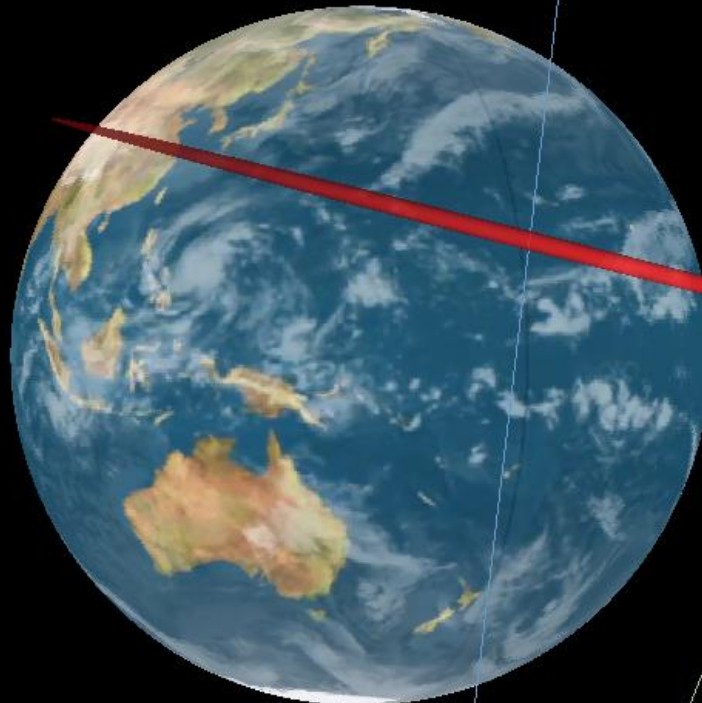


Assessing GEO Close Encounter Warnings for Spacecraft Operations

INTERNATIONAL WORKSHOP ON SPACE DEBRIS MANAGEMENT AND MITIGATION

November 9, 2018

Space Environment Research Centre Ltd., Weston Creek, Australia



Main Contributors

Thomas La

Nathaniel McGrawth

Dr. Sven Flegel

Outline

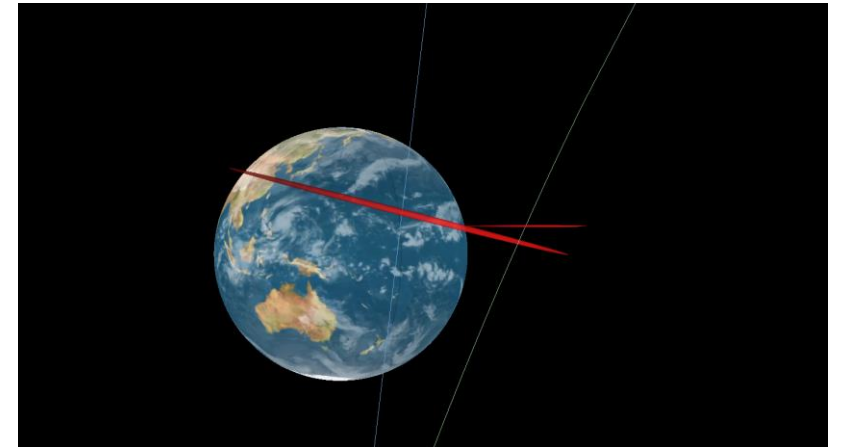
- Fundamentals

- Visualisation

- Assessment

- Example Applications

New Tool developed at SERC



Conclusions from [Flegel, 2017 - International Astronautical Congress 2017]

GEO Encounters

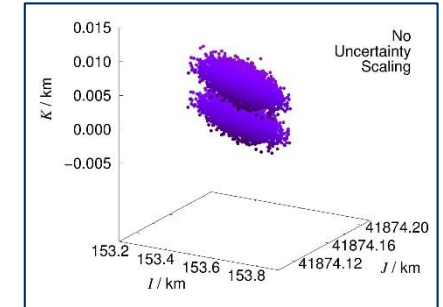
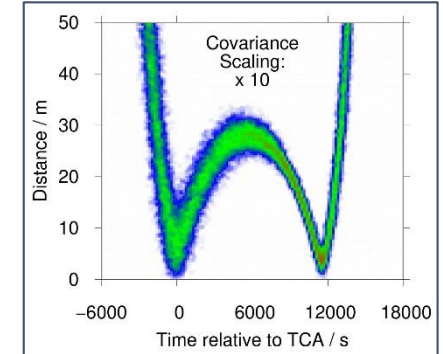
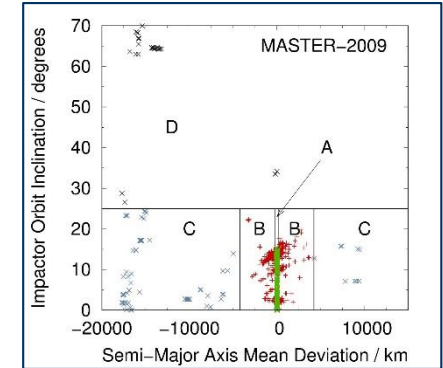
- Majority of GEO Close Encounters with GEO Libration (~61 %) and GEO Drift (~36 %) Objects
- $\Delta v_{\max} \sim 3 \text{ km/s}$ & $\Delta v_{\min} < 1 \text{ m/s}$

Collision Likelihood Metrics

Metric	Pro	Con
Collision Probability	Accounts for uncertainty	Abstract
Miss Distance	Insight into event	Single value no account of uncertainty
Conflict Probability	<i>Not studied here</i>	

State Uncertainty Accuracy

- Idea: **Status** of collision likelihood metric should not be changed due to residual error
- Requirement difficult to impose in face of hard to predict perturbations which affect state & uncertainty during prediction span



Conclusions from [Flegel, 2017 - International Astronautical Congress 2017]

GEO Encounters

- Majority of GEO Close Encounters with GEO Libration (~61 %) and GEO Drift (~36 %) Objects
- $\Delta v_{\max} \sim 3 \text{ km/s}$ & $\Delta v_{\min} < 1 \text{ m/s}$

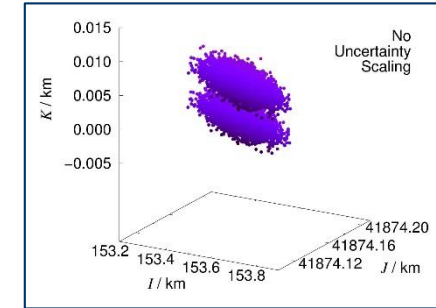
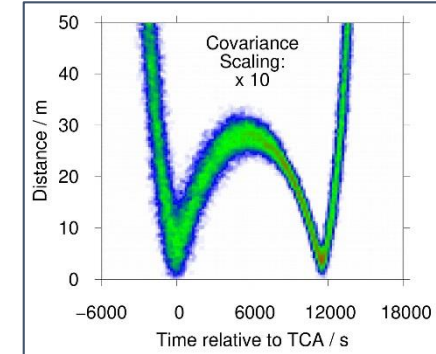
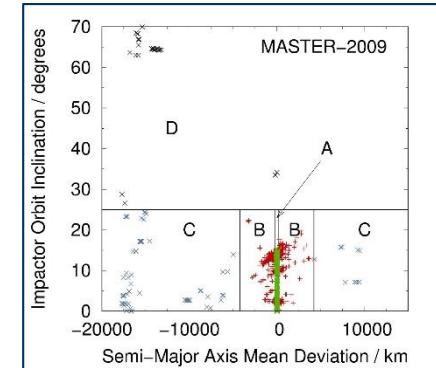
Collision Likelihood Metrics

Metric	Pro	Con
Collision Probability	Accounts for uncertainty	Abstract
Miss Distance	Insight into event	Single value no account of uncertainty
Conflict Probability	Not studied here	

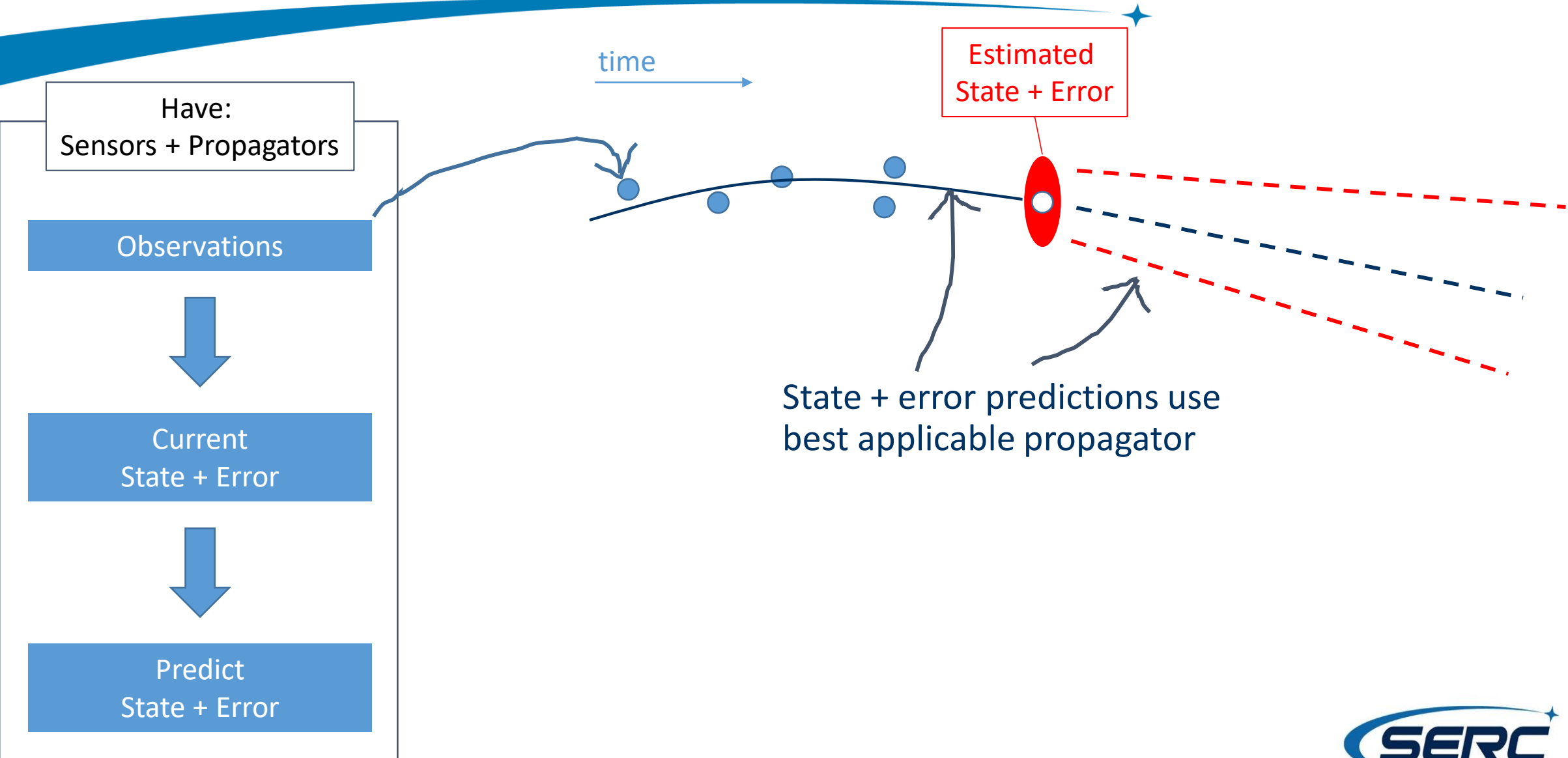
State Uncertainty Accuracy

- Idea: Status of collision likelihood degraded due to residual error
- Requirement difficult to implement due to perturbations which affect state & uncertainty during prediction

Uncertainty can be included



Fundamentals



Conjunction Data Messages

```

CCSDS_CDM_VERS      =1.0
COMMENT              =CDM_ID:1579154
CREATION_DATE        =2016-02-24T03:16:29
ORIGINATOR           =JSPOC
MESSAGE_FOR          =LEO SAT 1
MESSAGE_ID           =99999_conj_99998_2016056082403_05503
COMMENT MEETS EMERGENCY CRITERIA
TCA                  =2016-02-25T08:24:03.742
MISS_DISTANCE        =254 [m]
RELATIVE_SPEED       =4088 [m/s]
RELATIVE_POSITION_R  =128.7 [m]
RELATIVE_POSITION_T  =-211.6 [m]
RELATIVE_POSITION_N  =59.9 [m]
RELATIVE_VELOCITY_R  =8.3 [m/s]
RELATIVE_VELOCITY_T  =-1120.5 [m/s]
RELATIVE_VELOCITY_N  =-3932 [m/s]
COLLISION_PROBABILITY =4.306701e-05
COLLISION_PROBABILITY_METHOD =FOSTER-1992
OBJECT               =OBJECT1
OBJECT_DESIGNATOR    =99999
CATALOG_NAME         =SATCAT
    
```

General Situation Information

[...]

[...]

```

OBS_AVAILABLE      =246
OBS_USED           =245
RESIDUALS_ACCEPTED =99.8 [%]
WEIGHTED_RMS       =1.109
COMMENT Apogee Altitude = 807 [km]
COMMENT Perigee Altitude = 804 [km]
COMMENT Inclination = 98.5 [deg]
AREA_PC            =0.3084 [m**2]
CD_AREA_OVER_MASS  =0.026403 [m**2/kg]
CR_AREA_OVER_MASS  =0.01192 [m**2/kg]
THRUST_ACCELERATION =0 [m/s**2]
SEDR              =-2.8288e-05 [m/kg]
X                  =504.999523 [km]
Y                  =1001.351516 [km]
Z                  =7094.906152 [km]
X_DOT              =7.446012163 [km/s]
Y_DOT              =-1.026940851 [km/s]
Z_DOT              =-0.383622809 [km/s]
CR_R               =72.84517 [m**2]
CT_R               =10.78702 [m**2]
CT_T               =1206.212 [m**2]
CN_R               =1.219566 [m**2]
CN_T               =-5.165142 [m**2]
CN_N               =19.36692 [m**2]
CRDOT_R            =-0.008242773 [m**2/s]
CRDOT_T            =-1.183242 [m**2/s]
CRDOT_N            =0.00225296 [m**2/s]
CRDOT_RDOT        =0.001206133 [m**2/s**2]
CTDOT_R            =-0.07541054 [m**2/s]
    
```

[...]

Object 1 position & Velocity



SERC Tool for close approach assessments

Simple formatting already provides better readability

```
Analyze CDM About
COMMON DATA
CCSDS_CDM_VERS = 1.0
COMMENT = CDM_ID:1579154
CREATION_DATE = 2016-02-24T03:16:29
ORIGINATOR = JSPOC
MESSAGE_FOR = LEO SAT 1
MESSAGE_ID = 99999_conj_99998_2016056082403_055034008986f
COMMENT MEETS EMERGENCY CRITERIA
TCA = 2016-02-25T08:24:03.742
MISS_DISTANCE = 254 [m]
RELATIVE_SPEED = 4088 [m/s]
RELATIVE_POSITION_R = 128.7 [m]
RELATIVE_POSITION_T = -211.6 [m]
RELATIVE_POSITION_N = 59.9 [m]
RELATIVE_VELOCITY_R = 8.3 [m/s]
RELATIVE_VELOCITY_T = -1120.5 [m/s]
RELATIVE_VELOCITY_N = -3932 [m/s]
COLLISION_PROBABILITY = 4.306701e-05
COLLISION_PROBABILITY_METHOD = FOSTER-1992

OBJECT 1 DATA
OBJECT = OBJECT1
OBJECT_DESIGNATOR = 99999
CATALOG_NAME = SATCAT
```



Visualisation

Orbits in ECI

High accuracy propagation
for states and errors at
Time of Closest Approach (TCA)

Lower fidelity propagation
for visualisation/assessment
around TCA

The screenshot displays a software interface for satellite visualization. At the top, there are three tabs: "Analyze", "CDM", and "About". Below the tabs are two small icons: a globe and a satellite. A "Load CDM" button is positioned below these icons.

The interface is divided into several sections on the left side:

- Orbit Frame:** A dropdown menu set to "ECI".
- Camera Focus:** A dropdown menu set to "Earth".
- Draw Elements:** A list of checkboxes:
 - Coordinates
 - Orbits
 - Error Volume
 - Error Axes
 - Satellite Marker
 - To Other
- Satellite Properties:**
 - Orbit type: "GEO_EQUATORIAL"
 - Diameter [m]: "10.000" (with up/down arrows)
 - Orbit type: "GEO_INCLINED"
 - Diameter [m]: "10.000" (with up/down arrows)
- Position Uncertainty:**
 - Confidence [%]: "95.000" (with up/down arrows)

At the bottom left, there are three control buttons: a green play button, a blue square stop button, and a blue circular refresh button. Below these buttons is a horizontal timeline slider with a white marker.

The main visualization area on the right shows a 3D model of Earth with a satellite orbiting it. The satellite is represented by a red triangle on the orbit. The orbit is shown as a green elliptical path. The background is black with a grid of blue lines. In the top right corner of the visualization area, the "SERC" logo is displayed. Below the logo, the following data is shown:

- Time from TCA [s]: 0.00
- Range [km]: 0.000619561
- Rel. Velocity [km/s]: 0.802656

At the bottom of the visualization area, there is a circular timer showing "+/- 3:50:0.0" and a horizontal timeline slider with a white marker.

Visualisation

Orbits in ECEF

Orbits in geostationary
better understood
in Earth co-rotating frame

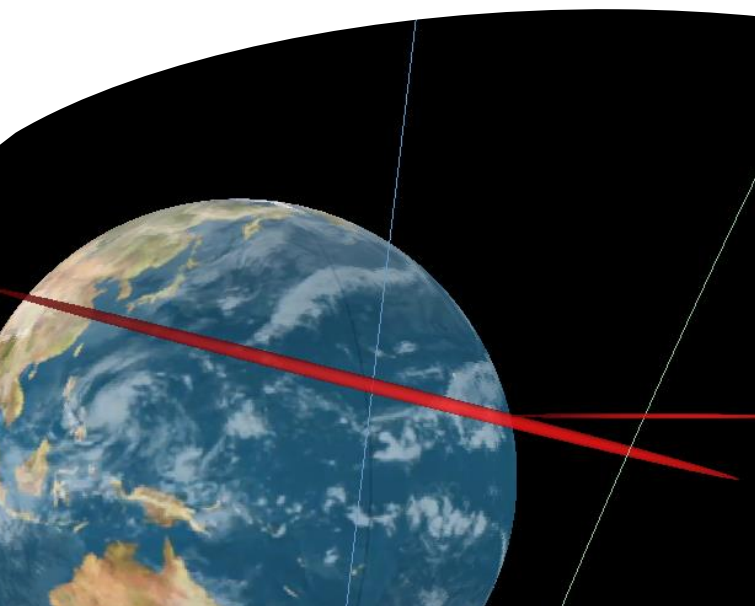
The screenshot displays a satellite simulation interface with the following components:

- Navigation:** 'Analyze', 'CDM', and 'About' buttons at the top.
- Visual Aids:** Two small icons (Earth and a V-shaped orbit) and a 'Load CDM' button.
- Configuration:** 'Orbit Frame' set to 'ECEF' and 'Camera Focus' set to 'Earth'.
- Draw Elements:** A list of checkboxes for 'Coordinates', 'Orbits', 'Error Volume', 'Error Axes', 'Satellite Marker', and 'To Other', all of which are checked.
- Satellite Properties:** 'GEO_EQUATORIAL' and 'GEO_INCLINED' orbit types, both with a diameter of 10.000 m.
- Position Uncertainty:** 'Confidence [%]' set to 95.000.
- Playback:** Play, stop, and refresh buttons, along with a progress slider.
- Real-time Data:** A panel on the right showing 'Time from TCA [s]: 0.00', 'Range [km]: 0.000619561', and 'Rel. Velocity [km/s]: 0.802656'.
- Visualization:** A central 3D view of Earth with a satellite marker and a large, vertically oriented elliptical orbit path. The SERC logo is in the top right of this view.
- Time Control:** A circular timer showing '+/- 0:10:0.0' and a horizontal slider for time navigation.



Visualisation

Position Uncertainties

Back-Bone of
collision likelihood
estimations



Analyze CDM About

Load CDM

Orbit Frame
ECI

Camera Focus
LEOSAT2

Draw Elements




- Coordinates
- Orbits
- Error Volume
- Error Axes
- Satellite Marker
- To Other

Satellite Properties


LEOSAT1
Diameter [m]: 10.000

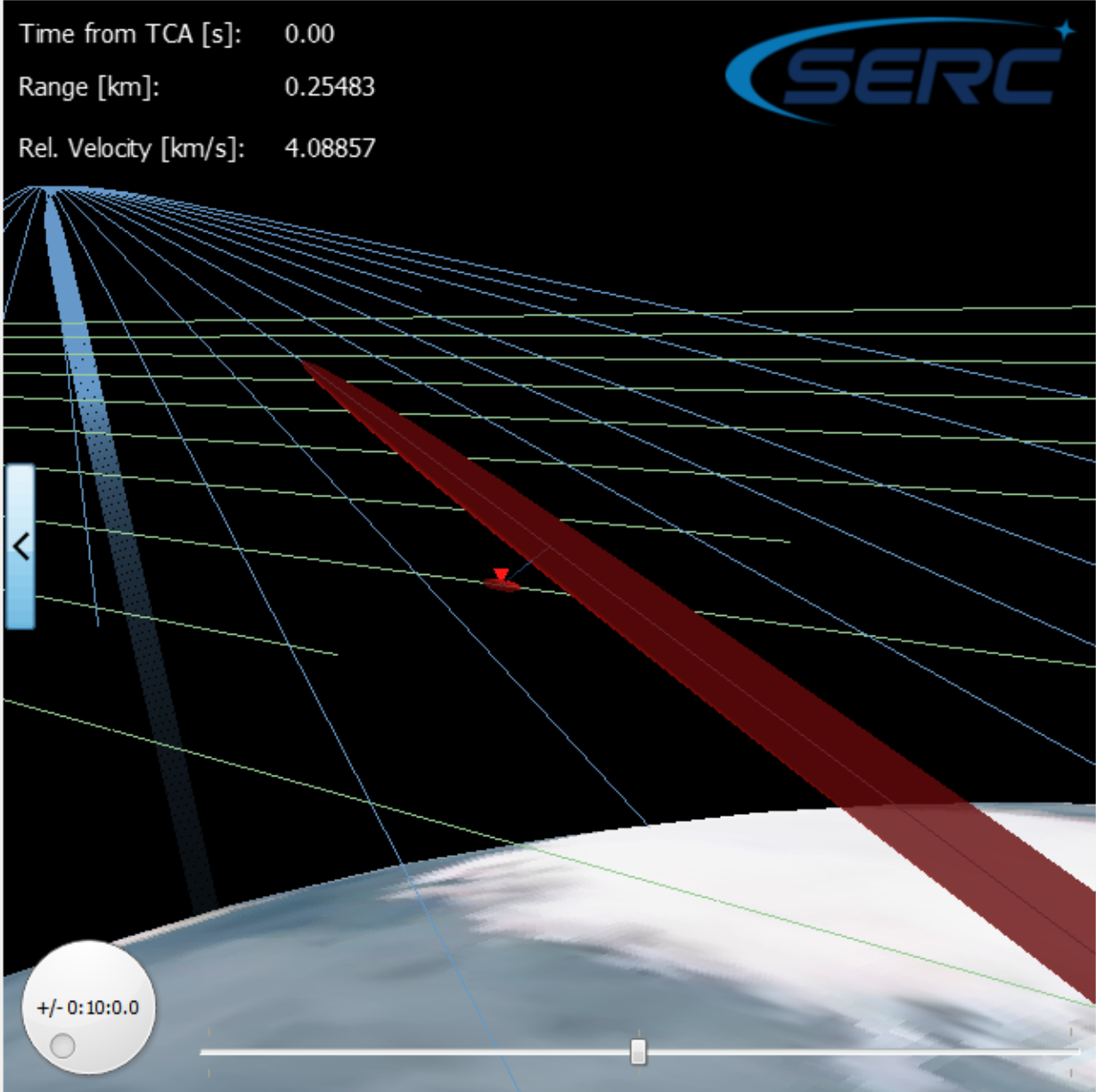
LEOSAT2
Diameter [m]: 10.000

Position Uncertainty
Confidence [%]: 55.000

Time from TCA [s]: 0.00
Range [km]: 0.25483
Rel. Velocity [km/s]: 4.08857





<

+/- 0:10:0.0

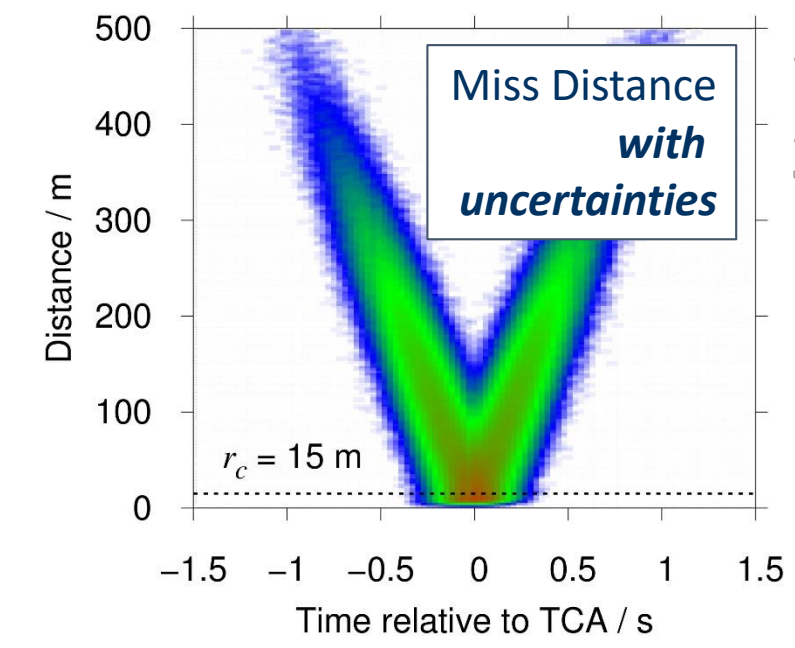
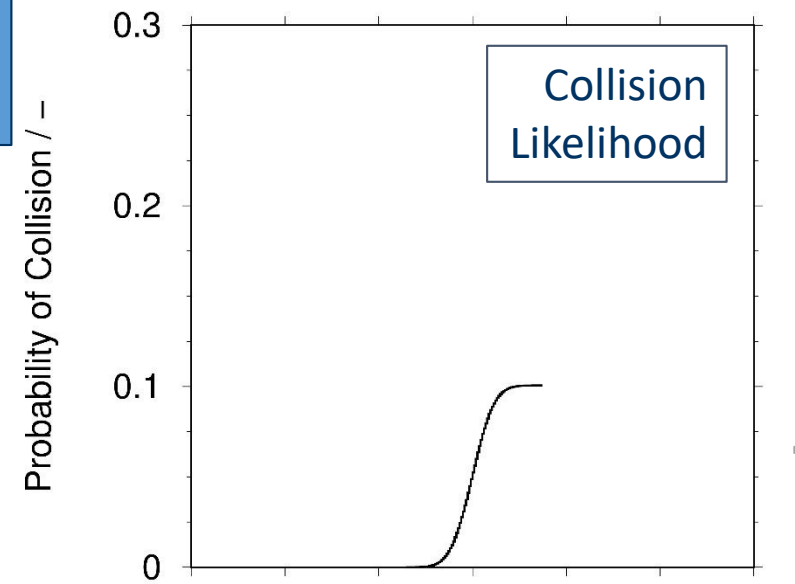
Analysing a Scenario Next Up ...

The screenshot shows a software interface with three tabs: 'Analyze', 'CDM', and 'About'. Below the tabs are two icons: a globe and a V-shaped plot. The 'Analysis Methods' section has three checkboxes: 'Random Particles' (checked), 'Foster' (unchecked), and 'Patera' (unchecked). A large red 'DRAFT' watermark is overlaid on the interface. Below this, there are input fields for 'Random Particles', 'Sample Size' (set to 100000000), and 'Monte-Carlos' (set to 1). There are also input fields for 'Foster' and 'Patera'. At the bottom is a 'Run Analysis' button with a green play icon.

Visual support
e.g.

Additional Data & Features:

- Collision likelihood
- Time of highest collision likelihood
- Particle method allows non-Gaussian state errors
- Efficient testing for state error Gaussianity
- Recommendation of applicable methods
- Manual sensitivity analysis
- Compare different methods



[Flegel, IAC 2017]

Summary & Outlook



New SERC tool provides ...

- Easy viewing of **legacy Conjunction Data Messages**
- **Visual** of close approach
- State uncertainty **with confidence**
- Various visual cues and help functions (e.g. play / reset..)

New features coming soon ...

- Collision likelihood assessment using different methods
- More close approach meta-data
- Graphs
- Test for Gaussianity of Error around TCA



serc.org.au

info@serc.org.au



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Australian Government
Department of Industry,
Innovation and Science

Business
Cooperative Research
Centres Programme



Load CDM

Orbit Frame

ECI

Camera Focus

Earth

Draw Elements

- Coordinates
- Orbits
- Error Volume
- Error Axes
- Satellite Marker
- To Other

Satellite Properties

N/A

Diameter [m]: 10.000

N/A

Diameter [m]: 10.000

Position Uncertainty

Confidence [%]: 95.000



Time from TCA [s]: N/A

Range [km]: N/A

Rel. Velocity [km/s]: N/A

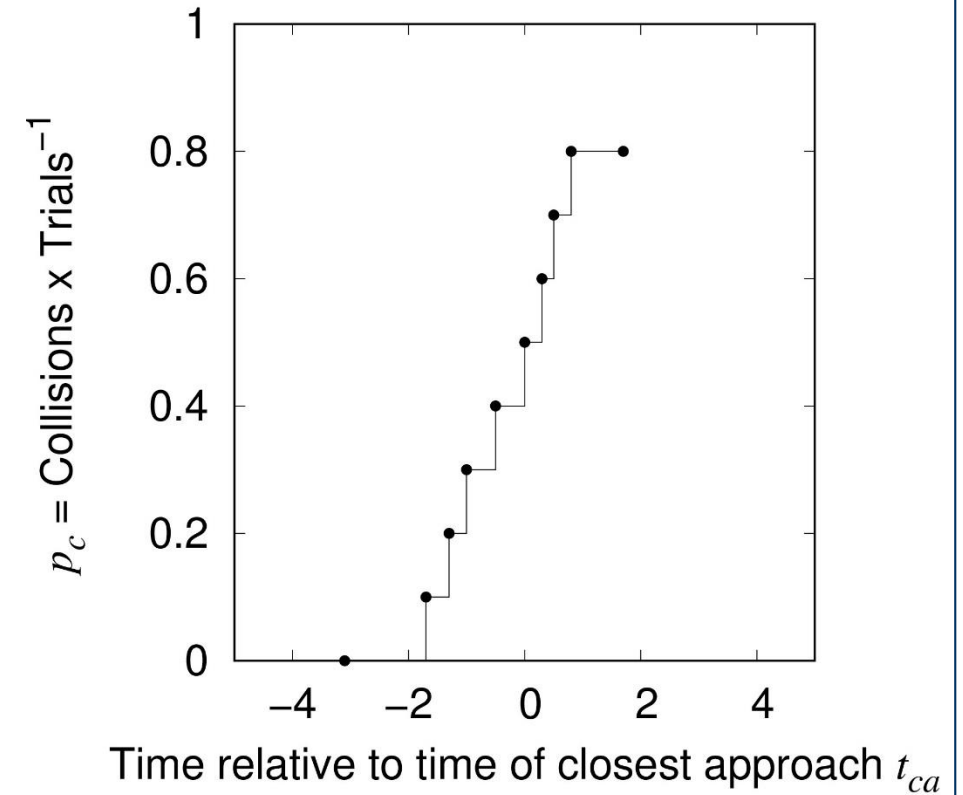
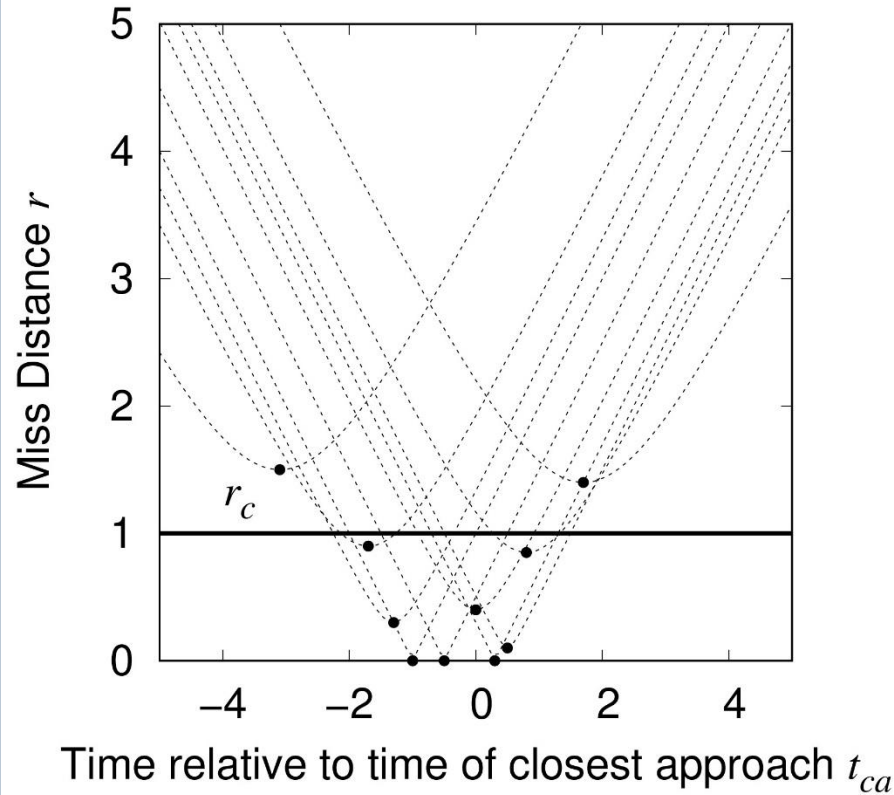
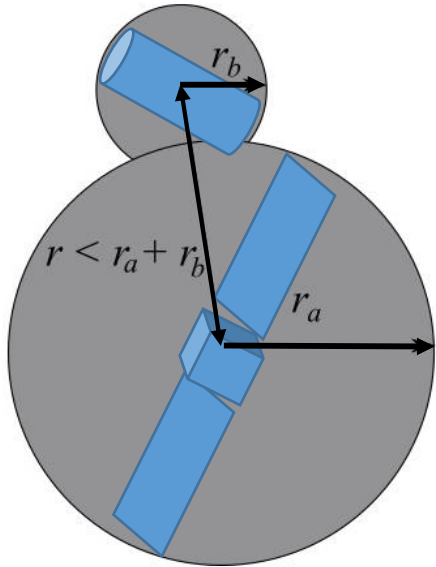


Particle Method Fundamentals

Condition for Collision:

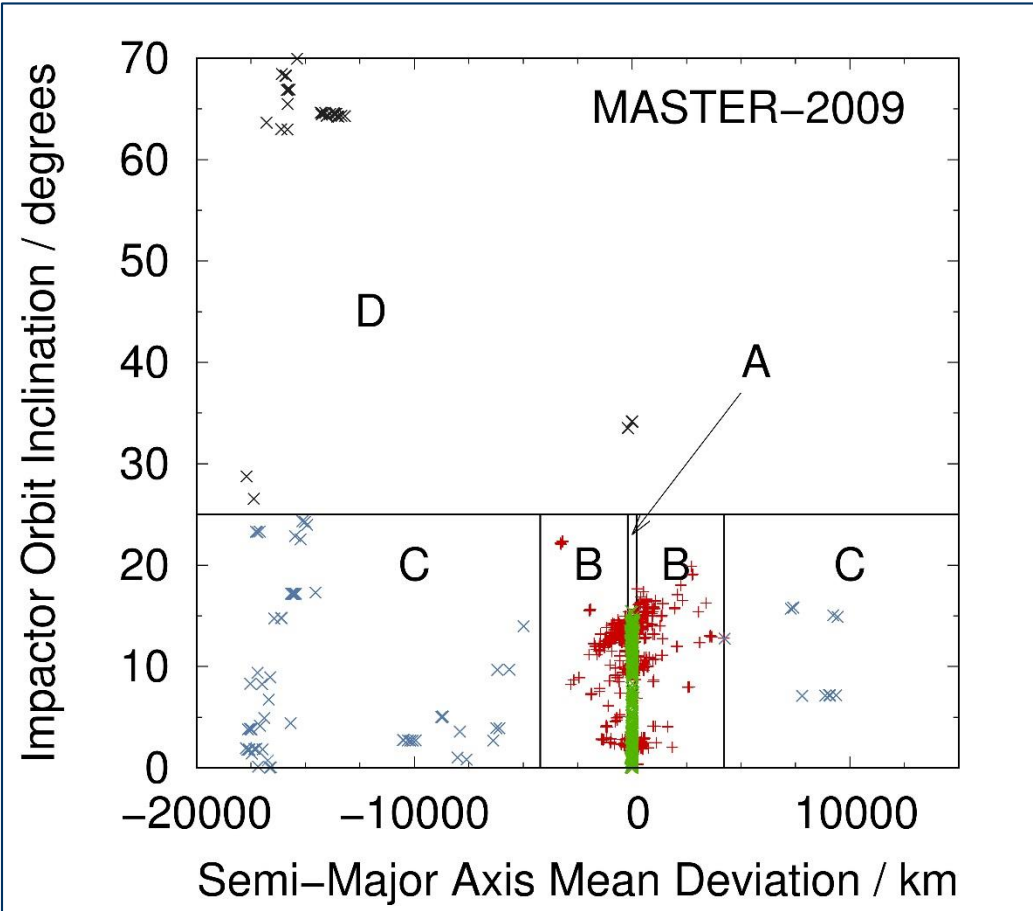
$$r < r_c$$

(r_c = combined
hardbody radius)



- Both objects considered spheres
- Collision Probability determined from number of particle pairs with $r < r_c$
- Results vary between samples
- Result only informative in combination with valuation of its variability (Central Limit Theorem, Chernoff-Hoeffding bound / Dagum bound)

GEO Encounters Characteristics

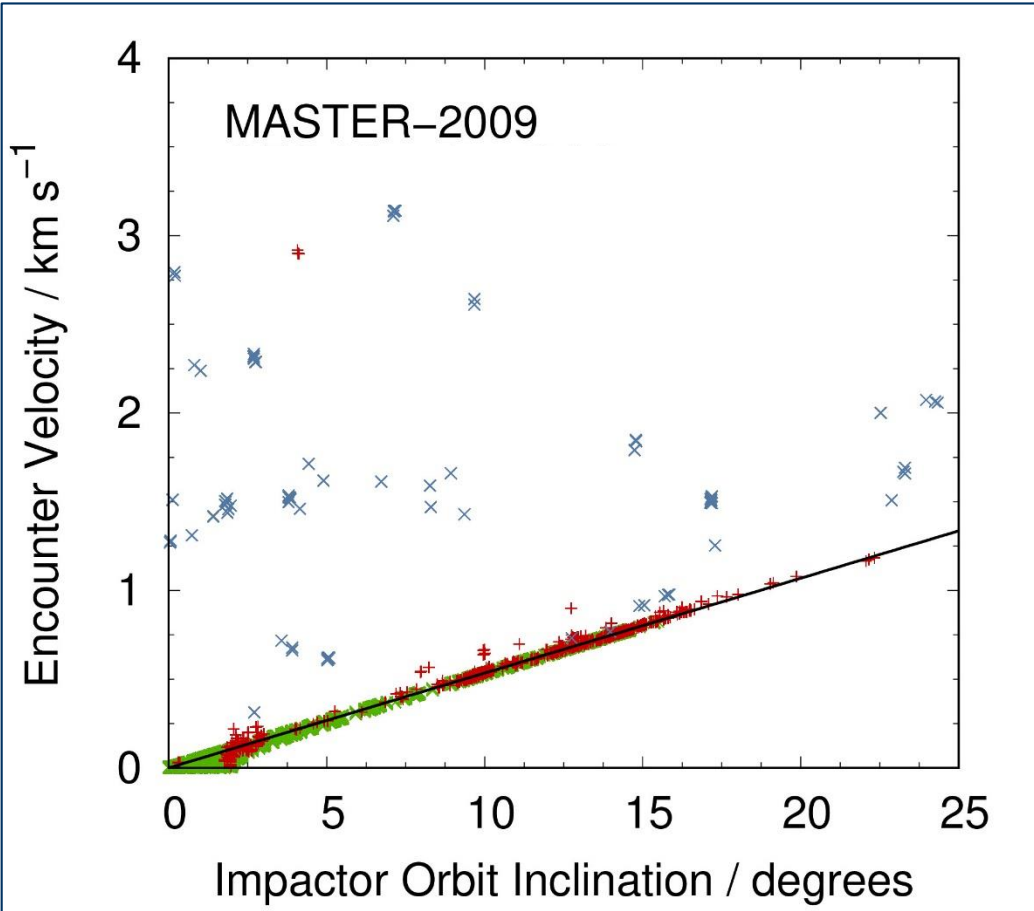


GEO Libration
61 %

GEO Drift
36 %

GEO Transient
2 %

Inclined
1 %



Encounter Velocities

- GEO Libration: generally < 1 km/s; as low as < 1 m/s
- GEO Drift: generally < 1 km/s
- GEO Transient & Inclined: generally > 1 km/s