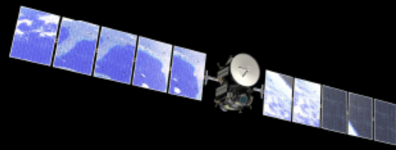


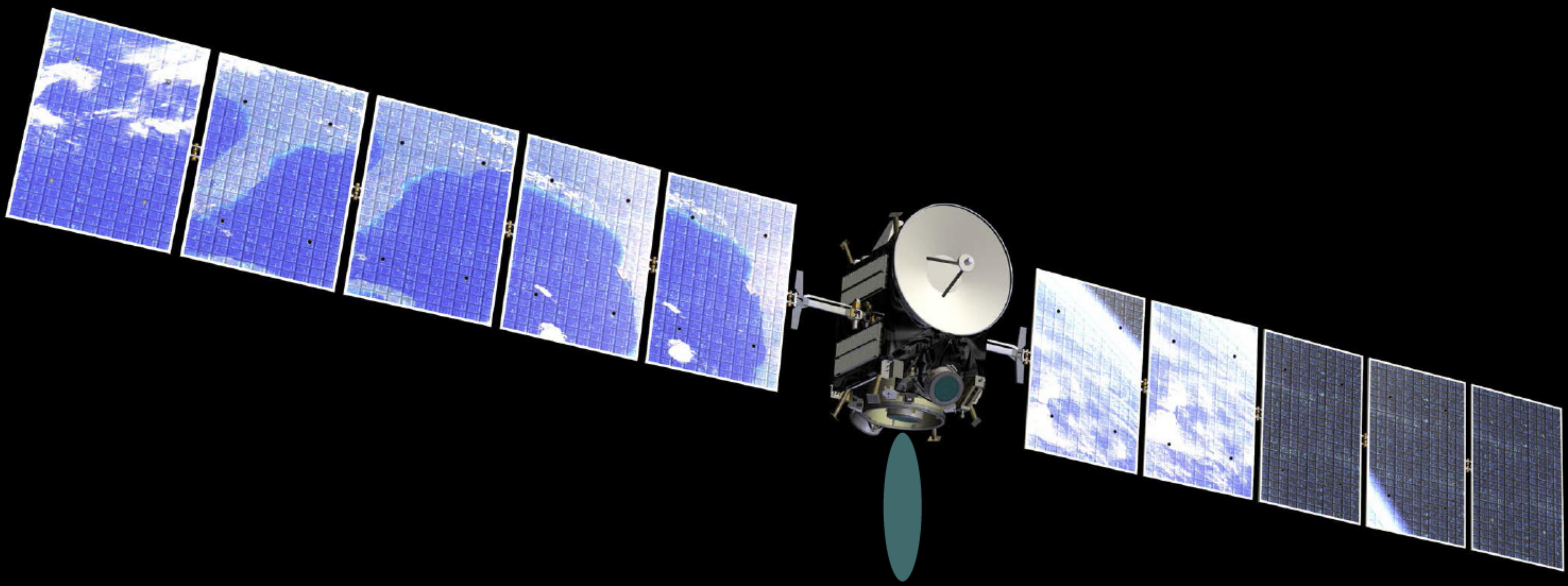
Thrust Direction Optimization: Satisfying Dawn's Attitude Agility Constraints

AAS 13-343

Gregory Whiffen
Jet Propulsion Laboratory

February 12, 2013

- Solar arrays spanning 20 meters provide power for thrusters and bus
- The long arrays create a large moment of inertial
- Spacecraft attitude is determined by “Power Steering”
- Given a pointing (thrust) direction, maximize power by keeping the arrays orthogonal to the Sun:



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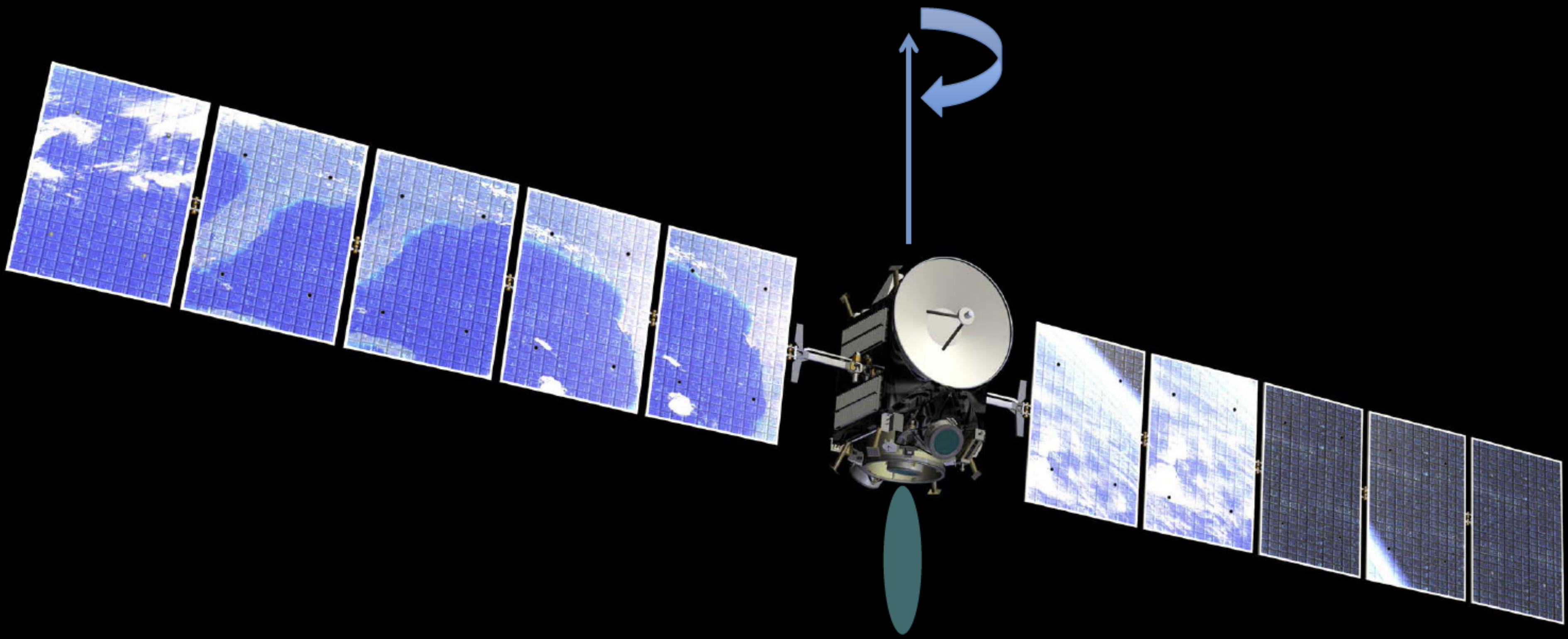

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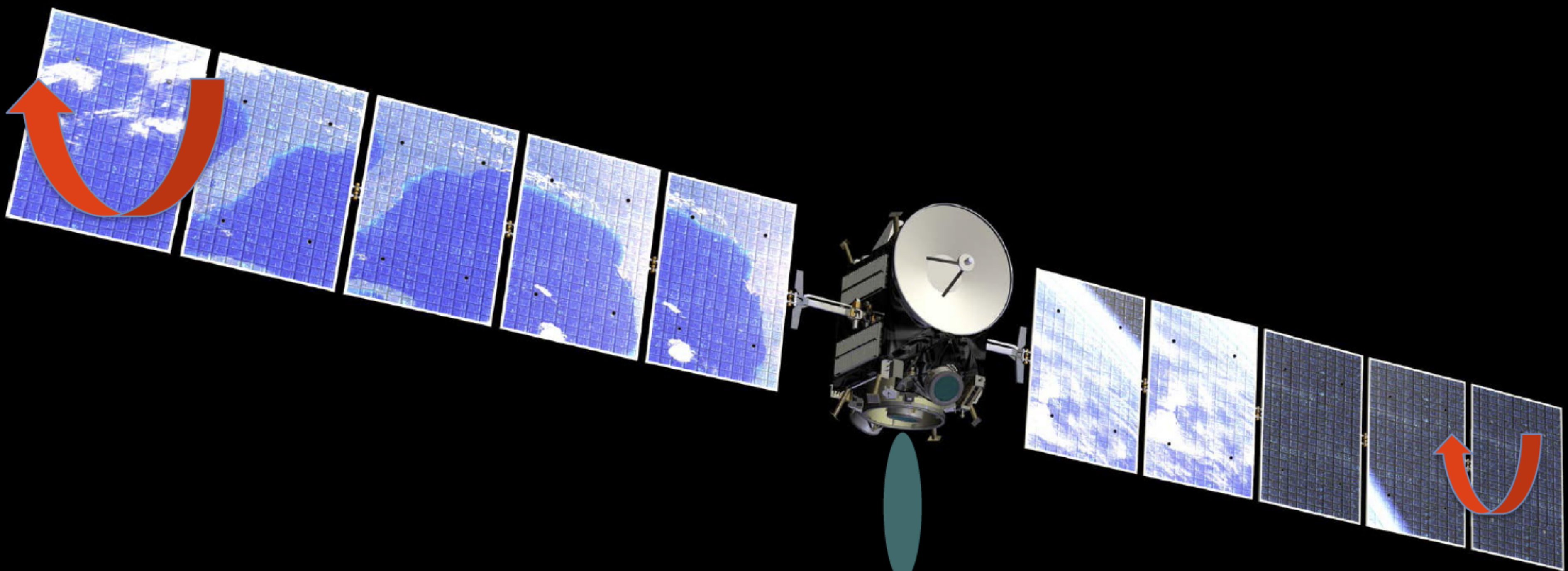
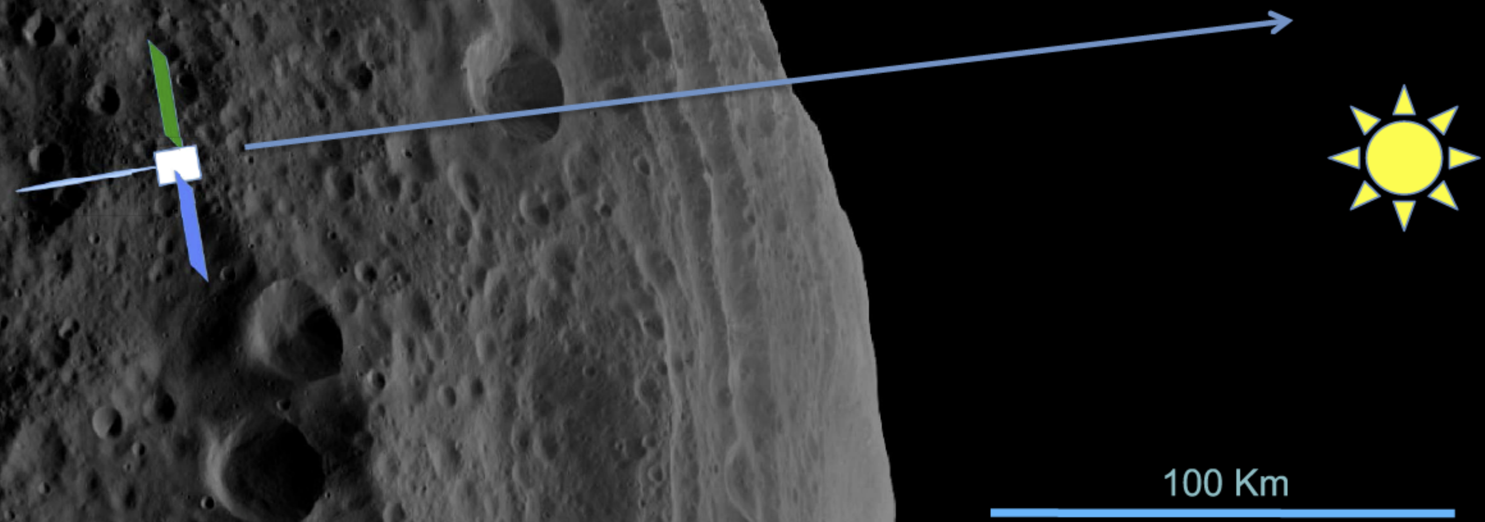


The Problem with Power Steering

- There are two "poles" that can require very rapid 180º attitude flips
- The flip involves the highest moment of inertial (solar arrays)
- The two poles are the Sun and Anti-Sun directions



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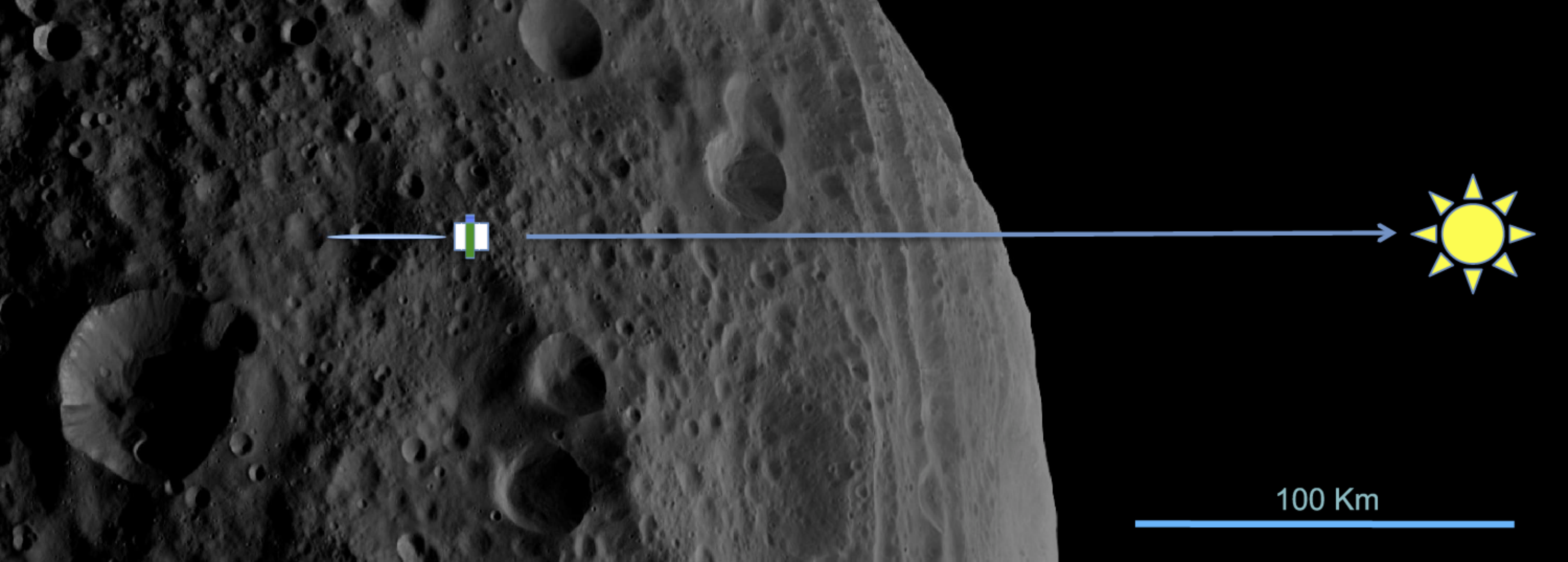

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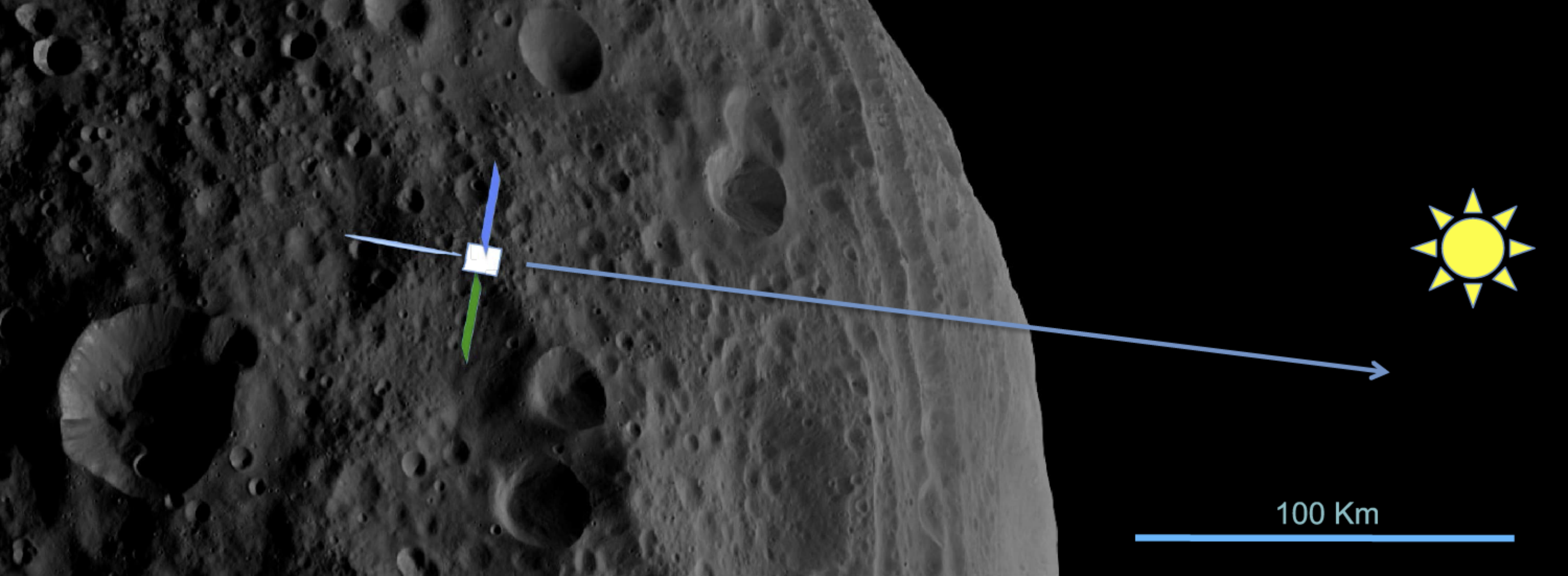


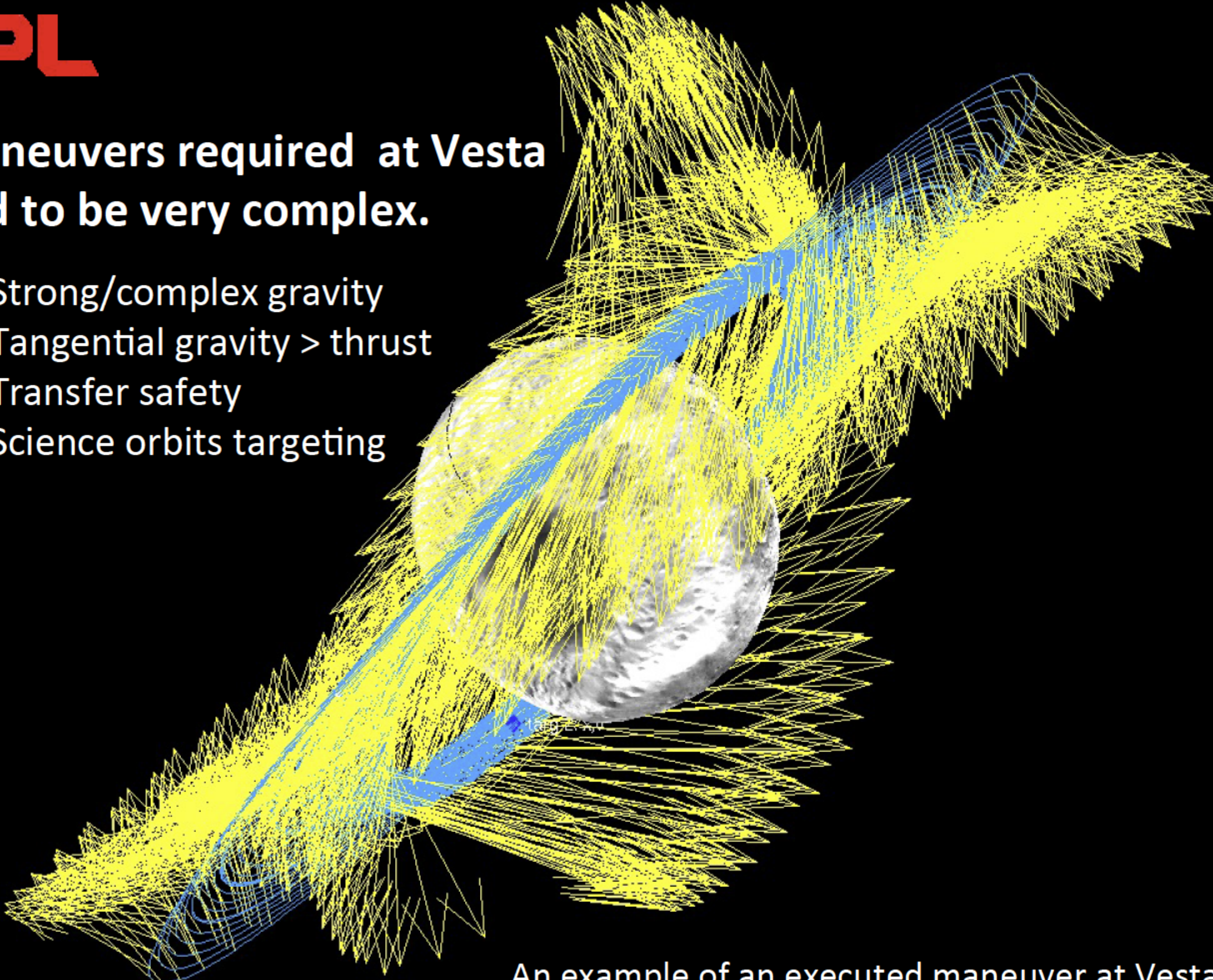
Dawn’s Attitude Control System

- Dawn’s attitude was controlled using thrust vectoring in two axes perpendicular to thrust and reaction wheels parallel to thrust
- Thrust vectoring was achieved with gimbals on the ion thrusters
- max excursion was < 5^o
- Thrust ~ 50 [mN]
- Spacecraft ~ 1200 [kg]

Weak Control: Low Agility

Maneuvers required at Vesta had to be very complex.

- Strong/complex gravity
- Tangential gravity > thrust
- Transfer safety
- Science orbits targeting



An example of an executed maneuver at Vesta, November 2011. Yellow vectors are thrust directions

Maneuver Design At Vesta

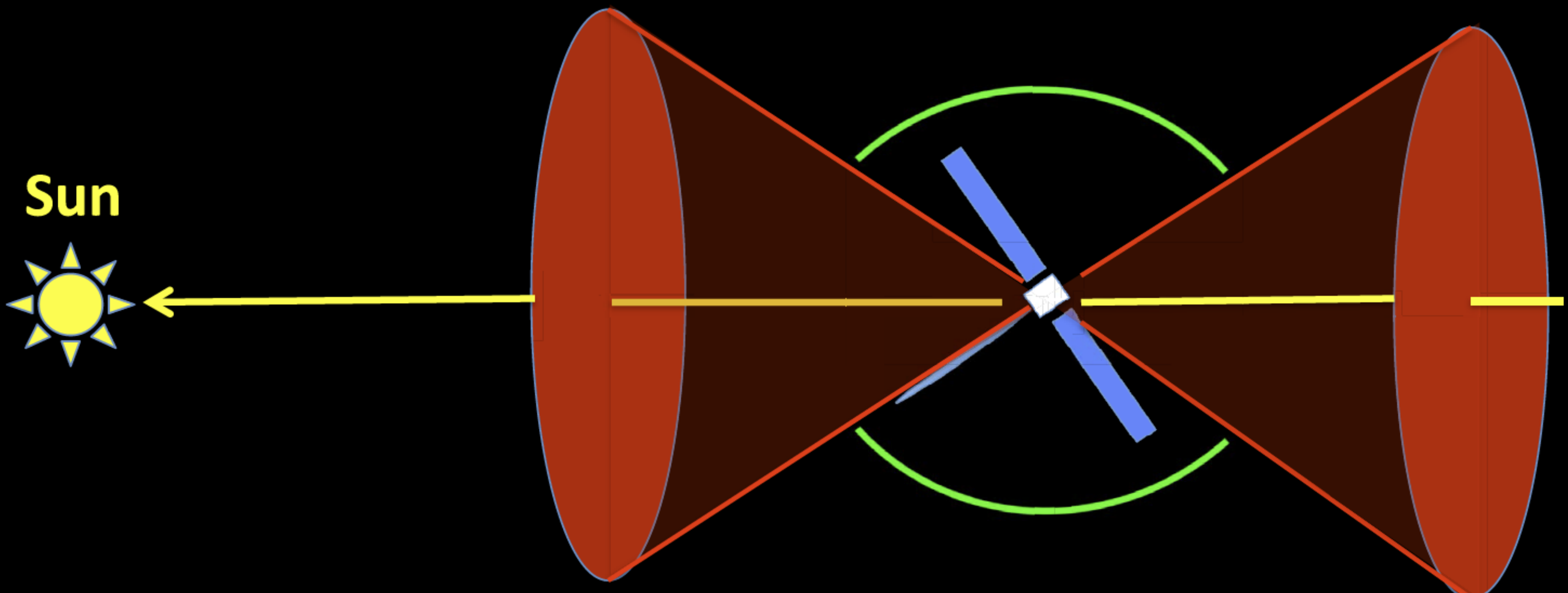
- Software: “Mystic” uses Static Dynamic Optimal Control
- Based on Bellman’s Principal of Optimality and Dynamic Programming (not NLP or calculus of variations)
- Very-high fidelity trajectory design tool used to design all maneuvers (High order gravity harmonics, multi-body gravity, radiation pressure, nonlinear thruster model, desat ΔV, etc.)
- Many operational constraints
- Original objective functions: Minimum Propellant or Minimum Time.

Attitude Agility Constraints

- **Must constrain thrust direction time evolution**
- Attitude agility constraints are:
  - **<u>Not analytic</u>**
  - **<u>Not predictable</u>** (unknown spacecraft momentum)
  - Monte-Carlo analysis necessary to evaluate fly-ability
- General rules exist to improve chances of fly-ability
  - Thrust “further” from Sun and Anti-Sun directions
  - Make attitude rates (accelerations) lower
  - Keep thrust direction movement continuous!

Attitude Agility Constraints

- **<u>Cone angle exclusion constraints do not work</u>**
  - Result in high accelerations
  - Discontinuous thrust directions
  - Does not address high rates or accelerations



Mystic Optimal Control Formulation

Objective Function:

$$J(v,w) = \int_{t_o=w_1}^{t_f=f(w)} F(x(t),v(t),w,t)dt + \sum_{i=1}^{M} H_i(x(t_i),v(t_i),w,t_i) + G(x(t_f),v(t_f),w,t_f)$$

State Equation:

$$\frac{dx(t)}{dt} = T(x(t),v(t),w,t)$$

Initial Condition Function:

$$x(t_0) = \Gamma(w)$$

STATE: x(t) = s/c position, velocity, mass
CONTROL: v(t) = thrust vector
CONTROL: w = initial time, flight time, initial state

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So Called "3 DOF" model

STATE: x(t) = s/c position, velocity, mass
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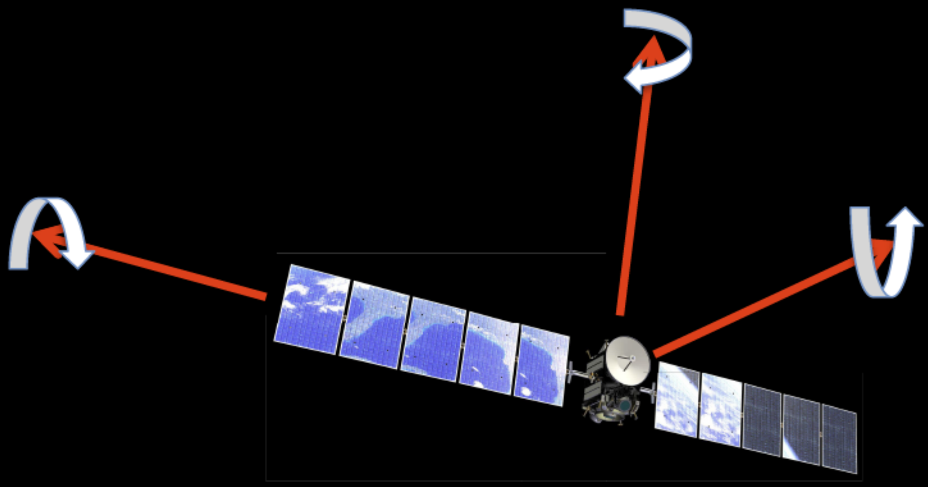
6 Degree of Freedom Model

- Include 3 attitude angles as part of the state vector



- Natural formulation for constraining attitude rate, accel.
- Account for attitude even when not thrusting
- Complexity of formulation make initial guesses difficult
- Many more local minima from spacecraft revolution
- Power steering algorithm will also create local minima
- **Essentially need to know the answer before starting!**

Thrust Direction Optimization

- Sought a new formulation with the advantages of 3 DOF
  - Fewer local minima
  - Simple initial guesses
- Provide ability to manipulate thrust directions and attitude rates
- Solutions must exhibit thrust direction continuity and smoothness

(1) Select direction(s) in some frame
(2) Find a thrust profile minimally or maximally far away
(3) Still achieve all other constraints and state targets

Thrust Direction Optimization

Direction Attractor

$$min_{v,w} \int_{t\in\tau} \left[1 - \hat{v}(t)\cdot\hat{D}(x(t),v(t),w,t)\right]^2 dt$$

Thrust

Direction Objective

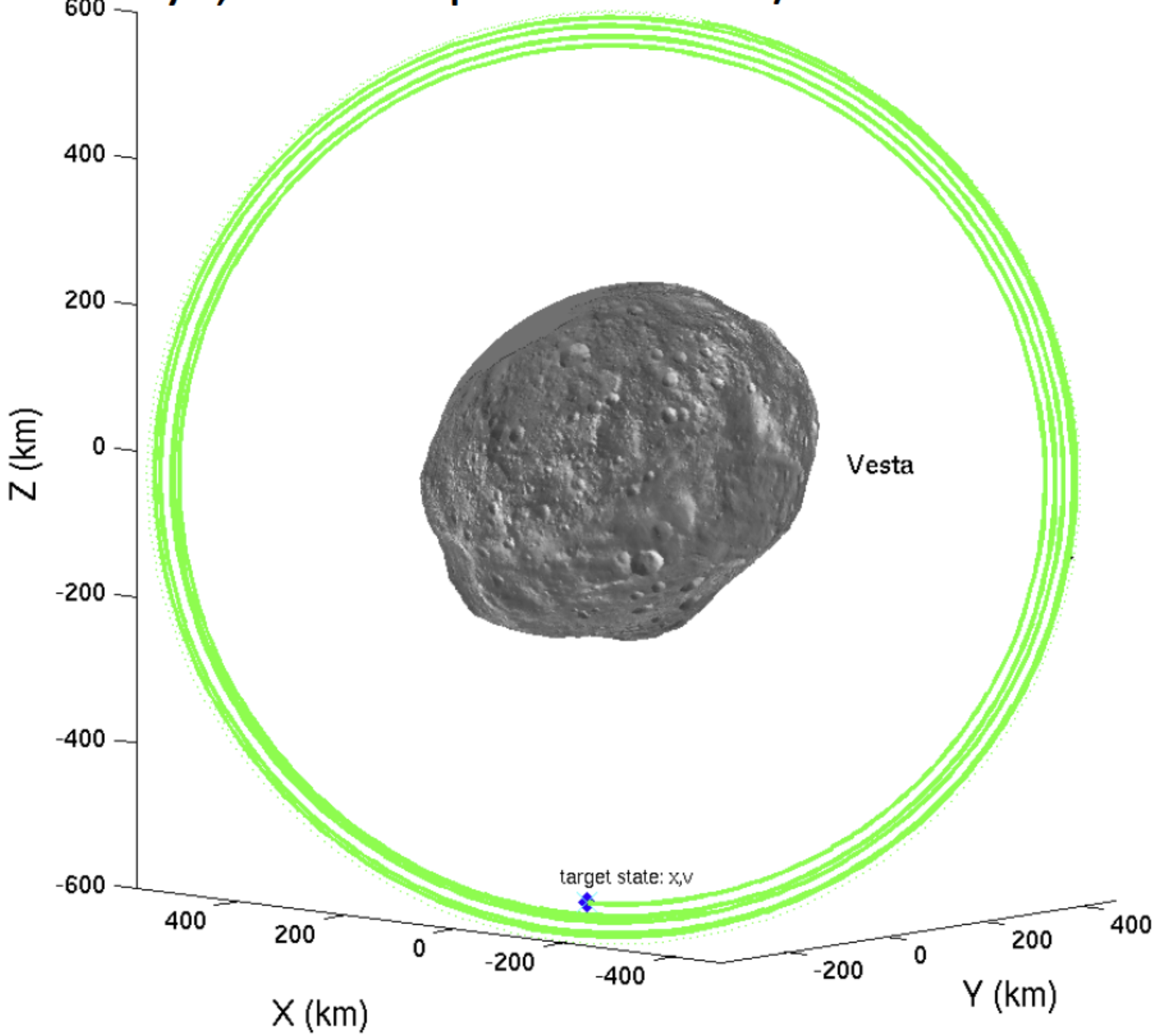
Pole Repulsor

$$min_{v,w} \int_{t\in\tau} \left[1 - (\hat{v}(t)\times\hat{S}(x(t),v(t),w,t))\cdot(\hat{v}(t)\times\hat{S}(x(t),v(t),w,t))\right]^n dt$$

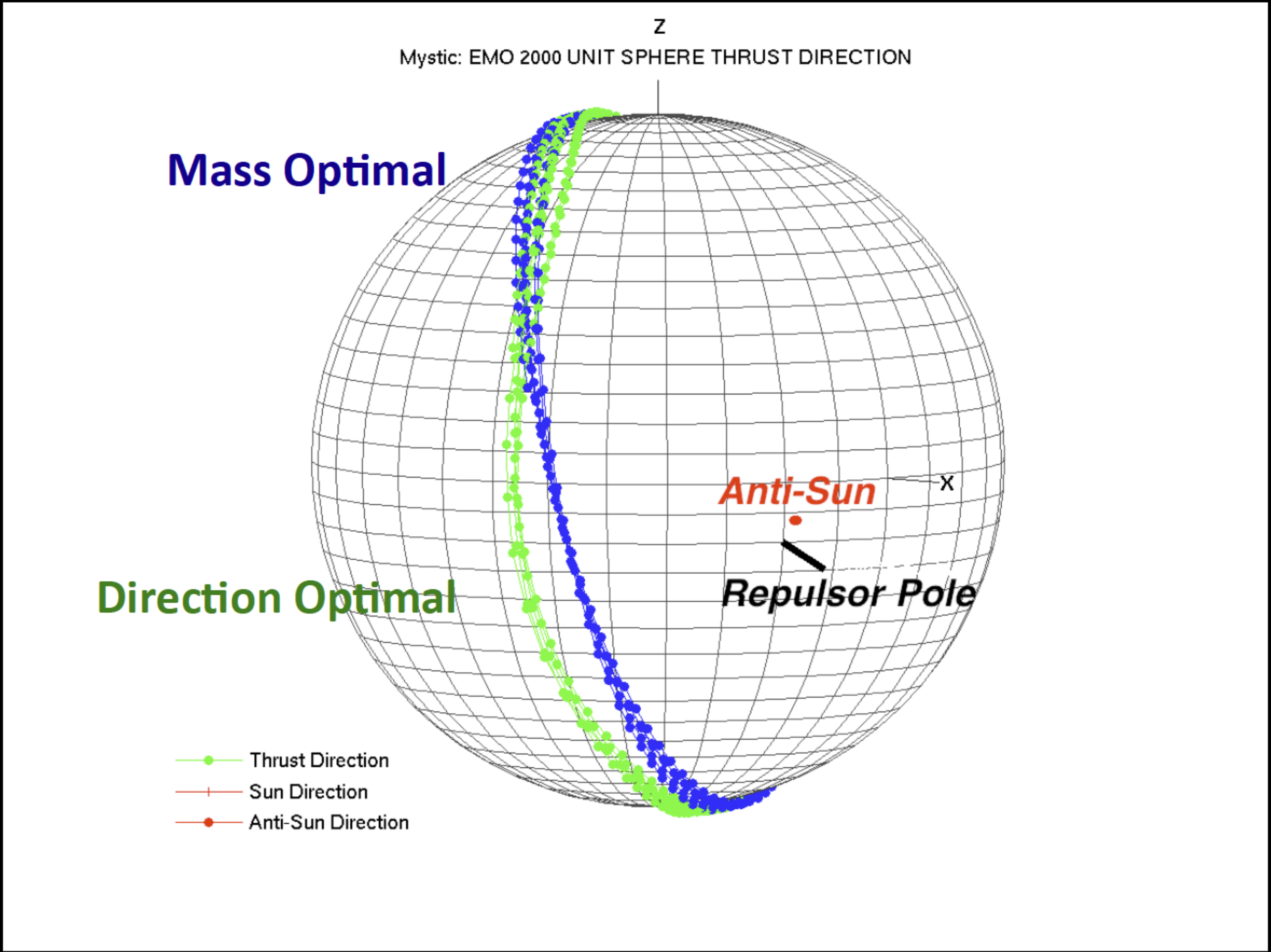
Attitude Pole to Avoid

Direction Optimization Example

R= 640 to 580 [km] transfer, 7 revolutions around Vesta, Time of flight = 2 days, Vesta Operations 11/2011



Pole Repulsor Example



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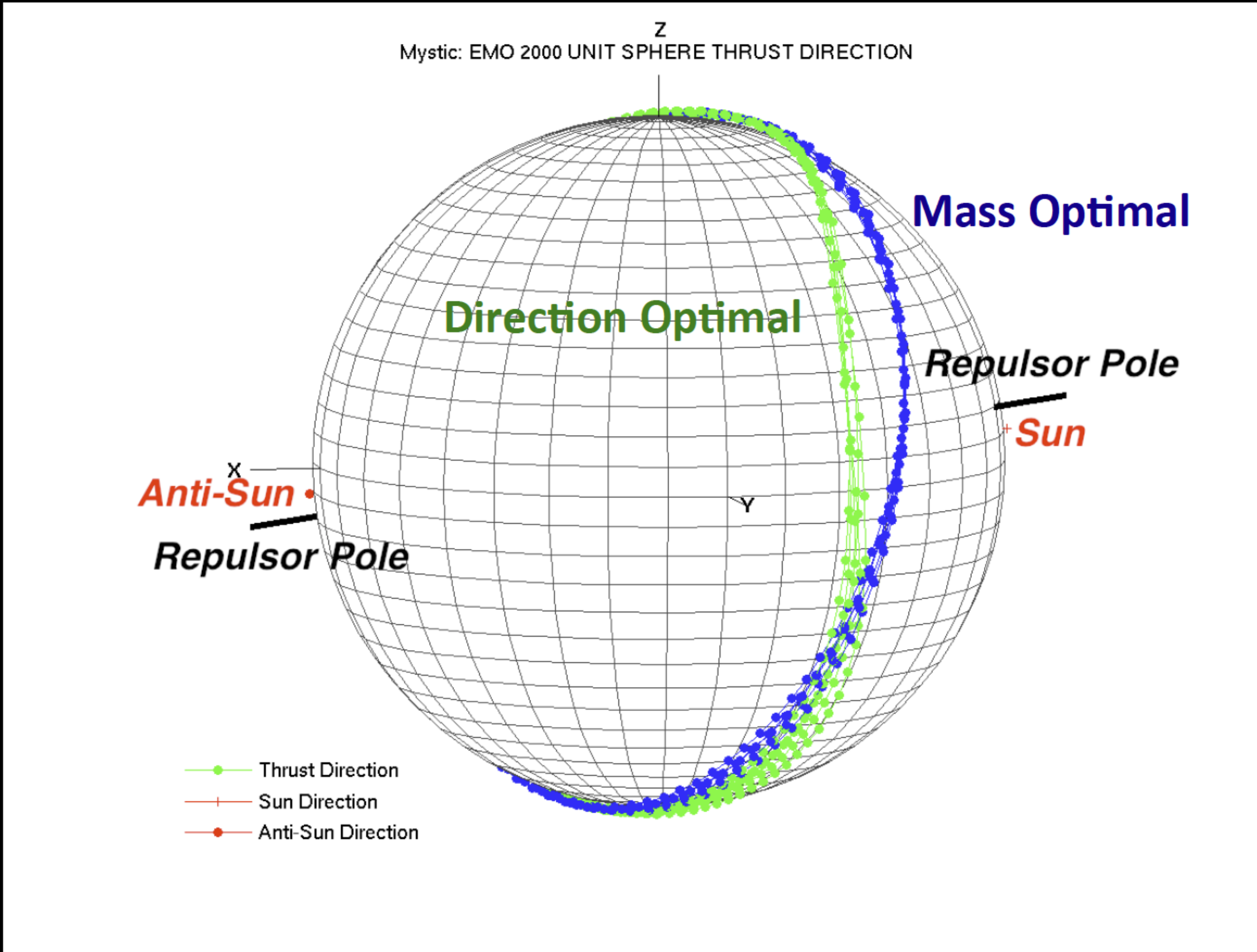
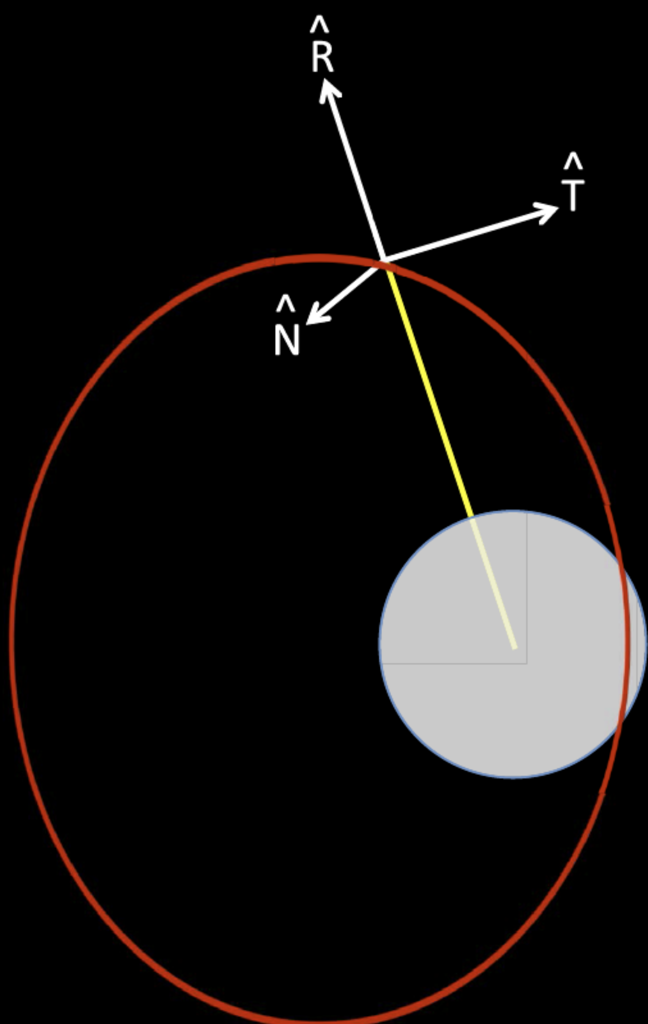


Radial-Normal-Transverse Frame



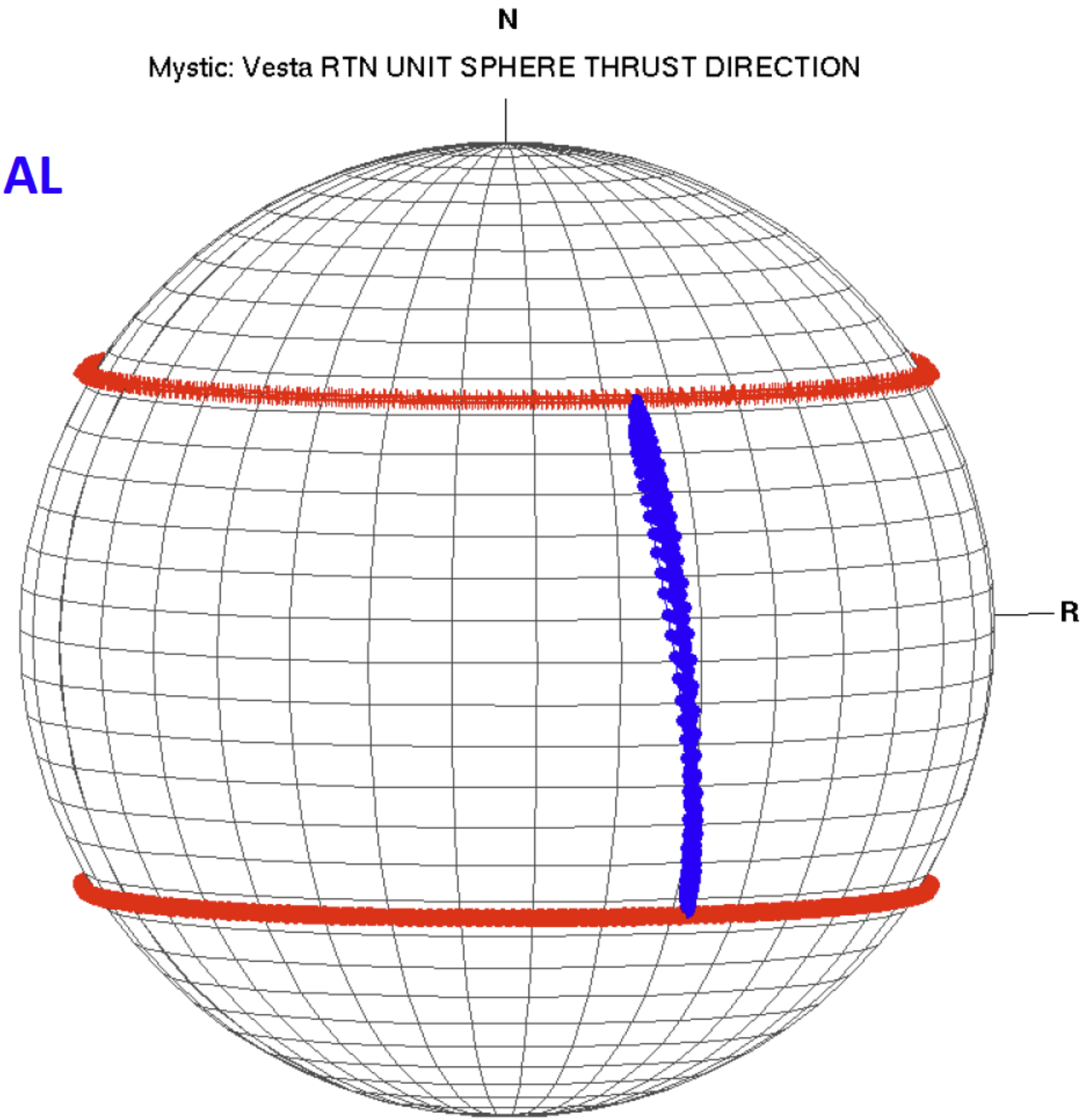
Rotating with S/C radius vector:

$\hat{R}$: radial direction

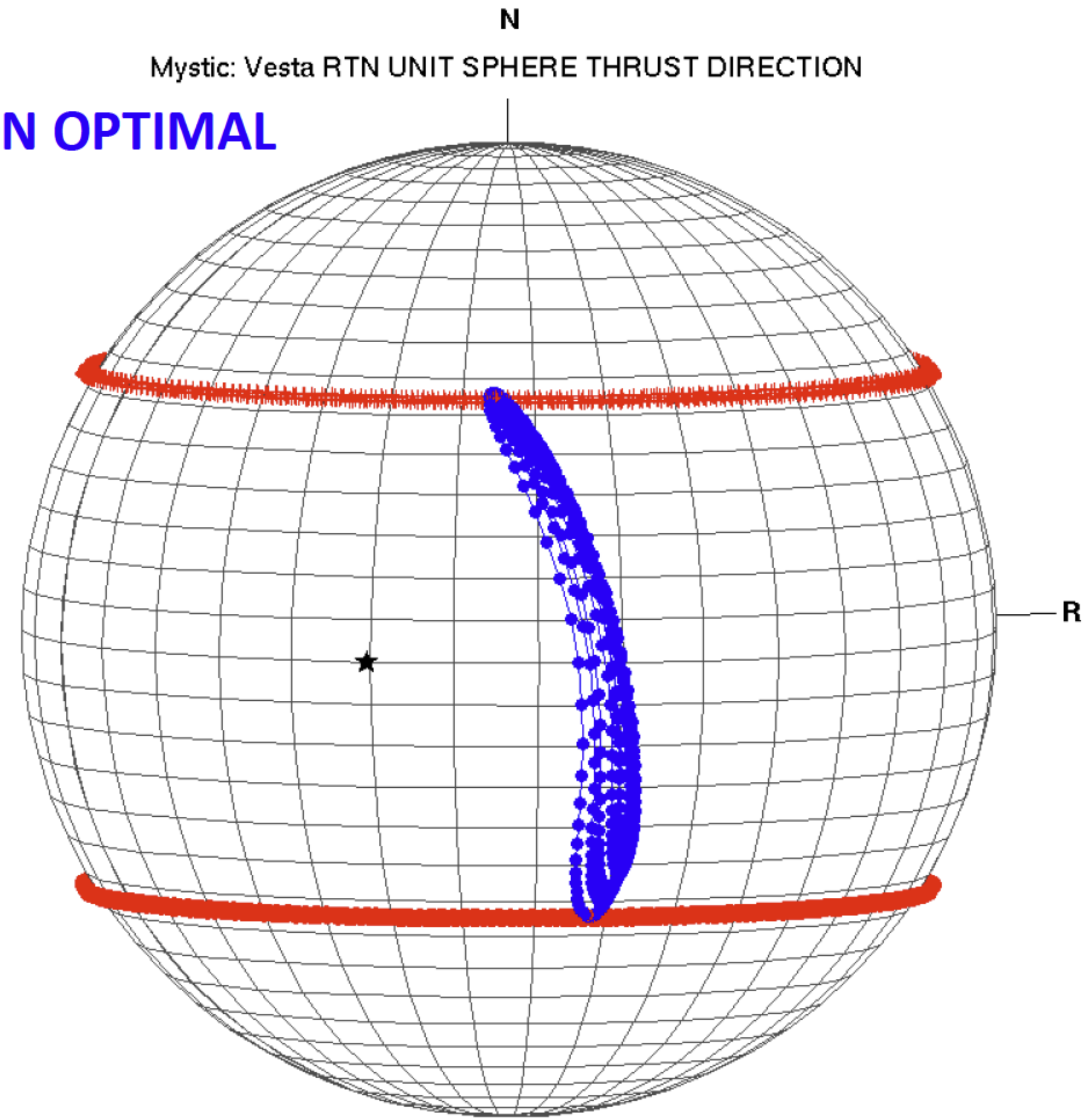
$\hat{T}$: Transverse direction = local horizontal nearest velocity direction

$\hat{N}$: orbit normal = $\hat{R} \times \hat{T}$

MASS OPTIMAL

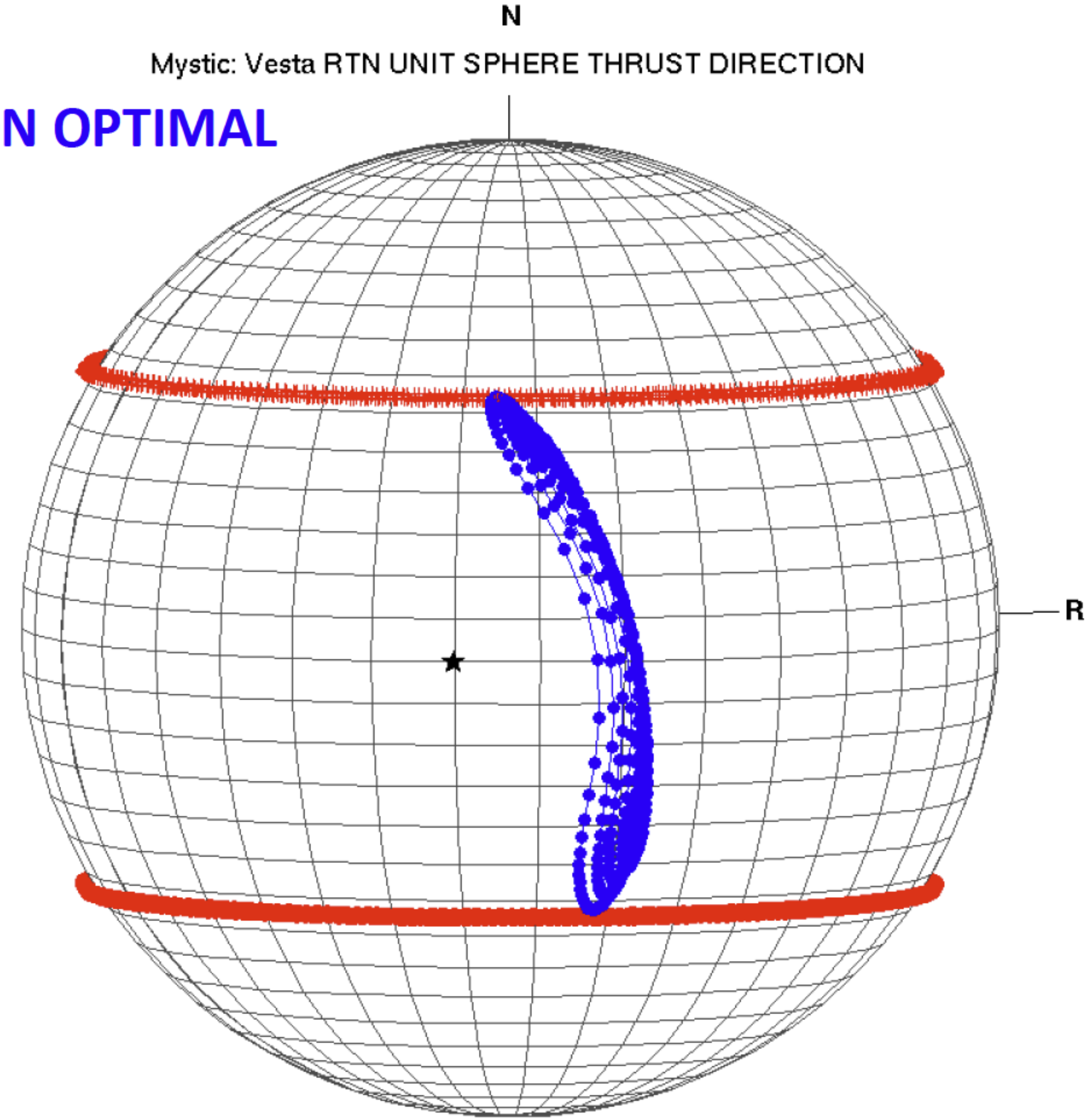


RTN DIRECTION OPTIMAL



START

RTN DIRECTION OPTIMAL



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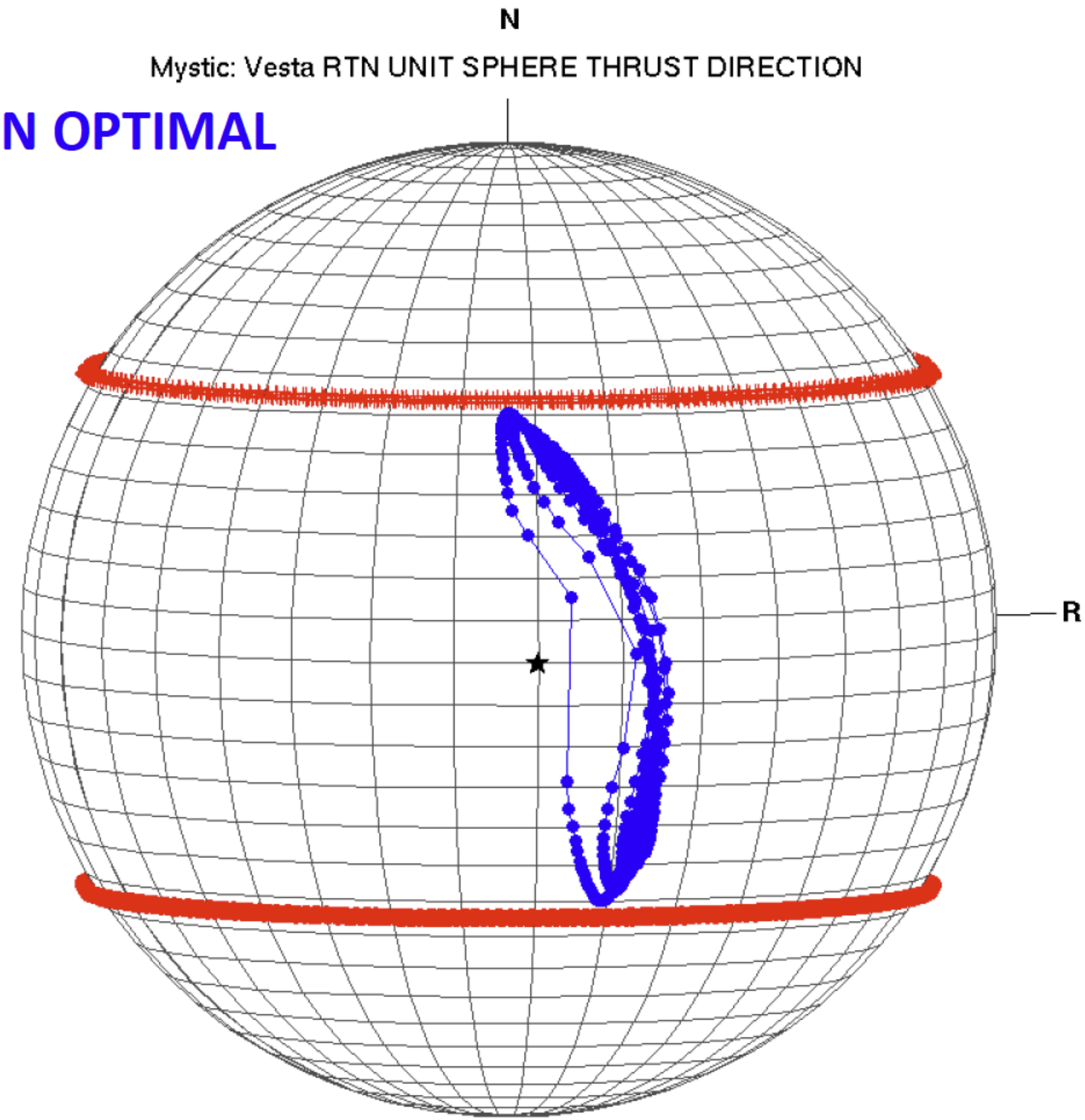

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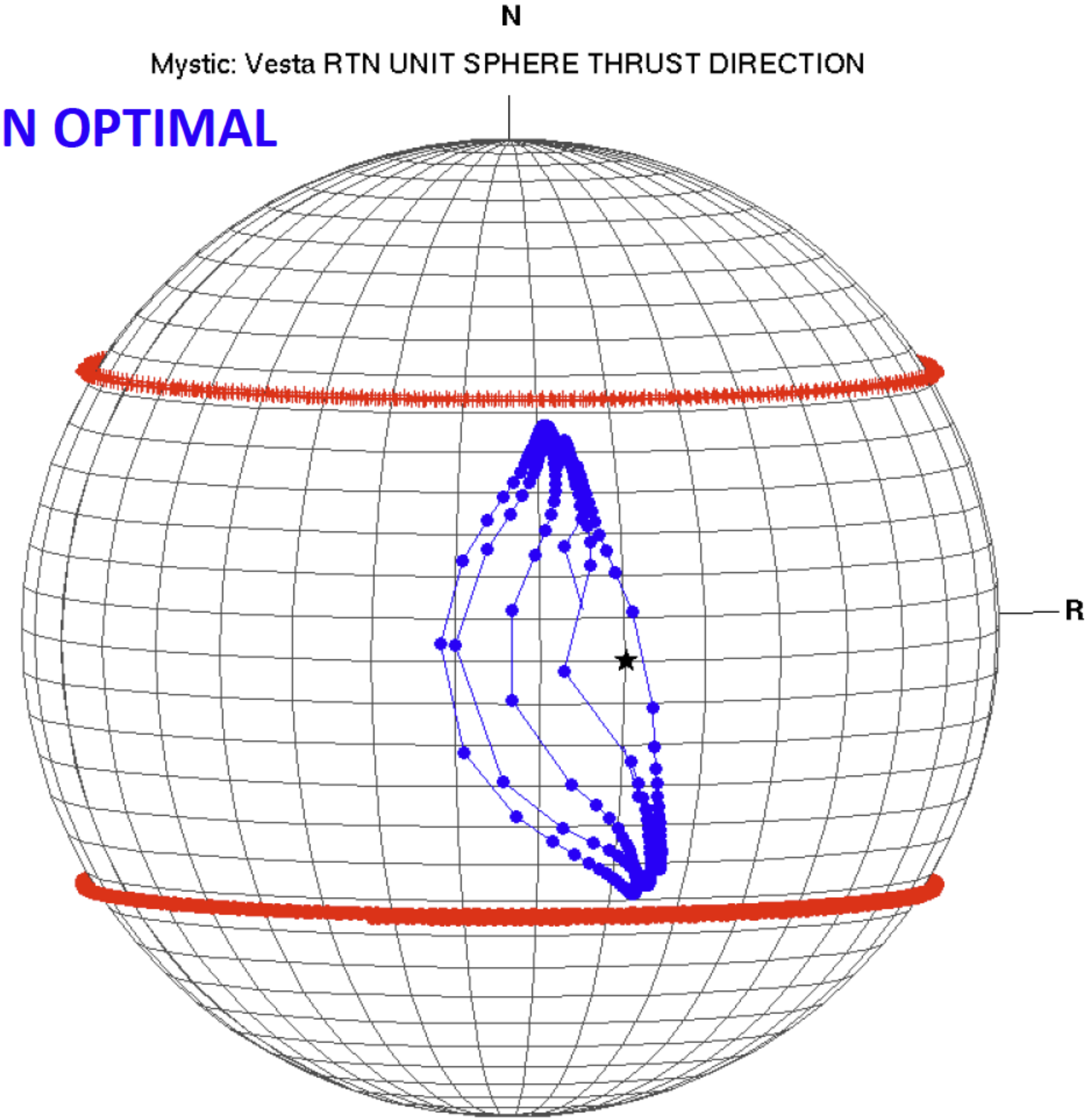

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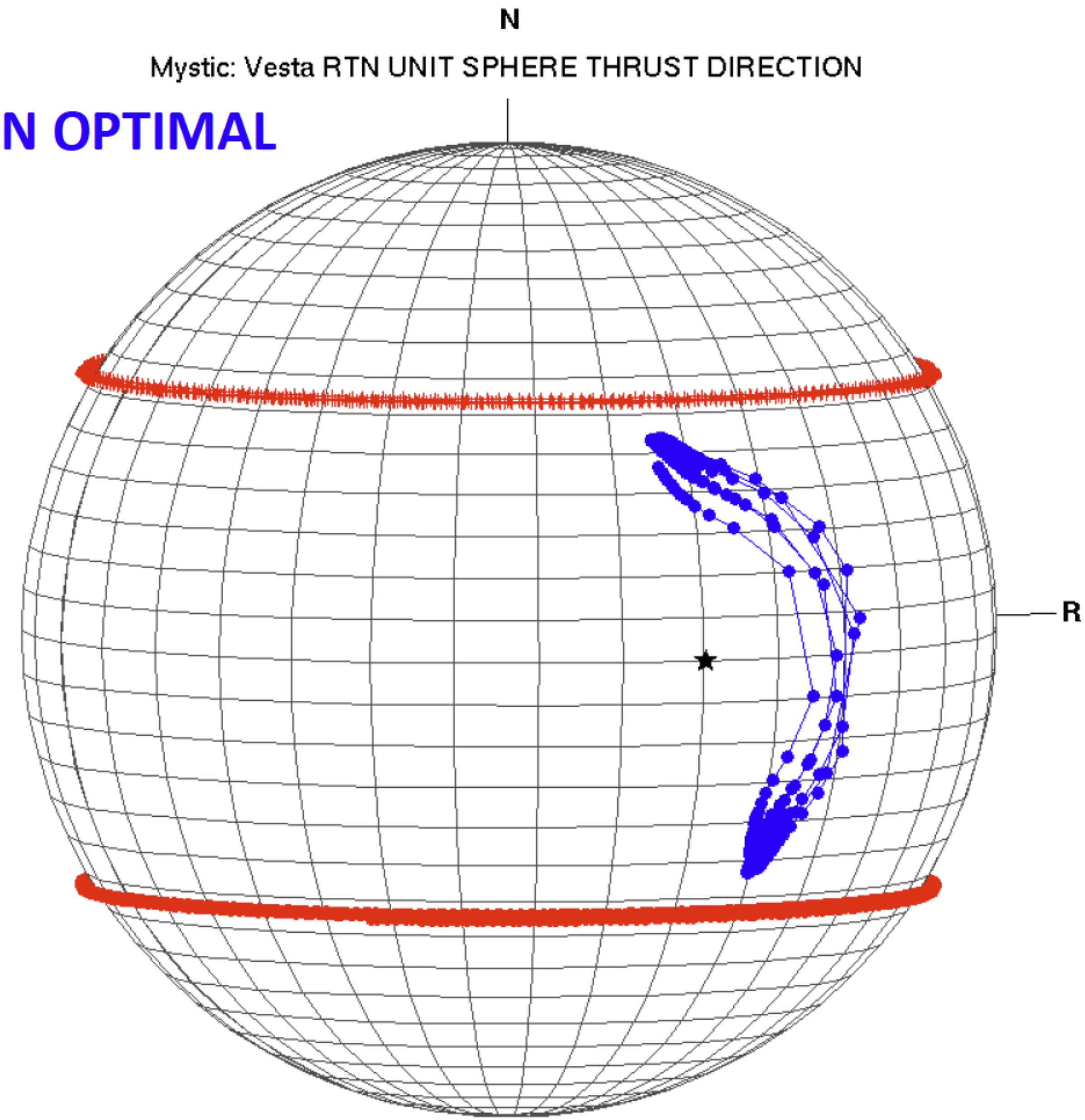

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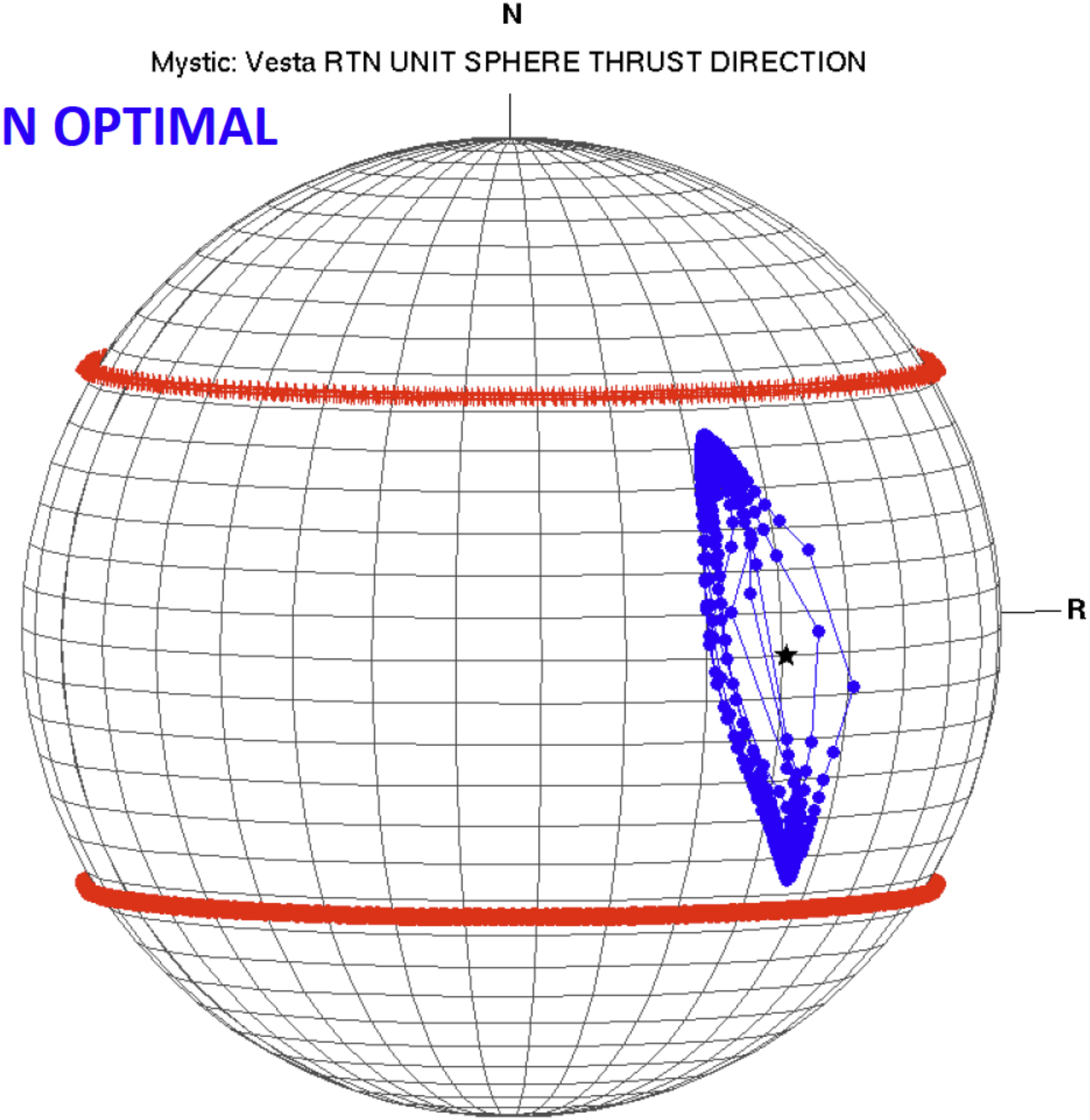

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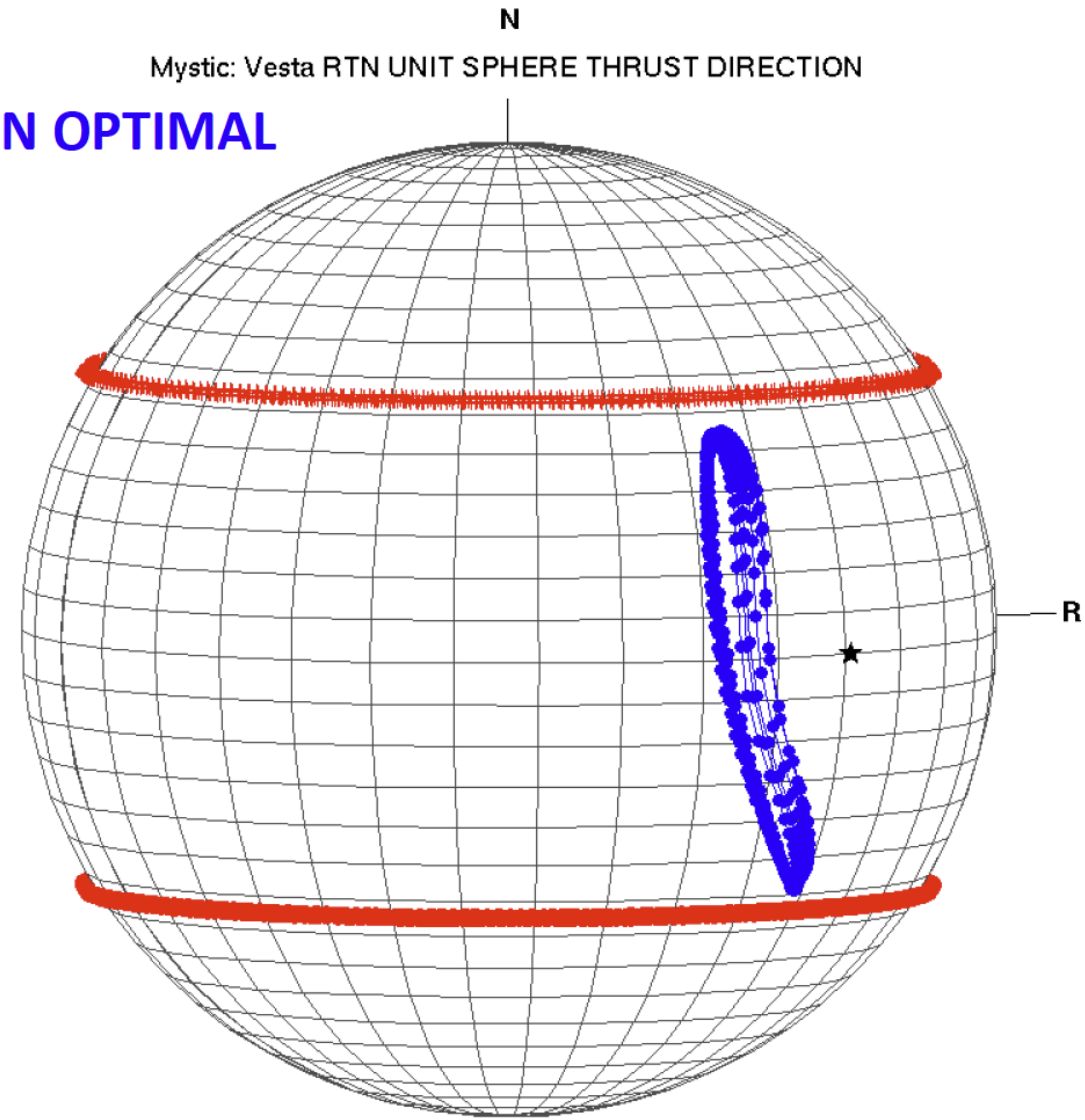

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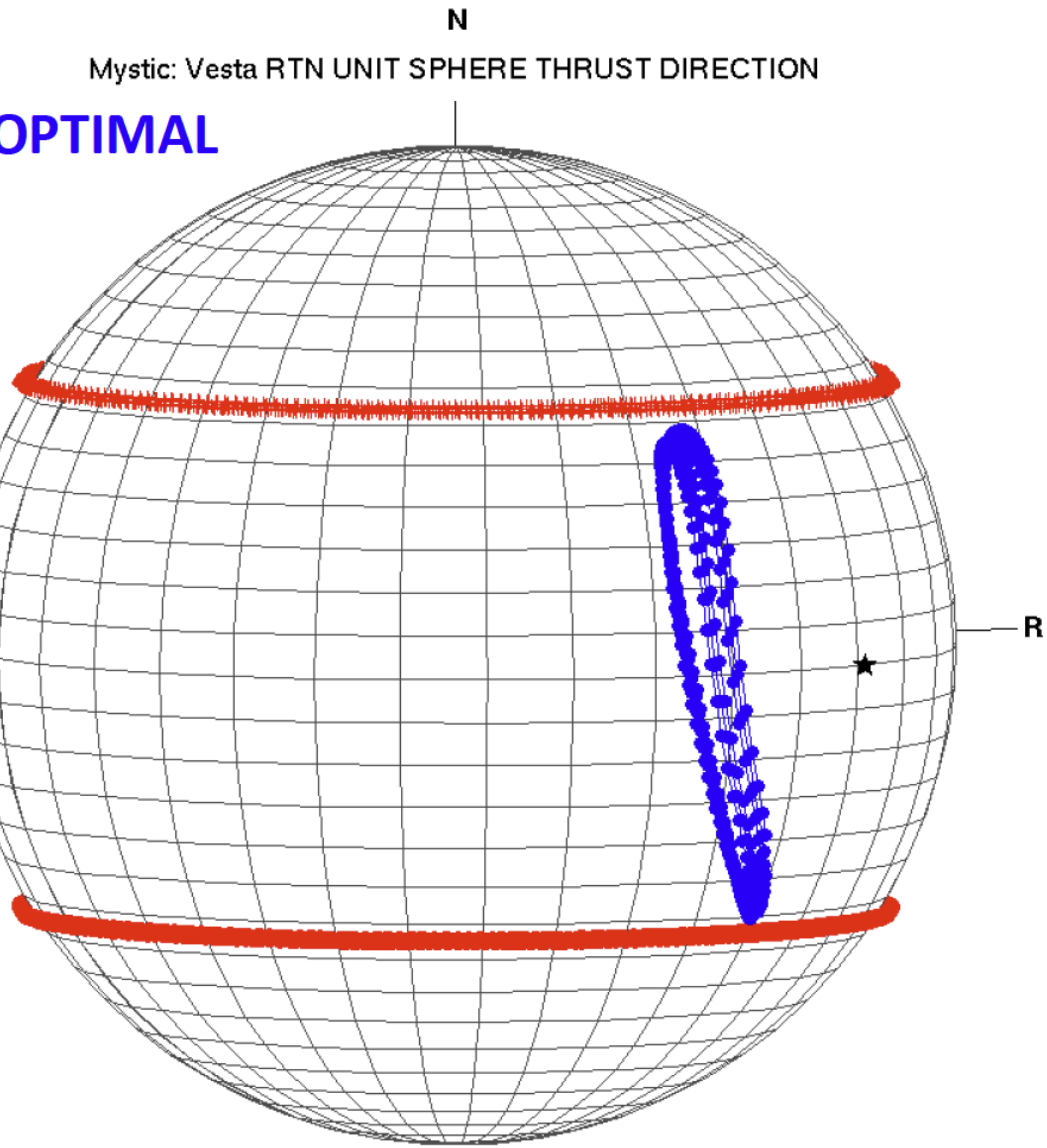

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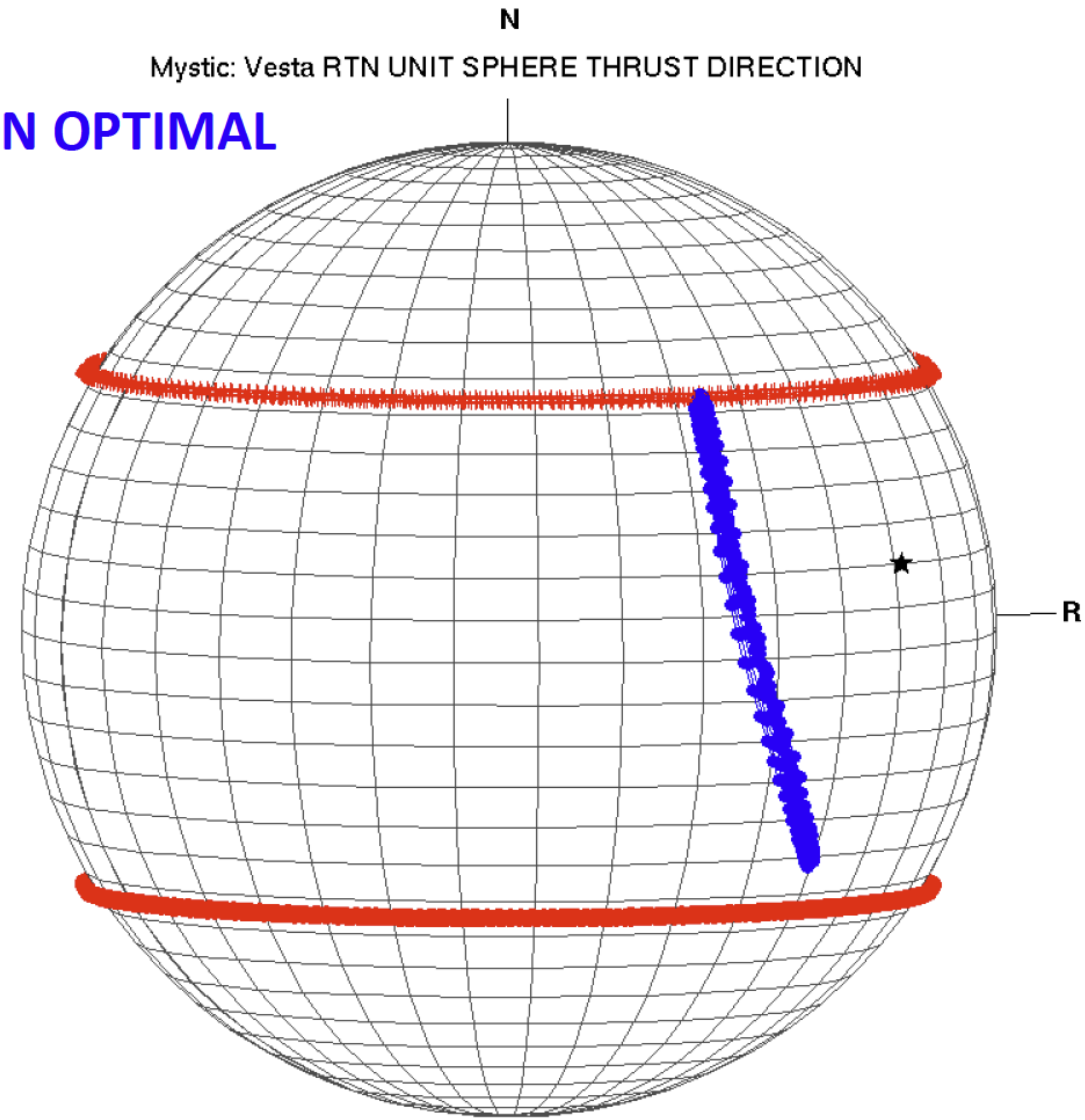

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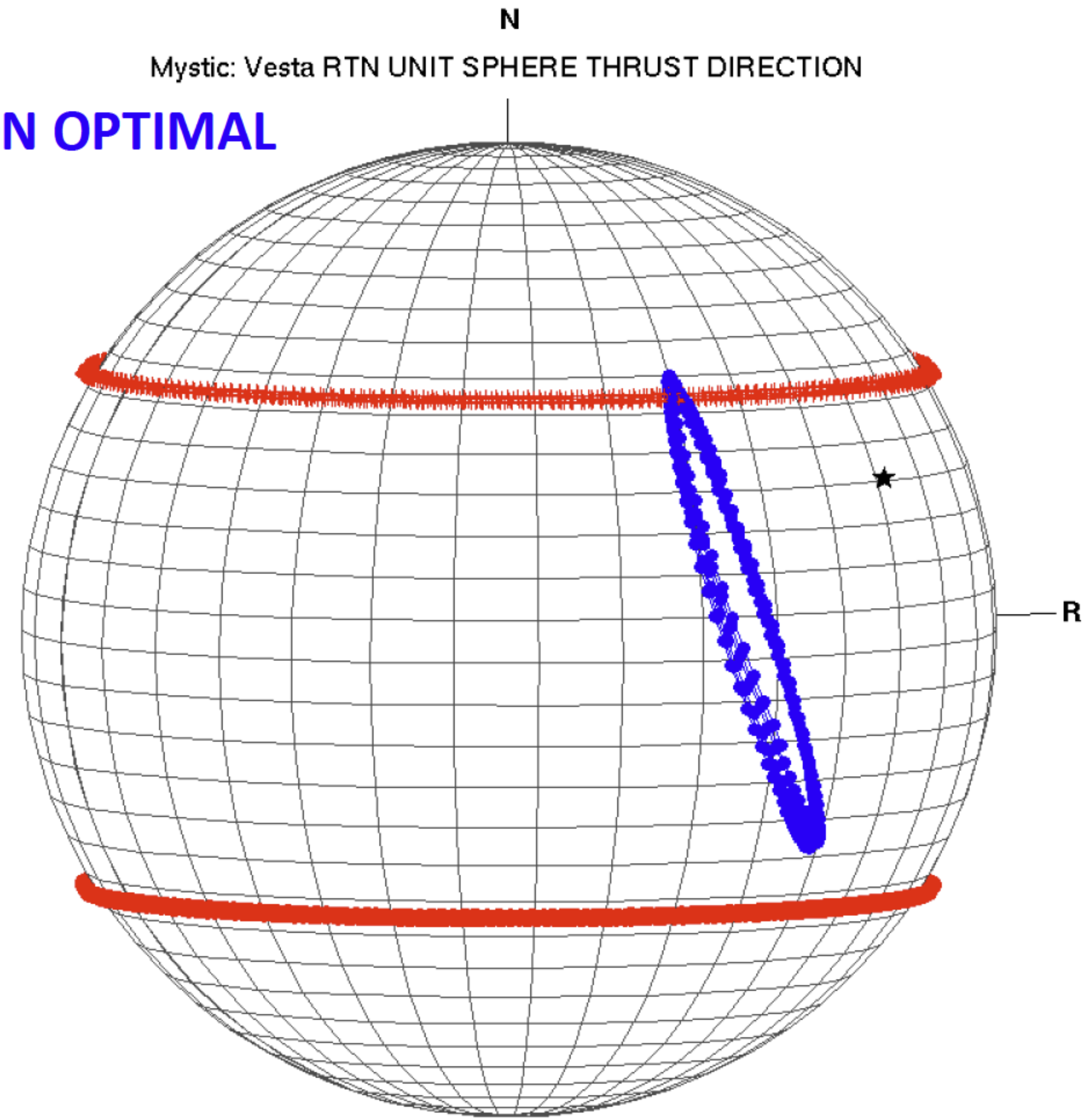

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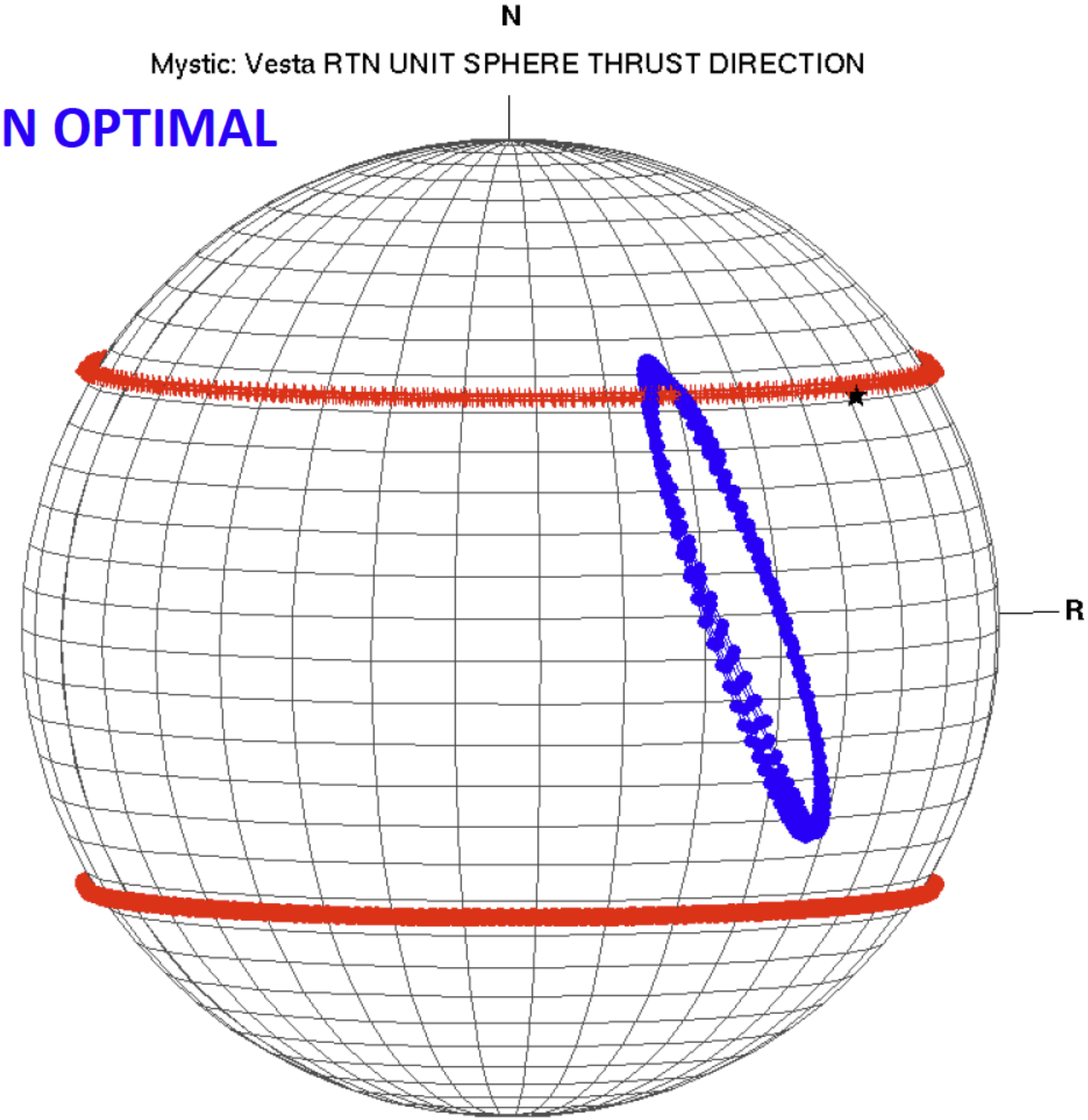

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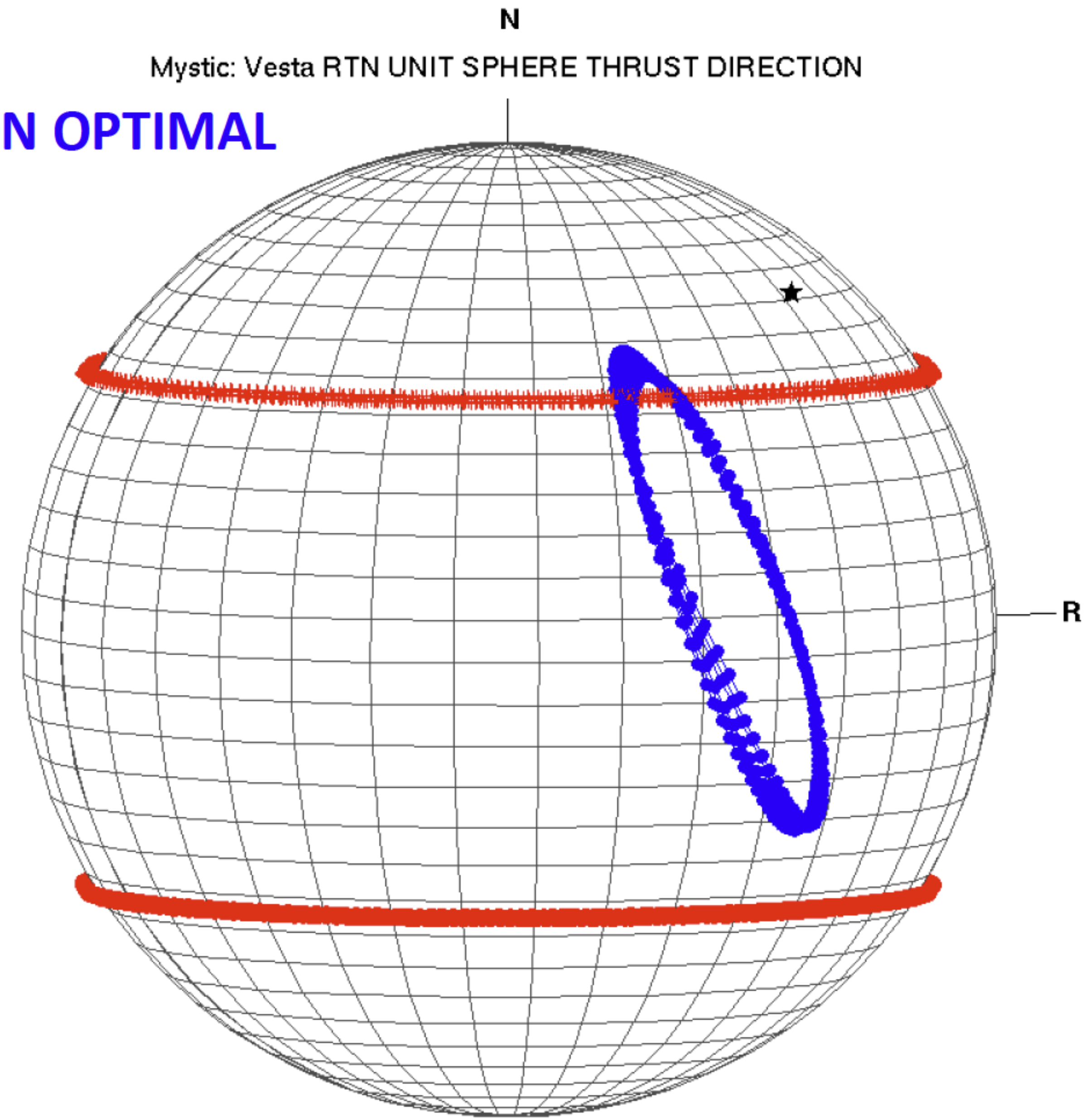

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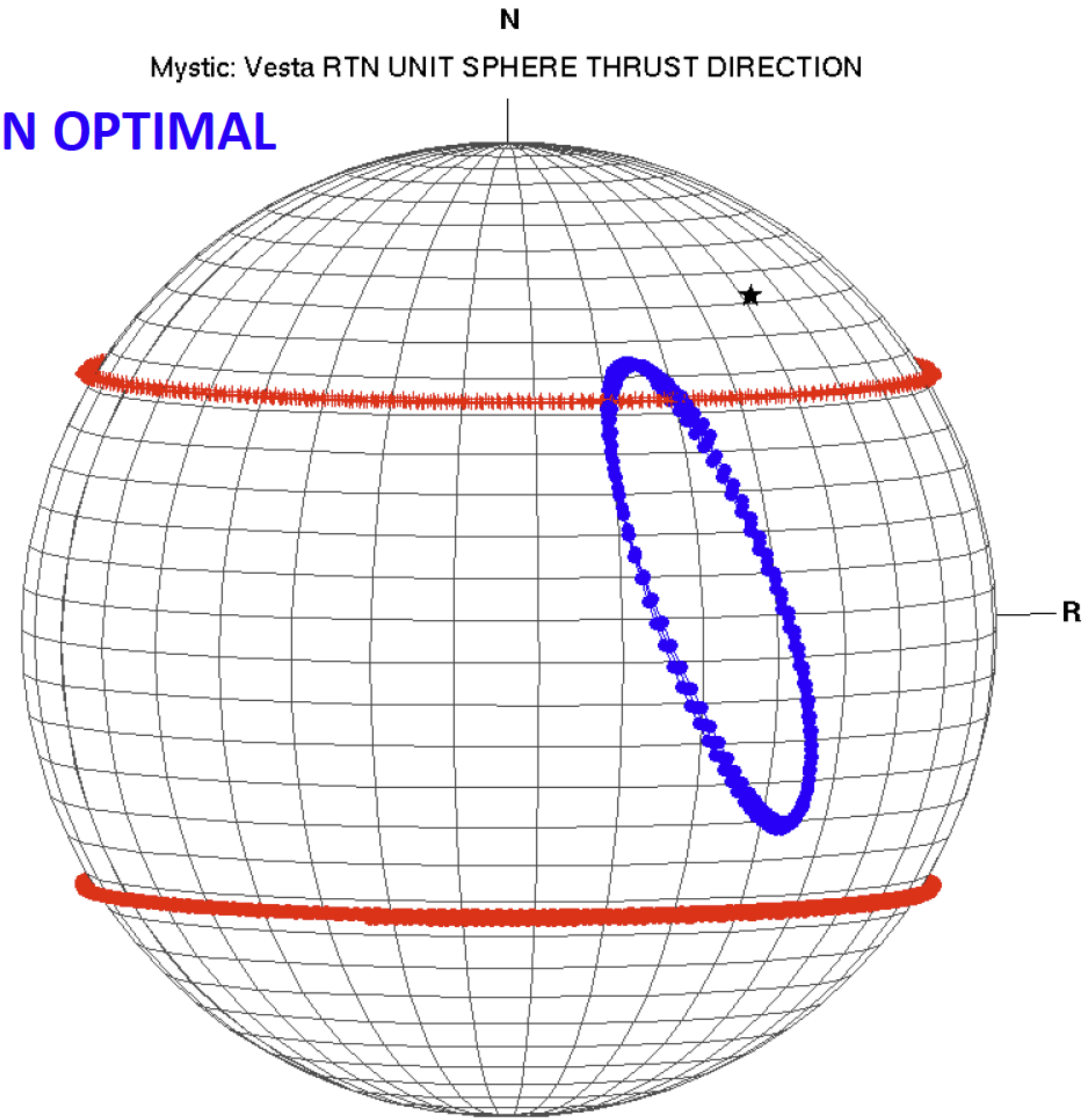

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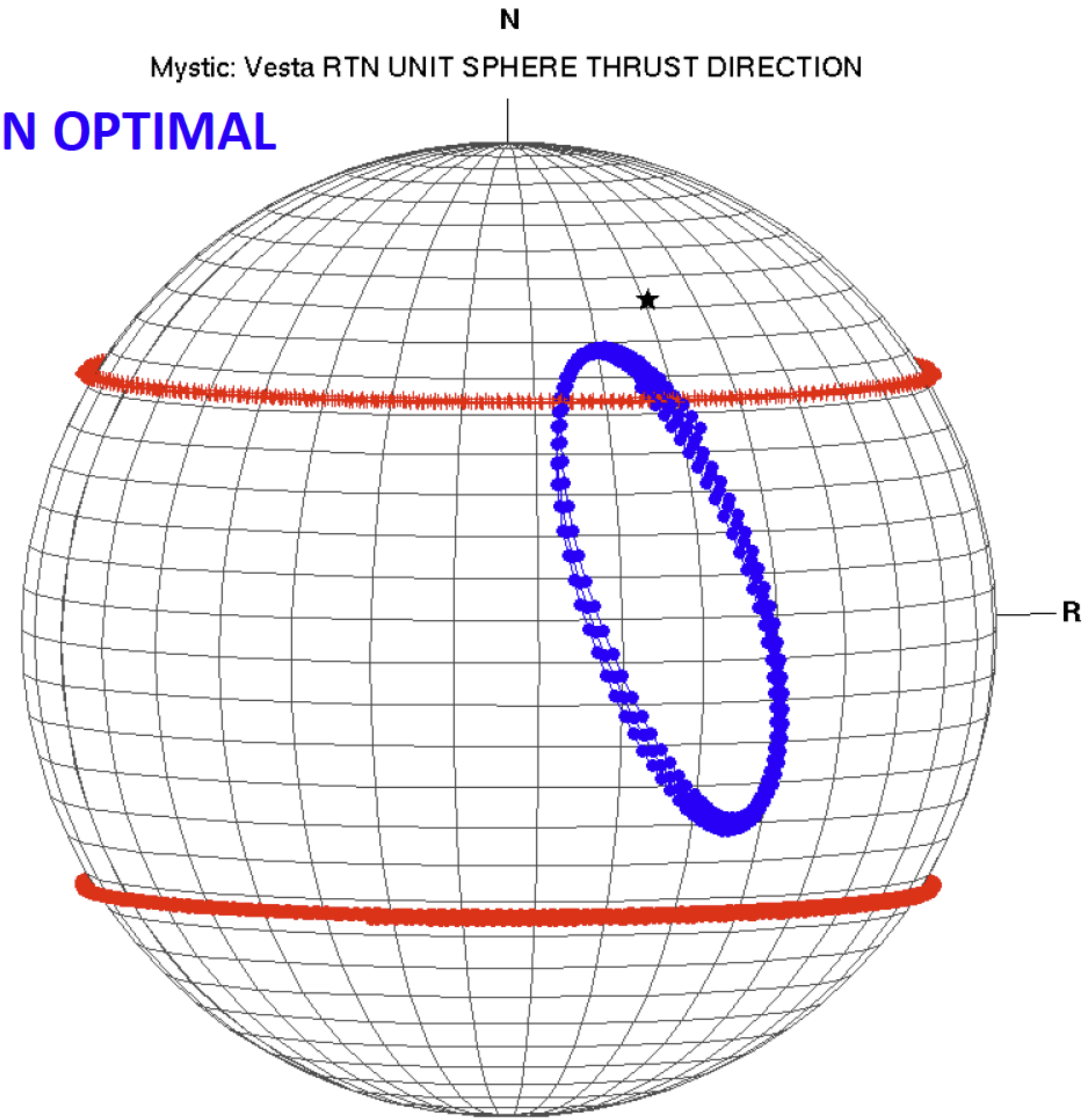

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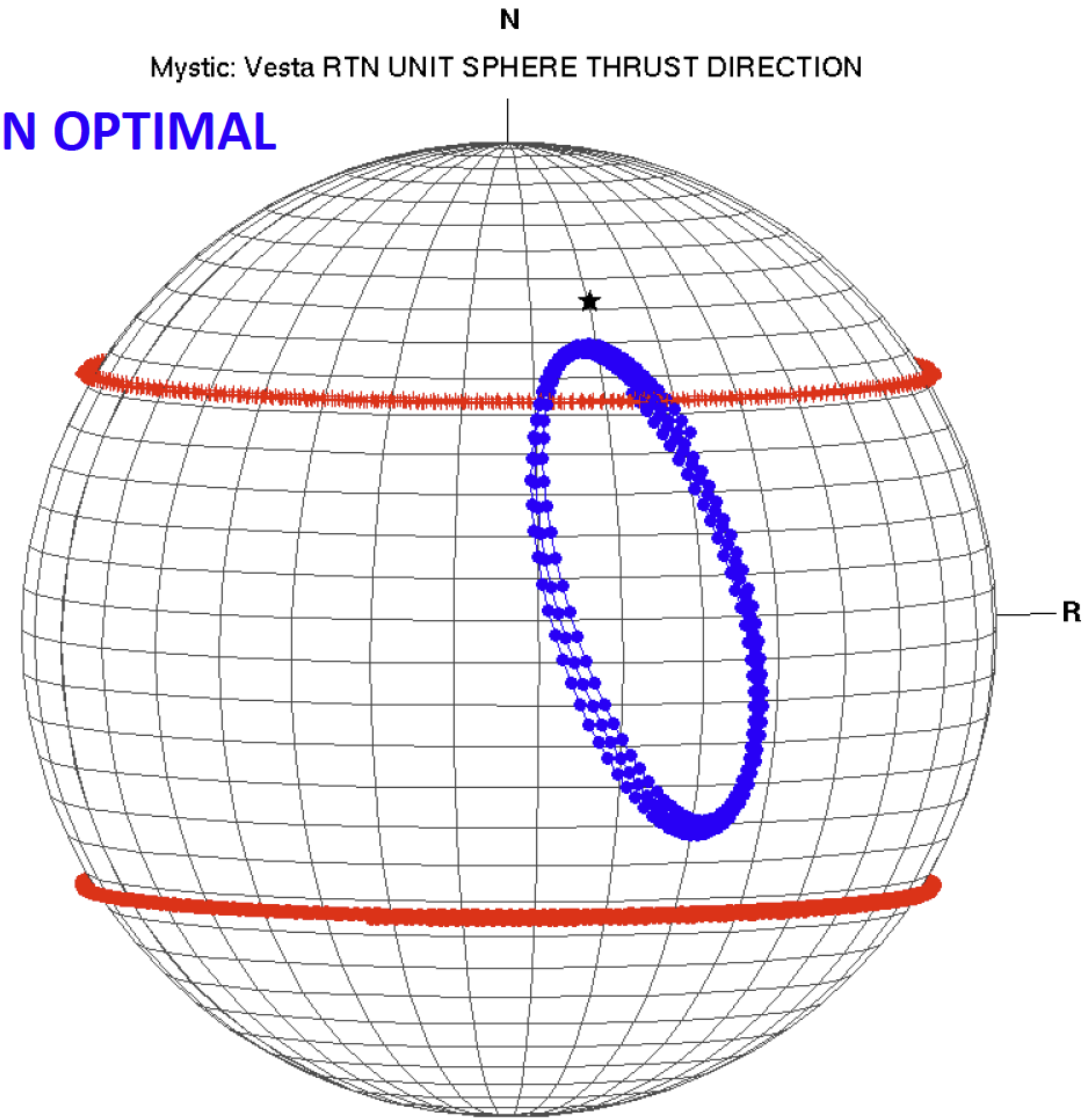

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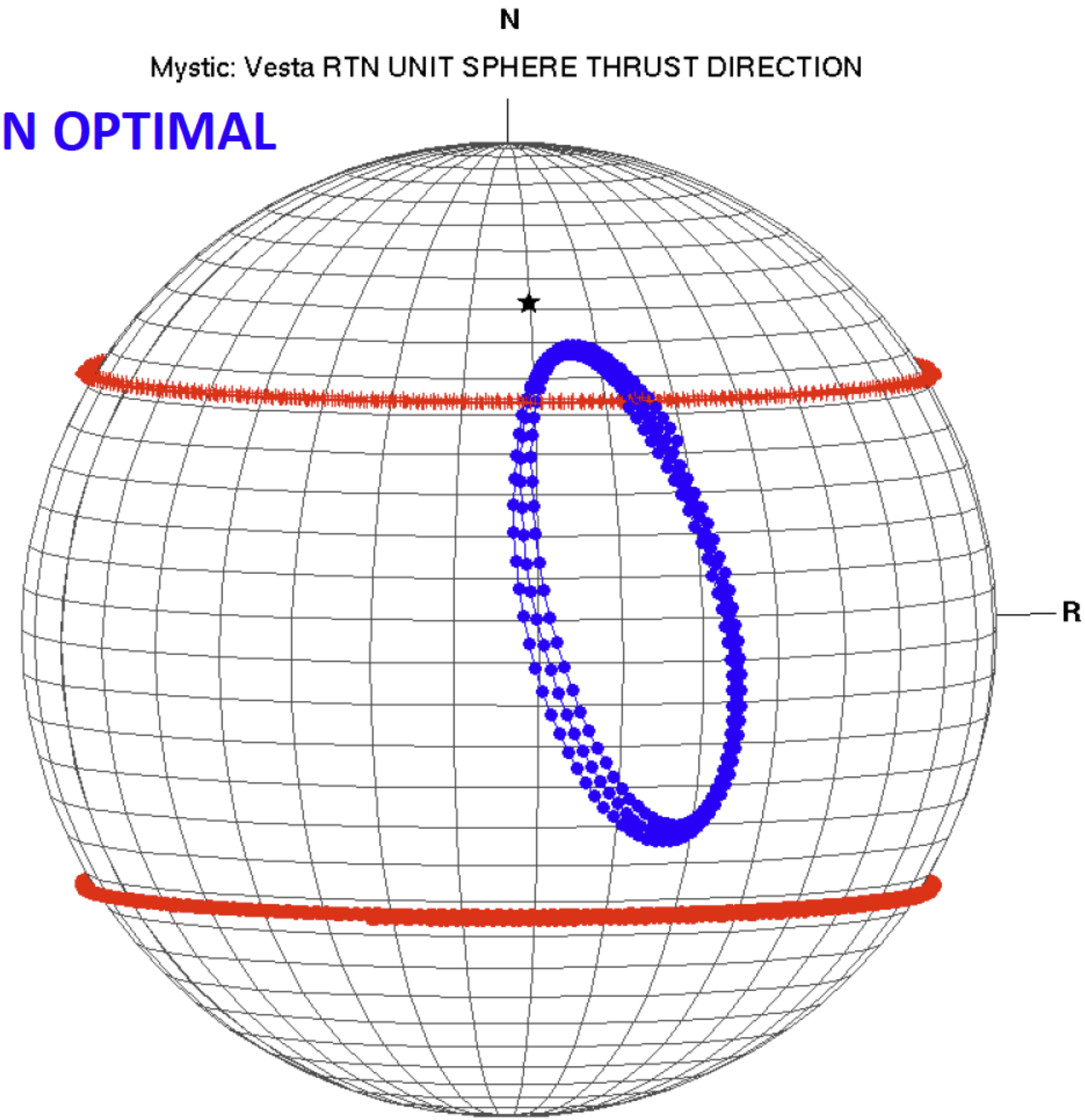

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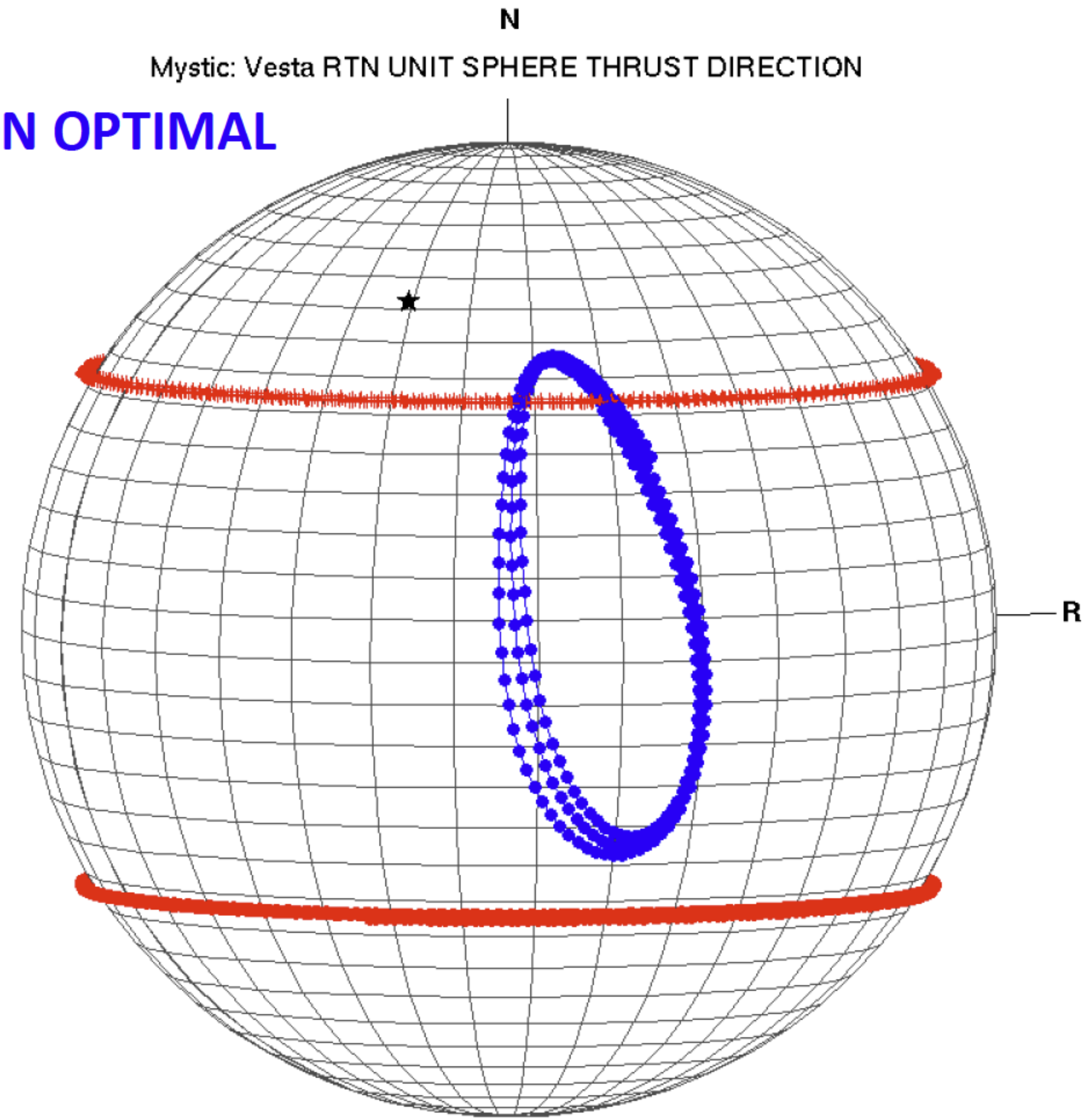

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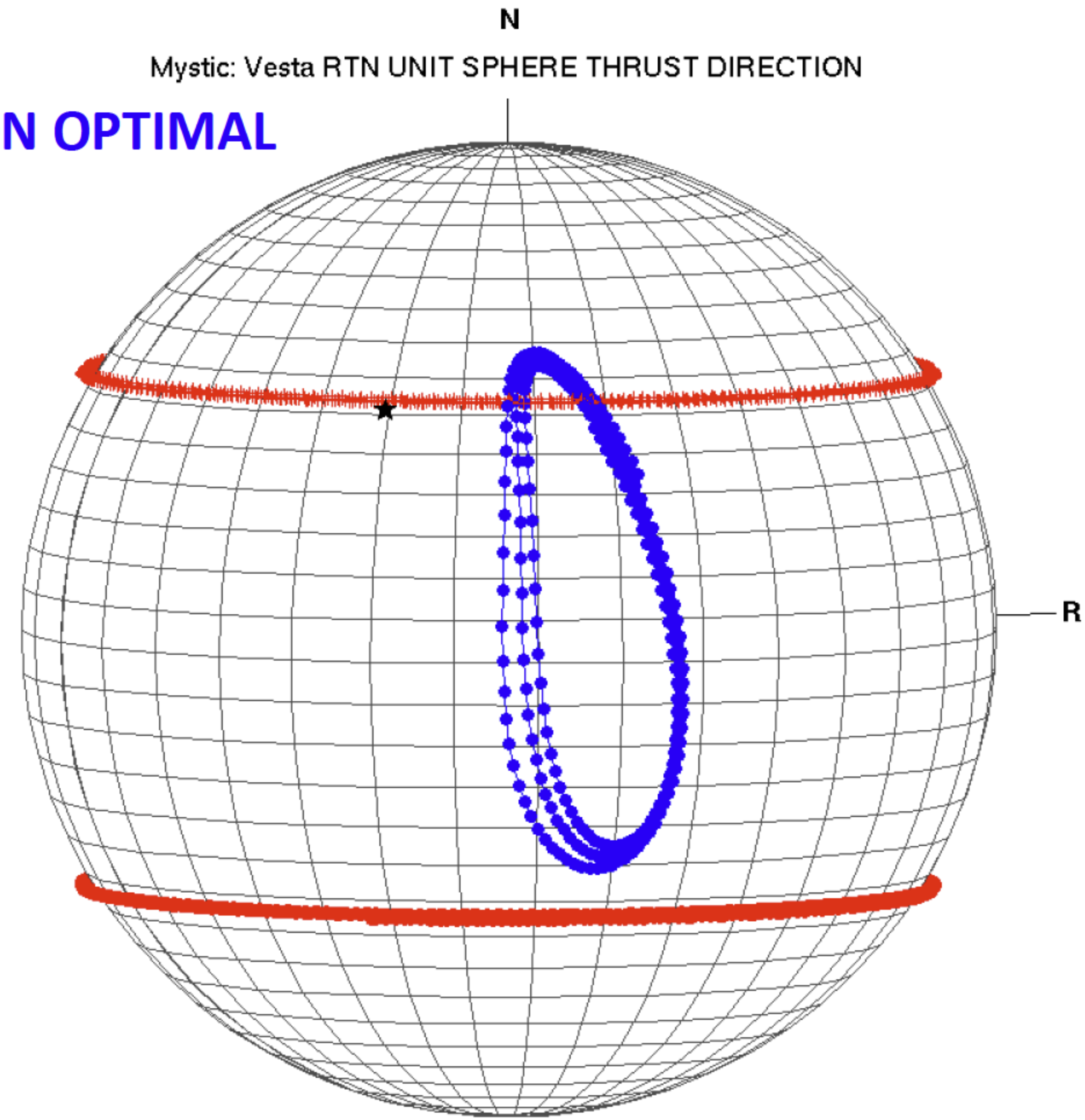

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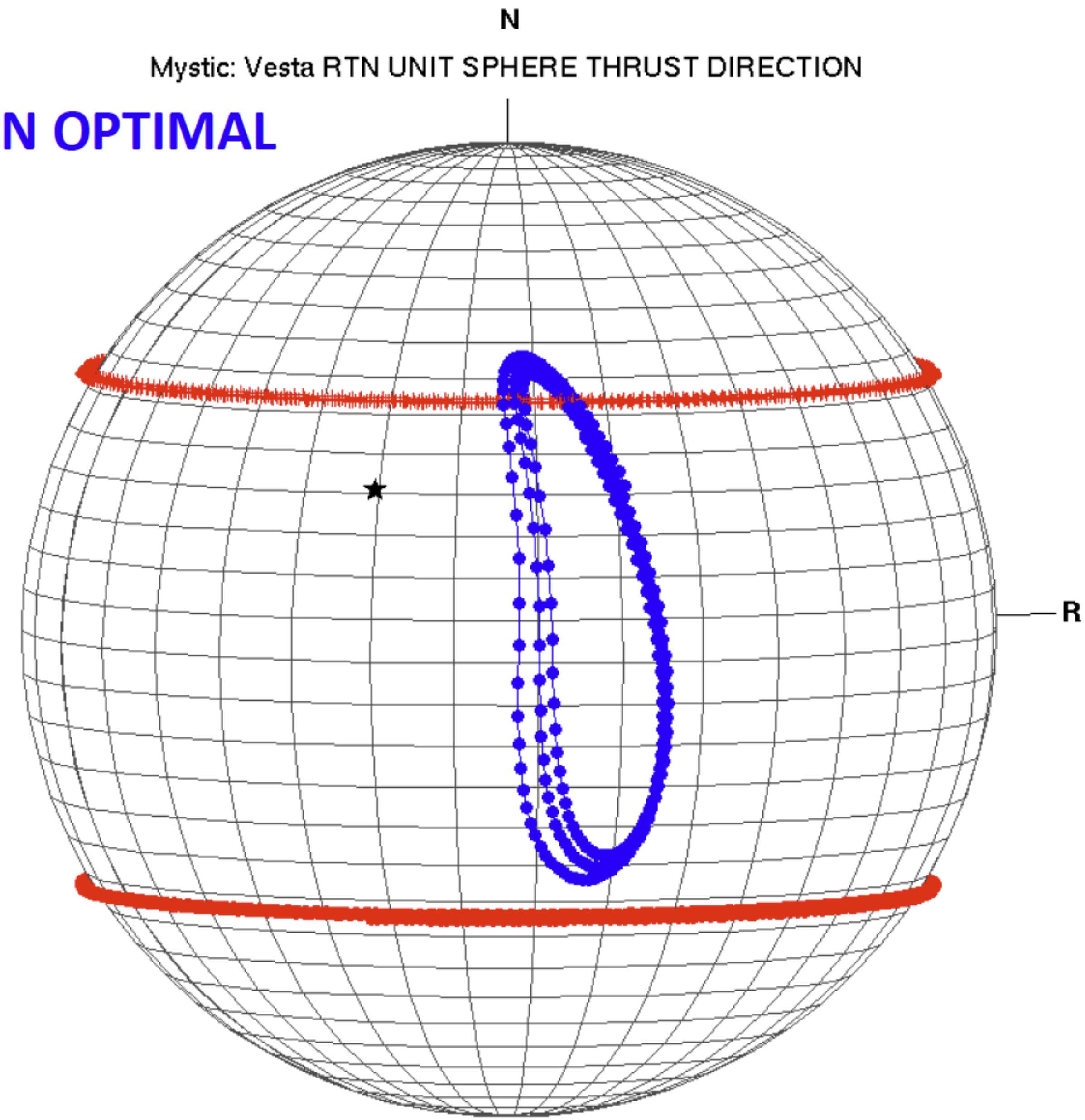

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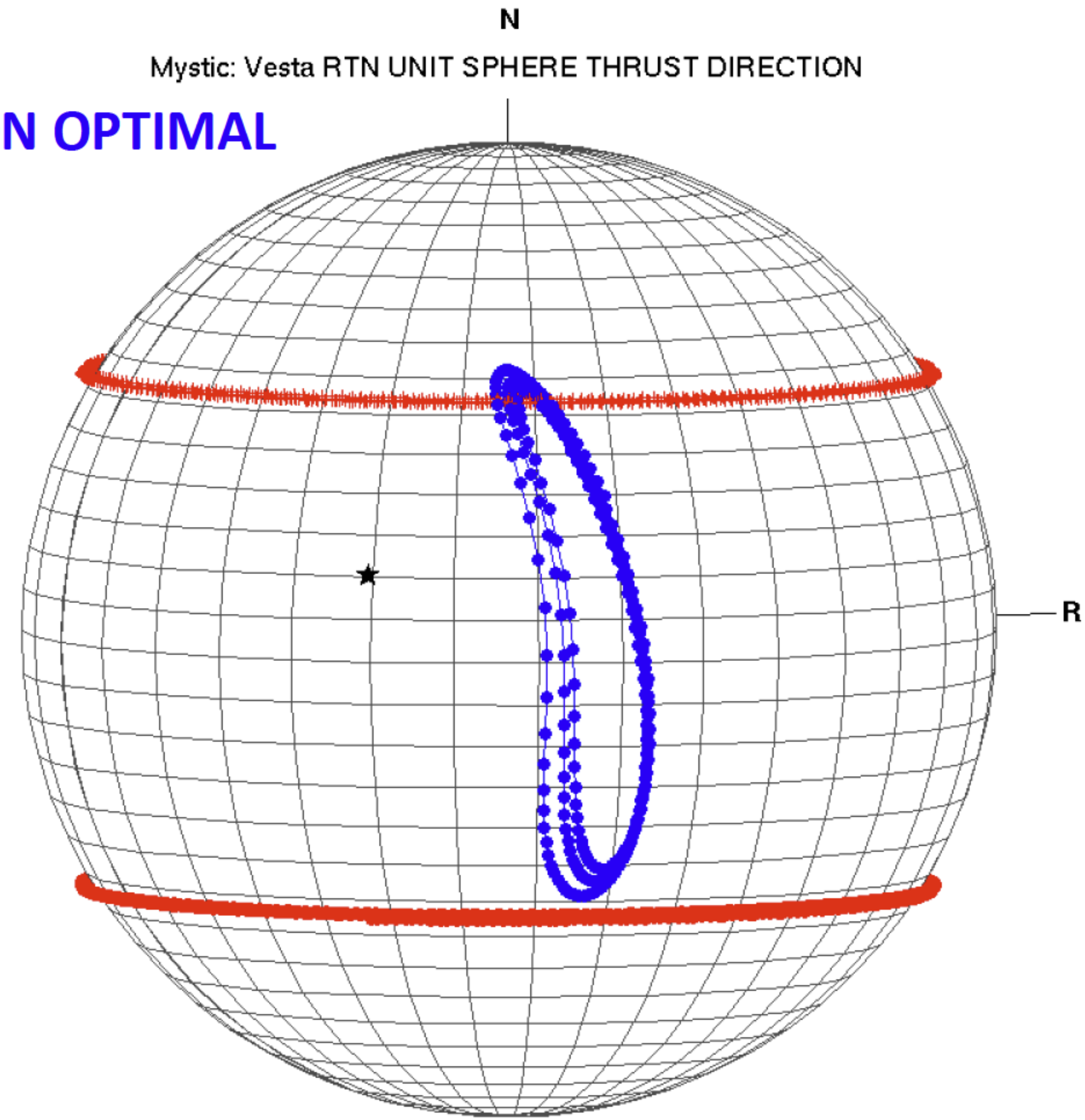

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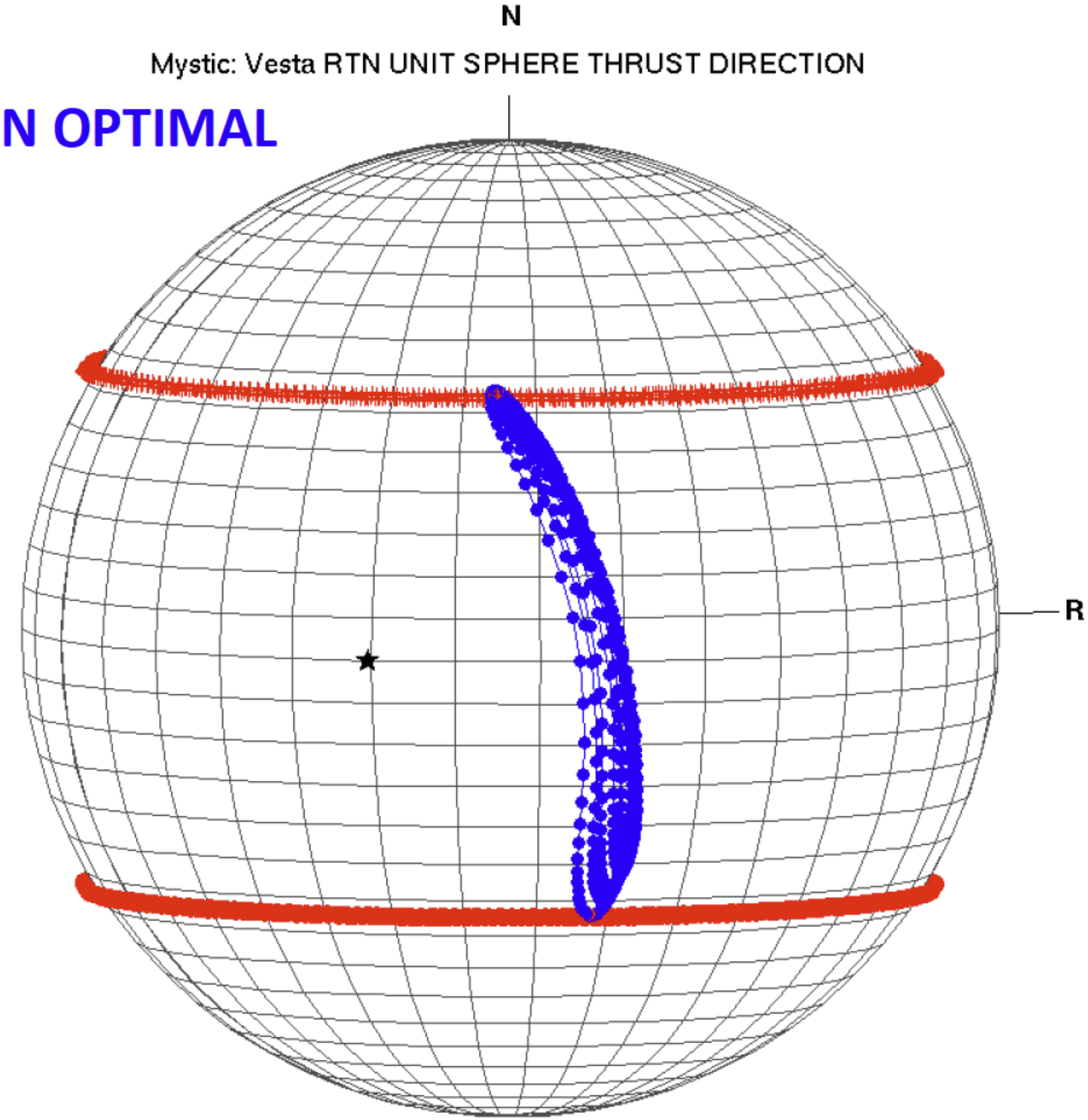

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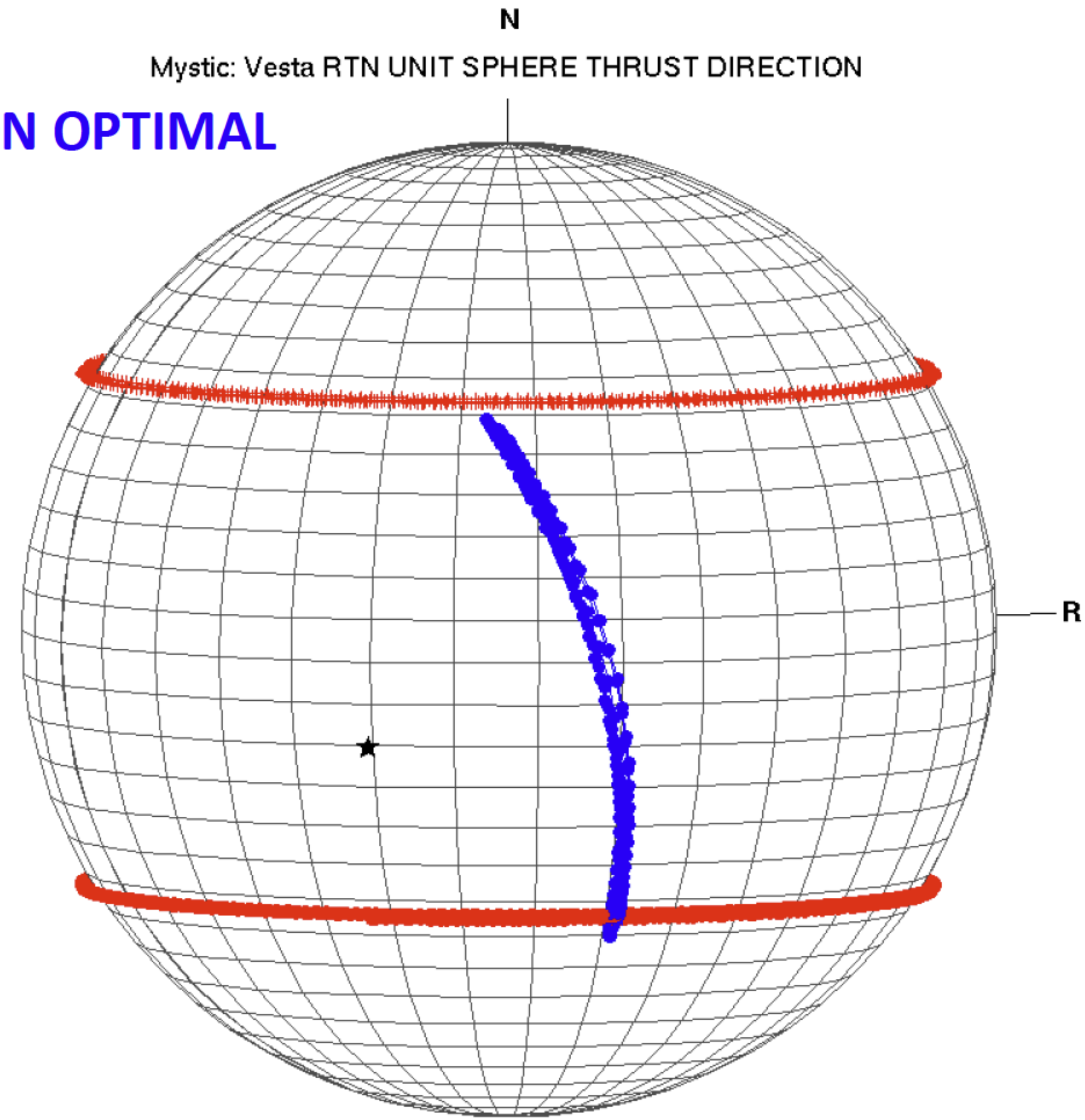

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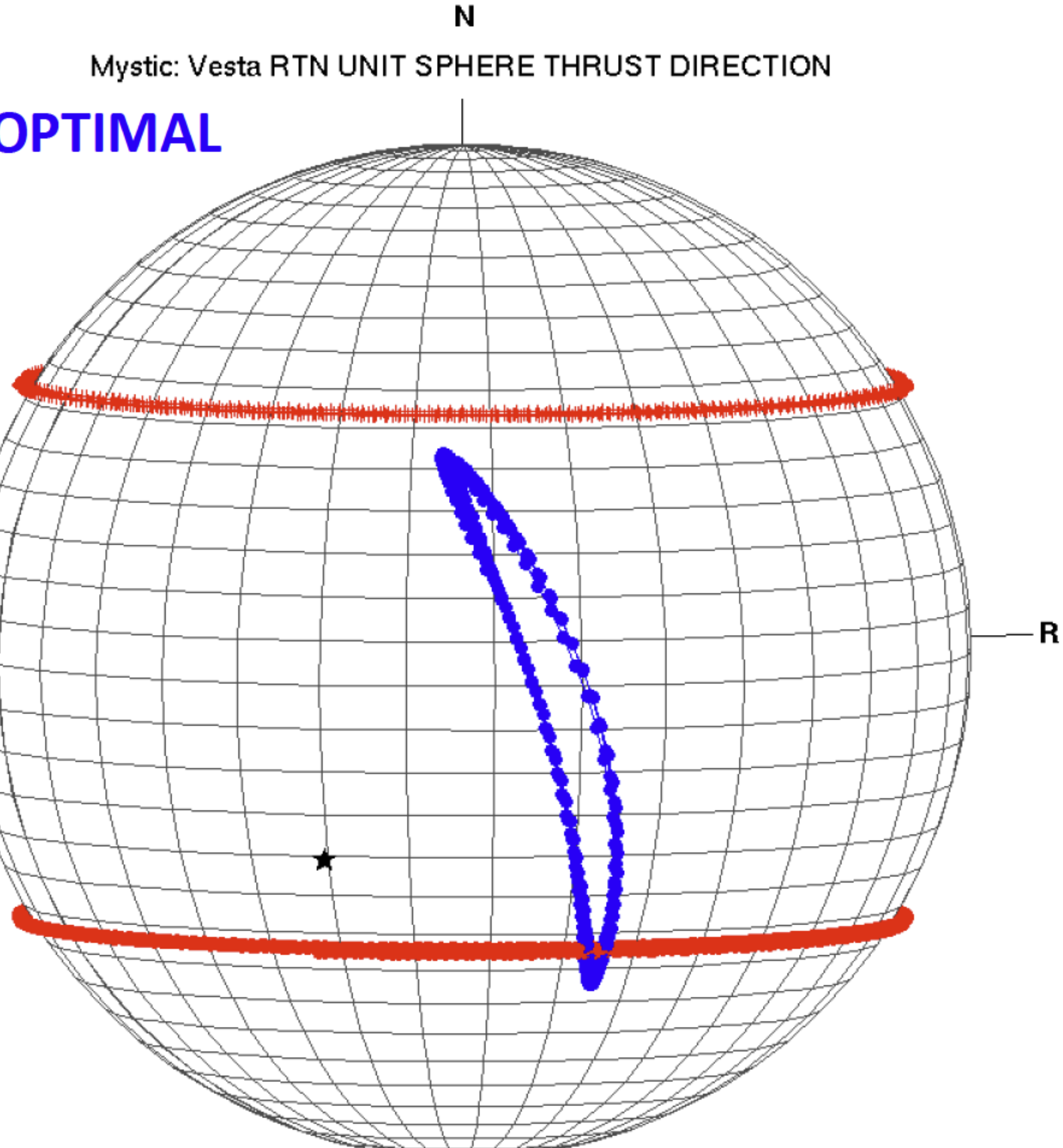

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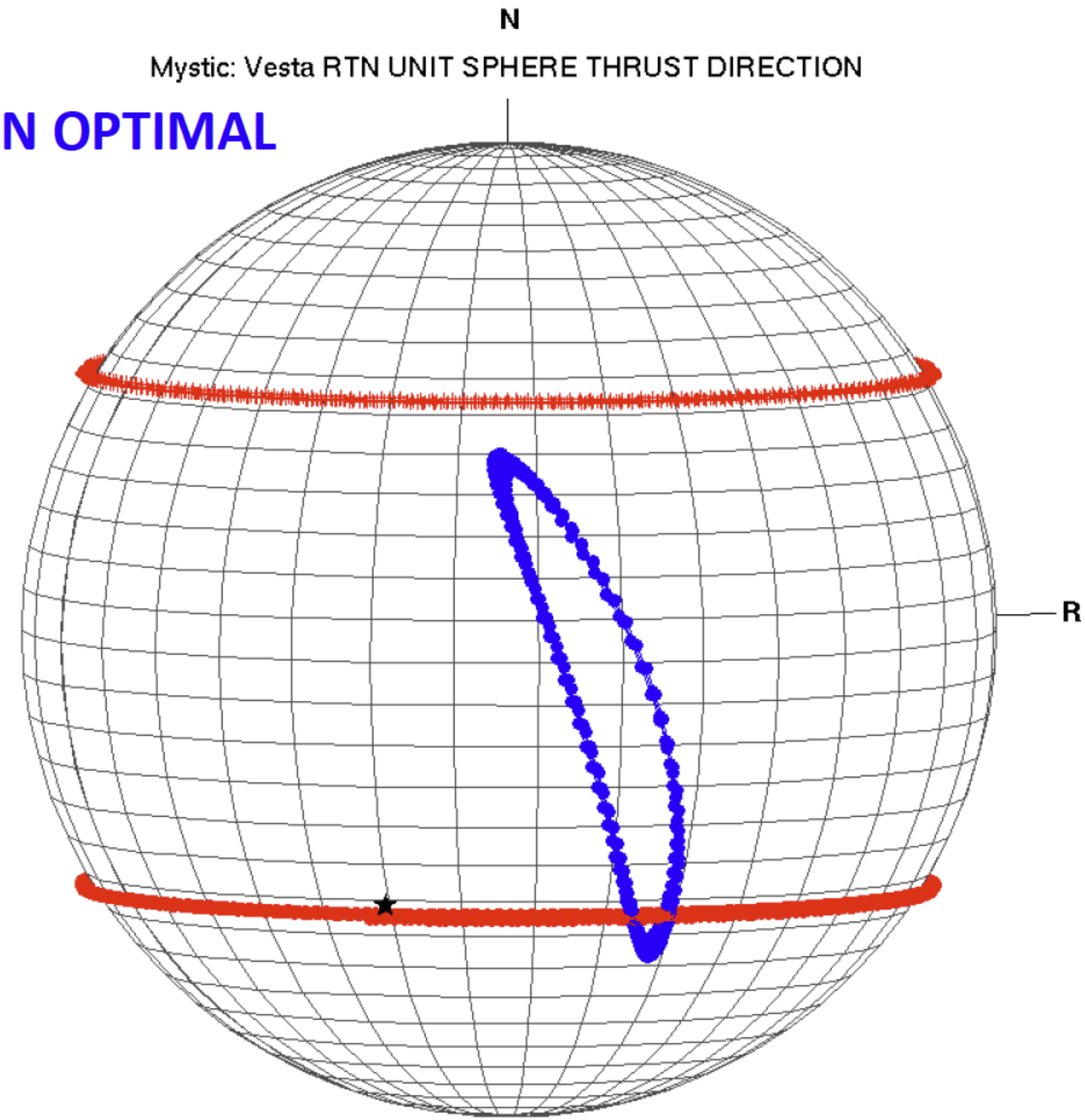

END

Conclusions

- Direction Optimization was essential to Dawn's success at Vesta
- Allowed for timely creation of fly-able maneuvers
- Solutions tended to exhibit direction continuity and smoothness
- Most effective formulation: Direction Attractor in RTN frame. Distant second: inertial frame pole repulsor.
- Generally best to choose frame in which thrust pattern is compact.
- There are many interesting, non-intuitive behaviors of direction optimal solutions