National Aeronautics and Space Administration

Developing an Alternative to the Problematic Trajectory B-Plane

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Program: Innovative Spontaneous Concepts

Project Objectives:

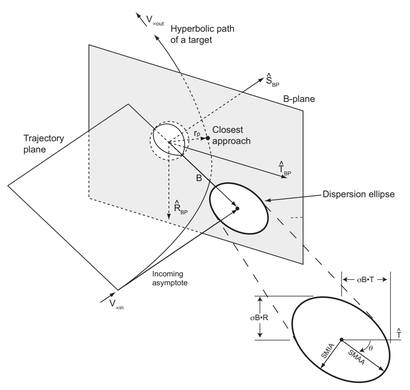
Navigators and maneuver designers have used the "B-Plane" successfully for decades. But there continue to be issues with using it inconsistently or incorrectly.

- **Document the problems with using the B-Plane**
- **Research and develop possible alternatives**
- **Evaluate alternatives in mission scenarios**

FY19 Results:

1. **Documented the benefits and detriments of using the B-Plane**
2. **Developed candidate coordinate frames (2 new, 1 adapted)**
3. **Assessed candidates against actual mission scenarios**
4. **Neared completion of a technical paper**

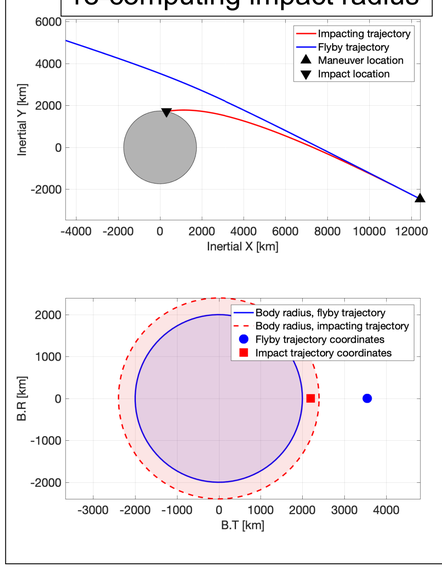
The B-Plane



Why is the B-Plane used?

- Convenient mapping from 3D to 2D
- Linear relationship with maneuver ΔVs
- Simplifying assumptions are often benign
- Long history of successful usage

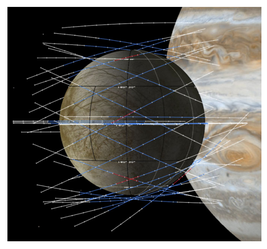
The perils of not re-computing impact radius

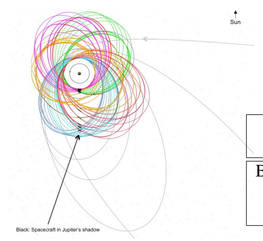


What are the B-Plane's shortcomings?

- Assumes a two-body (Keplerian) trajectory
- Assumes a hyperbolic (not captured) trajectory
- Not intuitive to understand for a wider audience
- Multiple possible definitions for out-of-plane component
- Does not show velocity information
- Inconsistent usage is subtle and prevalent
  - Not including partial derivatives of $\hat{S}$
  - Not including partial derivatives for event-relative mapping time
  - Using one B-Plane for multiple solutions
  - Varied choice of reference direction
  - Varied choice of mapping time

Maneuver Targeting Example for Europa Clipper Trajectory





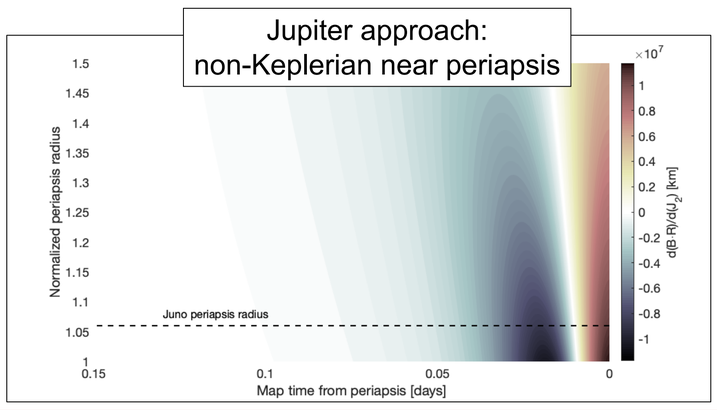
B-Plane targeting, showing that including partial derivatives of $\hat{S}$ is key

Target Type	Number of Iterations				Comp. Time (s)	ΔV (m/s)
	Average	Max.	Median	E03-TRG		
B-Plane (Varying Axis)	1.41	4	1	2	557.36	1283.41
B-Plane (Fixed Axis)	1.72	8	2	8	610.85	1283.41
Cartesian	1.52	4	2	2	580.14	1283.18

What are examples of when the B-Plane is insufficient?

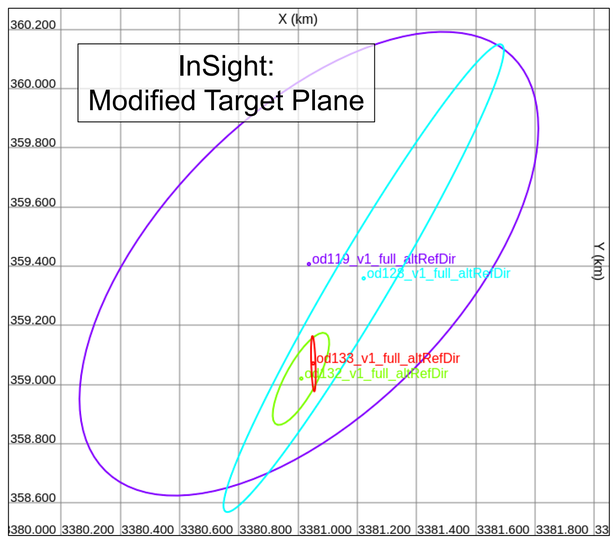
- Non-Keplerian trajectory (e.g. close flyby)
- Low velocity, distant flybys
- Low thrust spiral-in approach
- Swarm / multi-spacecraft
- Irregular central body shape

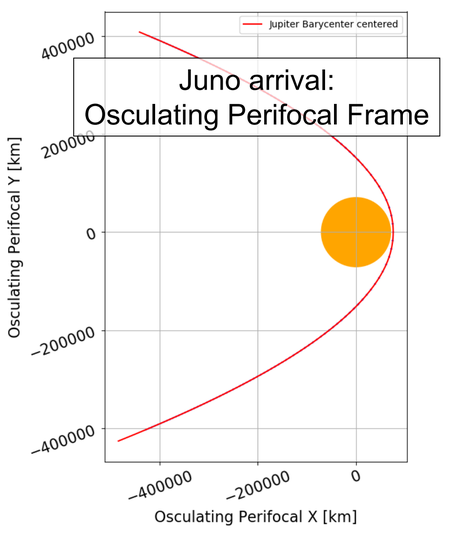
Jupiter approach: non-Keplerian near periapsis

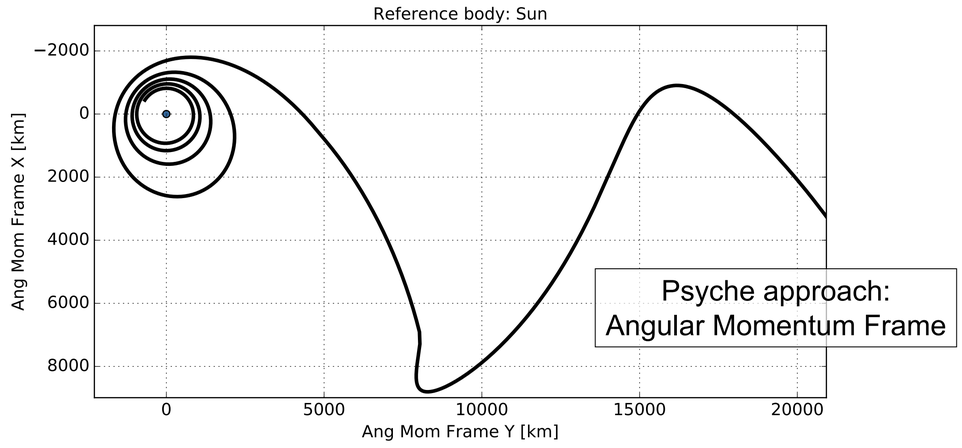


Alternatives

	Osculating Perifocal Frame	Angular Momentum Frame	Modified Target Plane
Definition	• Trajectory always in XY-plane • Periapsis always toward +X	• Plane normal is instantaneous angular momentum • Reference direction to define XY orientation is free	• Perpendicular to trajectory at periapsis • Reference direction to define XY orientation is free
Benefits	• Can depict entire trajectory in 2D • Always clear where periapsis is • No radius scaling required • Valid through capture	• Can depict entire trajectory in 2D • No radius scaling required • Valid through capture • Valid even in circular orbits	• No radius scaling required • Similar interpretation as B-Plane • Can easily assess impact probability • Doesn't assume a two-body trajectory
What is it good for?	✓ **Trajectory visualization**	✓ **Trajectory visualization**	✓ **Maneuver targeting** ✓ **Covariance mapping and visualization**
What is it not so good for?	✗ Maneuver targeting ✗ Covariance mapping and visualization	✗ Maneuver targeting ✗ Covariance mapping and visualization	✗ Trajectory visualization







Our recommendations

When using the B-Plane…

- ✓ Pick a sensible reference direction and clearly communicate it
- ✓ Be consistent about including/excluding the partials of $\hat{S}$ and interpreting the results
- ✓ Be consistent about including/excluding event time partials and interpreting the results
- ✓ Know when it's okay to depict multiple trajectories on a single B-Plane

When working with flyby / insertion / landing trajectories…

- ✓ Test the convergence properties and results using other frames for maneuver design
- ✓ Depict the trajectories in an alternate frame, especially when communicating with a wider audience

Benefits to NASA and JPL:

- A concise overview of the benefits and drawbacks of using the B-Plane
- Evaluation of several compelling alternatives
- Software to use the alternatives in JPL's institutional MONTE software for mission design and navigation

- Current and future missions can learn from the lessons we've collected, and can choose to adopt one of the alternatives for their purposes

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