Orbital Contact Analyzer — User Manual

Version:v1.0.0
Scope: Single-file, offline HTML app for simulating two Earth satellites and a ground station. The application uses a J2 perturbation model, renders 2D/3D views, visualizes sensor footprints and local horizons, and computes both satellite-to-satellite line-of-sight (LOS) and satellite-to-ground-station access intervals.

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1) Overview

This app propagates two satellites using a model that includes J2 secular perturbations, converts positions between ECI and ECEF frames, and visualizes:

- **2D Map** (equirectangular) with ground tracks, current markers, optional sensor footprints (FOV), optional local horizons, and communication links.
- **3D Globe** (WebGL) with full camera control, physically correct inertial and Earth-fixed views, a full-screen "Focus Mode", and an optional Head-Up Display (HUD) showing live orbital elements.
- **Data Tables** for both Inter-Satellite LOS and Ground Station Access intervals, with a single-click CSV export for all contact data.

Key design choices:

- **J2 Perturbed propagation:** Includes secular effects on RAAN (Ω) and Argument of Perigee (ω).
- **Spherical Earth model:** Used for all ground geometry, occlusion checks, and footprint calculations.
- **Physically Correct Inertial View:** In 3D, enabling "Inertial View" fixes the orbital planes in space and shows the entire Earth system (globe, terminator, footprints, station) rotating correctly underneath.
- **Global Epoch:** The simulation timeline is anchored to a single, user-defined UTC epoch.

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2) System Requirements

- A modern desktop browser with **WebGL** enabled (Chrome, Edge, Firefox, Safari).
- 8+ GB RAM recommended for long timelines or small time steps.
- Runs fully offline; no external network access is required.

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3) Concepts in Brief

- **Orbital Elements (per satellite):**
  a (km), **e**, **i (deg)**, **Ω RAAN (deg)**, **ω argp (deg)**, **ν_0 (deg)** (true anomaly at the global epoch), and **Min. elevation ε (deg)** to define the sensor footprint.
- **Ground Station:** A point on the Earth's surface defined by **Latitude**, **Longitude**, and a **Min. Elevation Mask (deg)** used to calculate access.
- **J2 Perturbations:** The application models the primary secular (long-term) effects of Earth's equatorial bulge, which causes the orbital plane (Ω) and the orbit's orientation within that plane (ω) to precess over time.

- **Frames:**
  ECI (Earth-Centered Inertial) for orbital dynamics; **ECEF** (Earth-Centered Earth-Fixed) for longitudes/latitudes and surface overlays.
- **Sensor Footprint (FOV):** The circular area on the Earth's surface visible to a satellite, defined by the minimum elevation angle (ε) from the ground to the satellite.
- **Local Horizon:** The physical limit of visibility from the satellite to the Earth's limb (a 0° elevation angle), appearing as a solid circle on the map/globe.
- **Inter-Satellite LOS:** A direct line-of-sight exists if the straight line connecting the two satellites is not obstructed by the spherical Earth.
- **Ground Station Access:** Access occurs when the elevation angle from the ground station up to a satellite is greater than the station's specified minimum elevation mask.

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4) Quick Start

1. **Open** the HTML file in your browser.
2. In **Simulation Controls**, set the **Epoch (UTC, ISO-8601)**, **Step Δt (s)**, and **Duration (min)**.
3. Configure orbital elements for **Satellite 1** and **Satellite 2**. Set the **Min. elevation ε (deg)** to define the sensor footprint (FOV).
4. Configure the **Ground Station** by setting its Latitude, Longitude, and Min. Elevation Mask.
5. Click **Recompute tracks**. Then click ▸ **Run** to animate.
6. Use the **Projection** dropdown to toggle between the 2D Map and 3D Globe.
7. For a larger view, click the **Focus Mode (`↗`)** button on the top-right of the map.
8. Observe the **Line-of-Sight** and **Ground Station Access** tables. Click **Export Contact Times (CSV)** to save all data.

> **Tip:** If nothing moves, verify the **epoch** format, ensure **duration** > 0, and click **Recompute tracks** again.

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5) Controls Reference

5.1 Simulation Controls (top-left)

- **Epoch (UTC, ISO-8601):** Global start; valid ISO string like `YYYY-MM-DDThh:mm:ssZ`.
- **Step Δt (s):** Simulation step. Smaller is more precise but computationally slower.
- **Duration (min):** Total span simulated from the epoch.
- **Playback speed:** Visual playback rate when running.
- **Buttons:**
  - ▸ **Run / Pause:** Start/stop time stepping.
  - ↺ **Reset:** Rewind to the epoch (keeps current inputs).
  - **Recompute tracks:** Re-runs the simulation with the current inputs.
  - **Export Contact Times (CSV):** Saves a CSV file with all computed LOS and GS Access intervals.

5.2 Satellite Panels

Satellite 1 (blue) and **Satellite 2 (orange)** each include:

- **a, e, i, Ω, ω, ν_0:** Standard classical orbital elements. **ν_0** is the true anomaly at the global epoch.
- **Min. elevation ε (deg):** The elevation angle from the edge of the ground footprint up to the satellite. This defines the size of the dashed FOV circle.
- **Visibility Toggles:** Independent controls to show/hide the Satellite marker, its Track, its FOV circle, and its Horizon circle.

5.3 Ground Station Panel

- **Show Ground Station:** Toggles visibility of the station and enables access calculations.
- **Latitude (°):** Station latitude (-90 to 90).
- **Longitude (°):** Station longitude (-180 to 180).
- **Min Elev. Mask (°):** The minimum elevation angle required for a satellite to be considered “in view” of the station.

5.4 View Controls (right-side card)

5.4.1 View Header

- **Projection:** Toggles between **2D Map** and **3D Globe** visualizations.
- **Focus Mode (`↗`):** Click to expand the view to fill the entire browser window for immersive analysis or presentations. The button icon changes to `↙`; click again to exit.

5.4.2 3D Globe Controls

- **Reset camera:** Re-centers and re-zooms the globe to frame the orbits.
- **Focus: None | Sat 1 | Sat 2**. Automatically follows the selected satellite. Disables free-look mouse rotation.
- **Show terminator:** Toggles the day/night shading on the globe.
- **Show link on LOS:** Toggles the visibility of the green line connecting satellites when they have line-of-sight.
- **Inertial view:**
  - **ON:** A physically correct inertial view. Orbital tracks are fixed in space while the Earth and all surface overlays (terminator, footprints, ground station) rotate underneath.
  - **OFF:** A standard Earth-fixed (ECEF) view where the camera rotates with the Earth.
- **Show Elements:** Toggles the visibility of a Head-Up Display (HUD) in the top corners of the view. The HUD displays key orbital elements for each satellite. The values for `a`, `e`, and `i` are static, while **Ω (RAAN)** and **ω (ArgP)** are updated in real-time to show the live effects of J2 perturbations.
- **Trail (min):** Limits the length of the orbital trail drawn behind each satellite to the specified number of past minutes.

5.4.3 Data Tables

Two tables are populated after clicking **Recompute tracks**:

- **Line-of-Sight Intervals:** Lists all time windows where the two satellites have a direct, unobstructed line of sight.
- **Ground Station Access Intervals:** Lists all time windows where a satellite is above the ground station’s minimum elevation mask.

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6) How The Physics Works (succinct)

- **Orbit propagation:** Two-body Keplerian motion with J2 secular perturbations applied to RAAN (Ω) and Argument of Perigee (ω) at each time step.
- **ECI↔ECEF:** Standard transformation using Greenwich Mean Sidereal Time (GMST) for Earth’s rotation.
- **Footprint (FOV):** The user’s **Min. elevation ε** is converted to a sensor half-angle (η) via the sine rule: η = arcsin((R_E * cos(ε)) / (R_E + h)). This angle defines the cone that creates the footprint circle on the surface.

- **Horizon:** Calculated as the physical limit of sight, where the elevation angle ε is 0°. The angular radius is $\eta = \arccos(R\_E / (R\_E + h))$.
- **LOS test:** Checks if the straight-line segment between the satellites' ECI positions intersects the Earth's spherical body.
- **GS Access test:** Calculates the elevation angle of the satellite relative to the ground station's local horizon. Access is true if this angle exceeds the station's **Min. Elevation Mask**.

Constants: Earth ($\mu = 398600.4418\ km^3/s^2$); Earth radius (R_E = 6378.137 km); J2 = 1.0826267e-3.

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7) Typical Workflows

A) Visualize a Sun-Synchronous Orbit

1. Set elements for a typical SSO (e.g., `a=7078 km`, `e=0.001`, `i=98 deg`).
2. Set a long **Duration** (e.g., `1440 min` for one day). **Recompute tracks**.
3. Switch to **3D Globe** and enable **Inertial view**. In the 3D controls, check **Show Elements**.
4. Scrub the timeline and observe that the orbital plane maintains its orientation relative to the Sun. Notice in the HUD that the value for **Ω (RAAN)** precesses slowly while other elements remain relatively stable, numerically confirming the SSO behavior.

B) Follow one satellite in inertial space

1. Switch **Projection=3D Globe**; enable **Inertial view**.
2. Set **Focus=Sat 1**.
3. The camera will now "chase" Sat 1's ECI position, keeping it centered while the Earth rotates underneath.

C) Extract all contact times

1. Configure both satellites and the ground station. **Recompute tracks**.
2. The **Line-of-Sight** and **Ground Station Access** tables will populate.
3. Click **Export Contact Times (CSV)** to save a single file containing both data sets, distinguished by a "type" column.

D) Conduct a presentation

1. Set up the desired scenario and click **Recompute tracks**.
2. Click the **Focus Mode (`↗`)** button to expand the visualization to full screen.
3. Use the scrub bar and playback controls to narrate the simulation. Click `↙` to exit.

7.1 Suggested Time Steps

- **LEO:** Δt = **1–10 s**, Duration = **60–120 min**
- **MEO:** Δt = **10–30 s**, Duration = **1–6 h**
- **GEO:** Δt = **30–60 s**, Duration = **12–24 h**
  Large Δt can visually alias fast motion; reduce Δt for close inspection.

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8) Simulation Fidelity & Limitations

This application is designed as an educational tool, a demonstration platform, and for first-order analysis. It prioritizes interactivity, speed, and the clear visualization of core orbital mechanics concepts. To achieve this, several simplifying assumptions are made. For mission-critical analysis, always use a high-fidelity, validated simulation suite.

8.1 J2 Dynamics Model

The J2 model is a significant improvement over simple two-body physics, as it correctly models the long-term precession of the orbit due to Earth's equatorial bulge. However, it does **not** include other major orbital perturbations, such as:

- **Atmospheric Drag:** Orbits will not decay; altitude and eccentricity remain constant. This is the largest source of error for LEO satellites.
- **Solar Radiation Pressure (SRP):** The small force exerted by sunlight is not modeled.
- **Third-Body Gravity:** Gravitational effects from the Moon, Sun, and other planets are ignored.
- **Higher-Order Gravity Fields:** Does not account for Earth's non-uniform mass distribution beyond the J2 term (e.g., tesseral harmonics).

8.2 Spherical Ground Model

All calculations involving the Earth's surface assume a perfect sphere. This simplification has the following consequences:

- **No Earth Oblateness:** The model does not use a standard ellipsoid (like WGS-84). This can introduce small errors in ground track position and access calculations. Geodetic vs. geocentric latitudes are not distinguished.
- **No Terrain:** Ground station access calculations do not account for local terrain (mountains, valleys) that could block visibility in the real world.

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9) Troubleshooting

- **Can't rotate the globe?** Check if **Focus** is set to Sat 1 or Sat 2. Set it to **None** to enable free-look camera controls.
- **Nothing moves / index stuck at 0:** Verify **Epoch** format; ensure **Duration** > 0; click **Recompute tracks**.
- **Blank screen when switching views:** This can happen during rapid layout changes. Try toggling Focus Mode again or resizing the browser window to force a redraw.
- **No footprints:** Ensure **Show FOV=Yes**. At very high altitudes, the sensor cone may not intersect the Earth.

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10) Release Notes (Frame Edition Draft)

This version represents a major upgrade from a simple two-body visualizer to a more capable analysis tool. Key highlights include:

- **J2 Dynamics:** The propagator now includes J2 secular perturbations for more realistic long-term orbital precession.
- **Ground Station:** A fully configurable ground station has been added, with calculations and data export for satellite access times.
- **Physically Correct 3D View:** The "Inertial View" has been completely overhauled to correctly show the Earth rotating underneath fixed ECI orbits. All coordinate frames are now handled correctly in all

views.

- **“Focus Mode” UI:** The new `↗` button expands the visualization to fill the entire browser window for immersive analysis and presentations.
- **Live Elements HUD:** A new Head-Up Display can be toggled in the 3D view to show live, propagated orbital elements (Ω and ω), making the effects of perturbations easy to see numerically.
