wavelength weights)
- **User-defined rays** (import from **Radiant Imaging™ ProSource** file, ASCII text file, or **ASAP** binary ray file)
- **Imported** – Binary/ASCII ray data from file
- **File-Based** (all ray data contained in a separate file)

Ray Direction Specifications

- **Single direction** (collimated beam)
- **Random directions into an angular range**
- **Random directions into a sphere**
- **Focus to/from a point in space**
- **Directions to a rectilinear grid of points**
- **Directions to a hexagonal grid in angle space**
- **Astigmatic Gaussian beam**
- **Focus to/from two astigmatic foci**
- **Multiple source angles (plane waves)**
- **Multiple source positions**
- **Randomly according to intensity distribution**
- **Laser Diode Beam**
- **M² Laser Beam**

Position Apodization Functions

- **Uniform** (no apodization)
- **Gaussian and super-Gaussian** (Hermite & Laguerre modes)
- **Rⁿ distance from a point**
- **Amplitude/Phase Mask** (from bitmap)
- **Super Gaussian Apodization** (useful for laser diodes)

Direction Apodization Functions

- **Uniform** (no apodization)
- **Lambertian relative to a given direction**
- **Inverse Lambertian relative to a given direction**
- **Sinⁿ or Cosⁿ relative to a given direction**
- **Gaussian**
- **Table of directions in spherical angle space**
- **Super Gaussian**

Wavelengths

- **Discrete wavelength list** -- each wavelength has an associated weight and color, and can be made active or inactive. There are built-in tools for setting wavelength sequences and wavelength weights such as photopic and scotopic spectral responses. **FRED** can also synthesize a given color specified by Chromaticity coordinates, Tristimulus, or RGB values using a selected set of wavelengths.
- **Spectral distribution** – a spectral distribution is simulated using Monte-Carlo probability techniques
- **Evenly spaced, sampled from a spectrum** – a set of evenly spaced wavelength samples are generated whose weights are set according to a spectral distribution

Acceptance Filters

Acceptance Filters maximize raytrace efficiency while preserving radiometric accuracy by designating multiple regions of the model as being of specific interest. Sources only generate rays into the regions of interest, ensuring good statistical sampling without wasting CPU cycles.

Spectral Distributions

The user can define the following spectral distributions which may be applied to sources, and as a detector response function:

- **Gaussian**
- **Black Body**
- **Discretely sampled wavelengths**
- **Import from IES TM-27-14**

IES Source Import

A detailed source model can be automatically created from an IES file according to the ANSI/IESNA LM-63-2002 format with IES orientation types A, B and C. The source is treated as a random volume emitter with dimensions matching the luminous opening values, ray directions according to the intensity distribution and power in Lumens.

Optical Coatings

- **Bare surface** with no coating
- **Table** of transmission and reflection coefficients as a function of wavelength (user-defined or digitized)
- **Thin film** layer prescription can be imported from *The Essential MacCleod™*, *Optilayer™* or user-defined
- **Table** of S-state and P-state reflection/transmission coefficients as a function of wavelength and angle
- **Polarization/waveplate** model (Jones Matrix)
- **Quarter-wave** (QW single layer)
- **User-defined Coating** provides a user-defined R & T with spatial dependence
- **Encrypted Thin Film Coating** provides analysis capability while protecting the thin film design IP

Scatter Modeling

Surface Scatter Models

Angle, β - β_0 and 3D scatter plots can be generated from single or composite scatter models. The diffuse polynomial and binomial, Harvey-Shack and ABg models can be created by the data fitting tools.

- **Lambertian**
- **Harvey-Shack** (smooth optical surface scatter)
- **ABg** (smooth optical surface scatter and others)
- **Phong** (Cos^n from specular)
- **Diffuse Black Paint** (generic model)
- **Particulates - Mie** (MIL-STD-1246, uniform distribution, Gaussian distribution, IEST-STD-1246D, sampled)
- **Diffuse polynomial** (coefficients of BSDF polynomial)
- **Diffuse binomial** (coefficients of BSDF binomial)
- **Tabulated** (table of sampled values input via a file)
- **User-defined** (via a BASIC script)
- **Tabulated PSD** (table of PSD vs. frequency)
- **K-Correlation** (analytic form of PSD)
- **Extended Harvey-Shack** (5 term model)

Scatter Importance Sampling Models

Importance sampling provides improved raytrace efficiency by directing rays only towards desired regions or directions.

- **Angular** spread about specular direction
- **Angular** spread about a given direction
- **Angular** spread about a given point
- **Towards** a given entity
- **Through** a given closed curve
- **Through** a given ellipsoidal volume

In addition, **FRED** can automatically determine importance sampling for scatter from a given surface to a specified “detector”.

Surface Roughness

Surface roughness models are used to describe surface phenomenology which cannot be accurately described by a BSDF model. Common applications might include manufacturing tolerance and machine processes (grit specs).

- **Sampled Random Surface Normal**

Volume Scattering

Wavelength-dependent Henyey-Greenstein (HG) or a general User-defined volume scatter model can be assigned to any optical material. The HG model is augmented by a library of published human tissue data.

Materials

Optical materials may be selected from up-to-date glass catalogs from major suppliers, specified in tables of wavelength-refractive index pairs (real, or complex to include absorption), or specified by n_d , v_d pair (model glass on ordinary glass line). A **Formula Glass** type has been added to widen the scope of glass alternatives. Absorption coefficients may be specified for any glass. **FRED** can also digitize refractive index data.

Glass Catalogs

- Schott
- Ohara
- Hoya
- Corning SA
- Custom (user defined)
- Archer
- Heraeus
- RPO
- Chengdu
- Hikari
- Sumita
- Pilkington
- Schott Radiation Hard
- CDGM
- NHG

Gradient Index (GRIN)

Gradient index materials are those whose index of refraction varies as a function of position, typically along the optical axis or radial with respect to it.

- **Axial-Radial** (polynomial in axial and radial distances)
- **Selfoc** (polynomial in radial distance from an axis)
- **General Polynomial** (polynomial terms)
- **Luneberg**
- **Maxwell**
- **Spherical** (polynomial in distance from a point)
- **User-defined GRIN** (via BASIC script)
- **Power Law** (for fiber modeling)

Birefringent and/or Optically Active:

- **Sampled** (as a function of wavelength)

Gluing

Optical elements may be glued together anywhere along their surfaces. **FRED** will determine during the raytrace whether or not the ray trajectory passes into a glued region. (**FRED** has default optical cement with $n_d = 1.5585$, $v_d = 44.6$)

Raytrace Controls

Raytrace controls provide the user with another extremely useful level of control over how rays interact with surfaces. The user may specify the following characteristics at each surface:

Allowed Operations

- Allow/Disallow the reflected specular ray
- Allow/Disallow the transmitted specular ray
- Allow/Disallow Total Internal Reflection (TIR)
- Allow/Disallow a reflected scatter ray
- Allow/Disallow a transmitted scatter ray
- Allow/Disallow an absorbed ray

Power Cutoff Thresholds

- Absolute/Relative transmitted specular ray power
- Absolute/Relative reflected specular ray power
- Absolute/Relative transmitted scatter ray power
- Absolute/Relative reflected scatter ray power
- Absolute/Relative absorbed ray power

Intersection Count Thresholds

- Count of total accumulated ray-surface intersections for a given ray
- Count of consecutive intersections on the same surface for a given ray

Ray Color after Intersecting a Surface

Ray color is set by the source specification. However as an aid to identifying particular ray-surface interactions, the ray color may be changed after encountering a surface. The user can individually specify the color of the transmitted, reflected, diffracted, and/or scattered rays on a surface-by-surface basis.

Parent Ray Specification

Many possibilities occur when a ray strikes a surface. The ray may be transmitted, reflected, scattered, diffracted or any combination of these depending on how the user has specified the surface properties. One of the rays is designated as the parent and all others are designated as children of the parent. The possible parent ray designations are:

- **Ray with the highest power** (default)
- **Reflected ray**
- **Transmitted ray**
- **Monte Carlo** (one ray incident generates one ray out. The output ray is chosen from all possible output rays via statistical probability.)

Ray Ancestry Level Thresholds

Ancestry levels may be set to control the number of generations of descendent specular and scattered rays.

Ray Manipulation Utilities

Rays can be manipulated before, during, or after a raytrace. Each operation can be applied to all or a filtered subset of the rays. Some of the allowed operations are:

- **Propagation by various criteria** (to a point, to a sphere, various distances, etc.)
- **Reverse direction**
- **Redraw ray trajectories** (with ray history file generated by the Advanced Raytrace feature)
- **Activate/Deactivate rays**
- **Ray deletion**
- **Print rays to text output window**
- **Read/Write incoherent ray data from/to text file**
- **Read/Write comprehensive ray data from/to binary file**
- **Write ray intercept data to text file or output window** (with ray history file generated by the Advanced Raytrace feature)

Coherent Scalar Field Synthesis

A user-defined coherent scalar field can be used as the basis for creating coherent raysets. The user controls the size of the coherent rays and their limiting ray angles. This feature can be used for coherent source simulation, spatial filtering, edge clipping, re-sampling, and more.

Raytrace Methods

Sequential/Non-sequential Raytracing

The default raytrace mode in **FRED** is non-sequential, that is, **FRED** determines the trajectory of a ray based upon the system geometry and the ray's initial parameters. However, the user is given the freedom to specify any number of individual sequential and mixed sequential/non-sequential paths to override the default non-sequential mode on a surface-by-surface basis. A Monte Carlo option (see Raytrace Controls) is available and can be specified on a surface-by-surface basis.

FRED stores its rays in a virtual ray buffer that automatically pages rays to disk as needed. The maximum number of rays in **FRED** is limited only available hard disk space.

Multi-threaded CPU Raytracing

Raytracing and analyses are multi-threaded. **FRED** can use a maximum of 17 threads while **FRED Optimum** can use a maximum of 127 threads.

Raytrace Options

FRED has many specialized raytrace options available:

Single Raytrace:

- **User-defined ray in any coordinate system**
- **Select ray from the current rayset**
- **Select ray from a defined source**

User can select and view extensive raytrace information relative to any coordinate system.

Advanced Raytrace:

- **Non-sequential raytrace with search algorithm options or sequential raytrace along a defined path**
- **Specific start/stop surfaces or intersection count raytracing**
- **Trace from sources or trace from buffer options**
- **Ray rendering control during the raytrace**
- **Optional determination of ray paths during the raytrace**
- **Optional suppression of ray scattering during the raytrace**
- **Optional suppression of the raytrace summary**
- **Optional ray history file for redrawing via the Ray Manipulation Utility, Ray Path Summaries, or Stray Light Report dialogs**

Targeted (Hamiltonian) Raytrace:

The user can select starting and ending position or direction coordinates anywhere in the optical model and **FRED** will find the ray trajectory that achieves those coordinates.

Ray Calculation and Analysis

Text-Based Analyses/Reports

- **Find best focus** (best focus position and direction of a set of rays)
- **Ray status** (status summary of all rays)
- **Ray-Surface summary** (surface-by-surface summary of ray count and total power)
- **Ray statistics** (surface-by-surface ray data statistics)
- **Incident/absorbed power** (surface-by-surface ray hit count, incident power, and absorbed power broken down by specular and scatter ancestry)
- **Paraxial calculations along a specified sequential path** (top-level system information [focal length, principal planes, pupils, etc.], paraxial raytrace, third order aberrations)
- **Ray paths** (specific ray trajectories)

- **Fiber coupling** (step-index or gradient index fibers including option to account for Fresnel reflection losses)
- **Automatic importance sampling determination** (computes the solid angle of the designated detector surface relative to specific surfaces; locates and positions importance sampling target; useful for stray light analysis)
- **Stray light report** (lists of specular and/or scatter stray light paths according to various user criteria)
- **Image artifact diagnostic** (lists the contributing raypaths for a region selected directly from the chart viewer for spatial analyses)
- **Entity counts report** (lists a count of each entity type in the model)
- **Entity references reports** (lists all entities that reference, or are referenced by, an entity)
- **Listing of entity positions/orientations** (in global coordinates or any other coordinate system)
- **Individual ray data**
- **List of ray error counts and their associated surfaces**
- **Zernike Wavefront Aberration Coefficients** (computes the Zernike aberration coefficients of a wavefront determined with the *wavefront* option of the *Coherent scalar wave field* described below)
- **Geometric OPD map** (map of geometric optical path differences of the rays)
- **Write intensity to a text file** (in ANSI/IESNA LM-63-2002 format)
- **Spectral Analysis** (analyze the spectral power distribution of a given rayset)
- **Surface Collector Visualization** (collect, display and export incident and/or absorbed power and/or irradiance on arbitrary surface shapes defined by *.OBJ or *.STL files)

Graphics-Based Analyses

- **Positional spot diagram**
- **Directional spot diagram**
- **Polarization spot diagram**
- **Gaussian beam size diagram** (size of coherent Gaussian beamlets)
- **Irradiance distribution** (positional coherent or geometric spread function – power/unit area) – *multi-threaded*
- **Intensity distribution** (directional coherent or geometric spread function – power/unit solid angle)
- **Photometric Illuminance**
- **Coherent scalar wave field** (amplitude, phase, real and imaginary parts, wavefront, etc.) *multi-threaded*
- **Energy density** (power/unit volume) *multi-threaded*
- **True color analysis** (the true color visual appearance of the image)
- **3D spot diagram** (Ray spots drawn in the 3D rendering window)
- **BSDF scatter function** (six different types of 2D and 3D of scatter function plots)
- **Coating characteristics** (Reflection/Transmission plots as a function of angle, wavelength, and/or polarization)
- **Material properties** (refractive index, absorption, etc. as a function of wavelength)
- **Source wavelength weights** (weights as a function of wavelength)

Digitizer - Graphically-Based Data Import

Import rectilinear or polar data from bitmap or other graphics-based file formats. The user can load the graphics file into a dialog and quickly import data with a few simple mouse clicks. This feature is available for:

- **Sampled coating curves**
- **Sampled materials refractive index curves**
- **Source wavelength list weighting**
- **Segmented curves**
- **Detailed source directional power apodization**
- **Detailed source ray direction distribution**
- **Spectra wavelength vs. spectral value**

Keywords

Assigned to any object in the document, keywords provide an additional layer of dynamic model management and configurability on top of the fixed organizational structure provided by the object tree hierarchy.

Visualization

Model geometry is rendered in 3D at all times. Changes to the model are automatically updated in the visualization window with no additional user intervention required. The user has complete control over every aspect of surface visualization. Visualization properties include:

- **Tessellation granularity**
- **Drawing mode** (flat shaded, smooth shaded, irregular wire frame, irregular point sampled, and fast iso-contour wire frame for explicit surface types)
- **Color of the ambient, diffuse, and specular components of surface rendering**
- **Shininess of the specular color component**
- **Opacity of a surface** (amount of transparency)
- **Local coordinate axes**
- **Anamorphic scaling in X,Y,orZ**
- **Cutaway clipping**
- **Object Isolation**
- **MPC Render Mode** allows FRED^{MPC} licenses to view the model using real-time raytracing on the GPUs instead of OpenGL

In addition, the user has quick and convenient control over view direction and position via simple mouse movements, various zooming options, and highlight selection options.

2D Charts

The user can customize every aspect of chart appearance. The user can also zoom or translate via simple mouse/keyboard manipulations. Some additional operations include:

- **View/edit numeric data**
- **Axis label changes**
- **Color scheme**
- **Copy data/graphic image to clipboard**
- **Save graphic to bitmap**
- **Save data to text file**
- **Window lock** (prevents window from auto-closing during certain system model updates)

3D Charts

The user can customize every aspect of the chart appearance. The user can also rotate the surface, zoom, or translate via simple mouse/keyboard manipulations. The visual appearance of the face-on view can be ported to the 3D rendering of the geometry. The user may also open an empty chart to be populated with chart data from a file. Some additional operations include:

- **Toggle perspective/face-on view mode**
- **Toggle the display of ceiling/floor contour plots**
- **Toggle flat rectangular pixel cell view mode**
- **Axis label changes**
- **Color scheme**
- **Compute data statistics**
- **Copy data/graphic image to clipboard**
- **Save graphic to bitmap**
- **Save data to text file**
- **Data Scaling** (normalization, raise to a power, log, etc.)
- **Data modification** (smoothing, truncation, etc.)
- **Complex Fourier transform**
- **Combine dataset with other datasets**
- **Encircled/Ensquared data**
- **Window lock** (prevents the window from auto-closing during certain system model updates)

BASIC Script Language

FRED's sophisticated built-in scripting development environment supports keyword highlighting and syntax assistance. **FRED** has an integrated BASIC compiler that implements its scripting language with over 2000+ commands. **FRED**'s modern and powerful implementation of the BASIC language supports modules, projects, user-defined libraries, and global variables that can be accessed from within any script. Users can write scripts that create/modify system geometry, sources, coatings, scatter models, etc., as well as perform raytracing and calculations. An Embedded Script Folder in the Tree offers the convenience of storing scripts within a **FRED** document. These scripts can be edited and executed during a simulation.