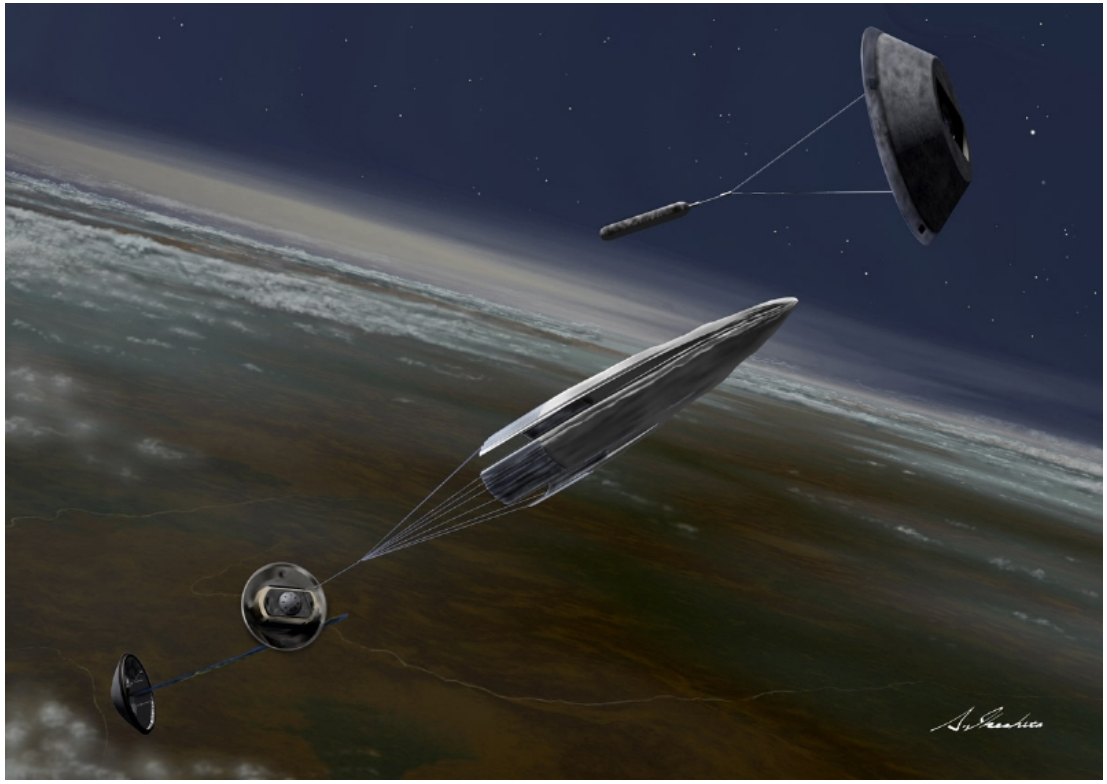
Hayabusa Reentry:
Trajectory Analysis and Observation Mission Design

Hayabusa Re-Entry MAC

International Planetary Probe Workshop-8

Portsmouth, Virginia

June 9, 2011



Alan M. Cassell (ERC Inc.)*, Gary A. Allen (ERC Inc.)*, Michael Winter (UARC), Jay H. Grinstead (NASA ARC)
Manny E. Antimisiaris (DFRC)
Jim Albers (SETI), Peter Jennsikens (SETI)

Outline

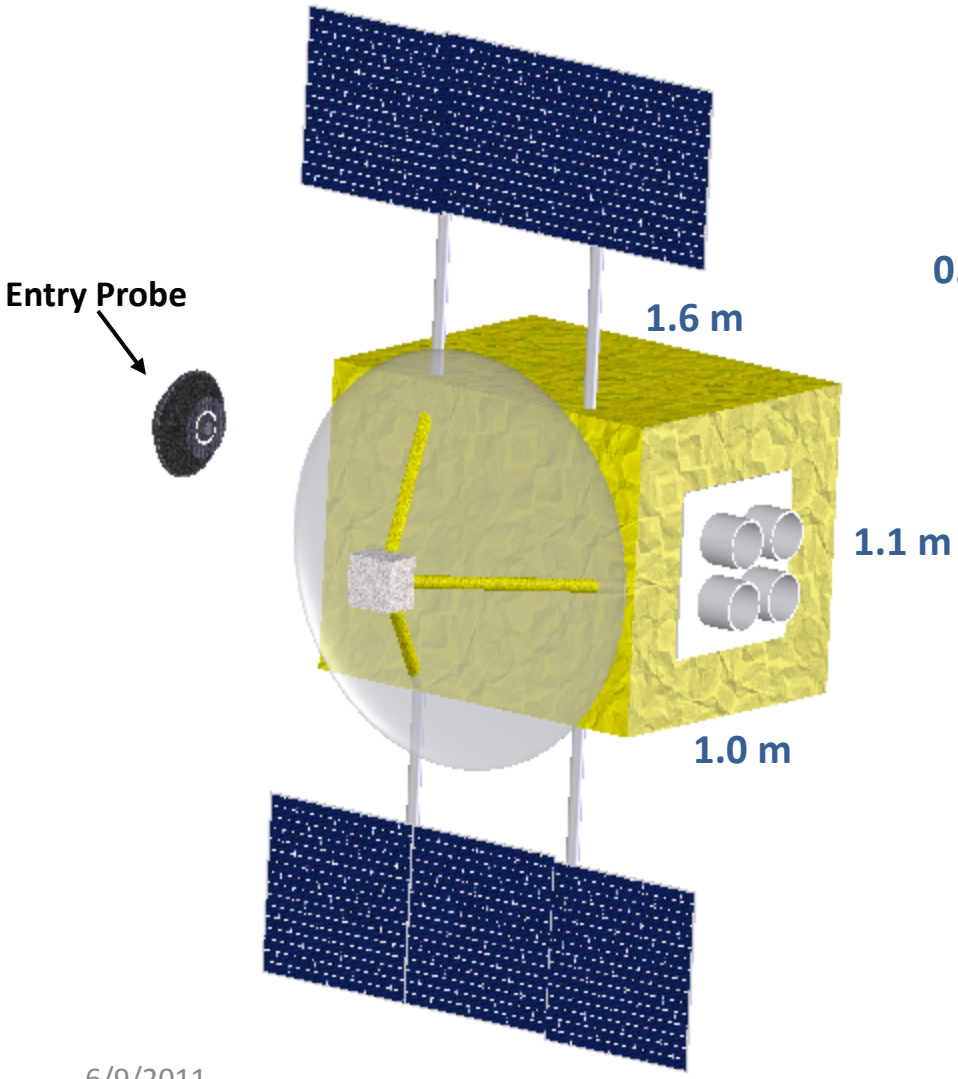
- Hayabusa Reentry Mission Overview
  - Objectives & Description
  - Terminal Approach Key Events
- Observation Mission Design and Planning
  - Process Overview
  - Analysis Tools- *Traj, STK, Observation Flight Simulation Tool*
  - Entry Environment and Trajectory Analysis
  - Observation Flight Planning Trade Study
- Mission Execution
  - Observation Flight Mission
  - Observer Aids - Star Charts (instrument pointing) and Observation Script
- Post Flight Trajectory Analysis
  - Comparisons- 6/11 Entry Trajectory vs Last OD Update
  - Calculated vs Observed Comparisons

Requirements and Constraints

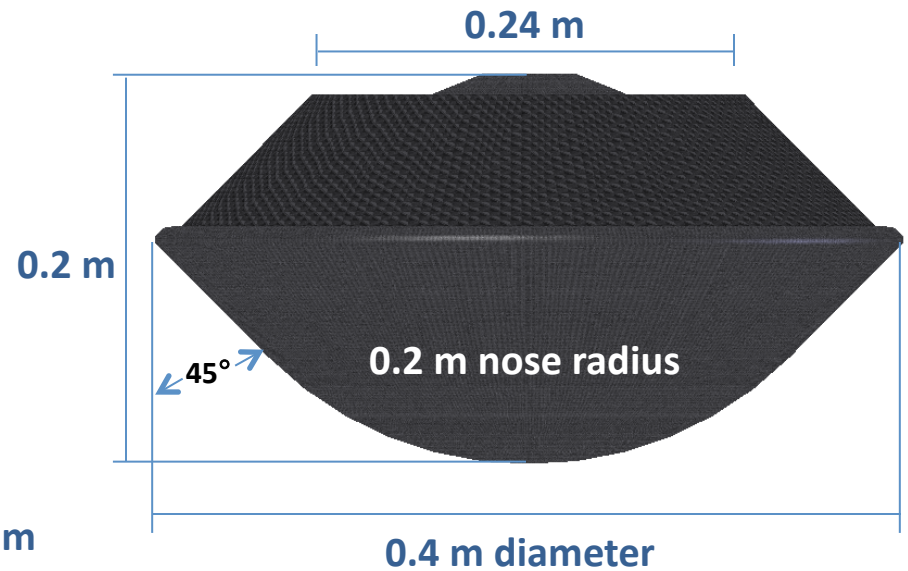
Objectives/Constraints	Rationale
Observe SRC Head-On as much as possible	More light collected by imaging instruments
Maintain velocity vector to observer angle of < 45 deg through peak heating	Optimal viewing geometry for 45 deg sphere cone reentry body
Maintain < 16 deg elevation angle during peak heating window	Ease of tracking through DC-8 windows
< 250 km range to SRC at peak heating	Ensures enough brightness
Maintain +/- 60 km keep out zone on either side of ground track	Safety- Debris avoidance
Maintain level flight at 12 km altitude	Facilitates manual tracking of SRC and minimizes atmospheric absorption from H_2O

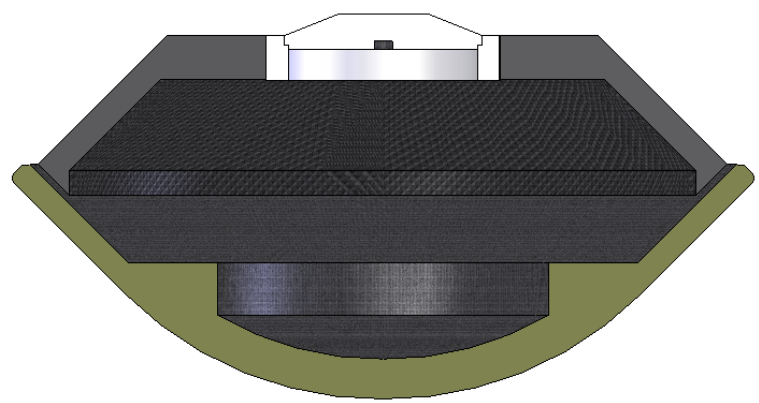
Hayabusa Spacecraft and Entry Probe

Spacecraft Bus



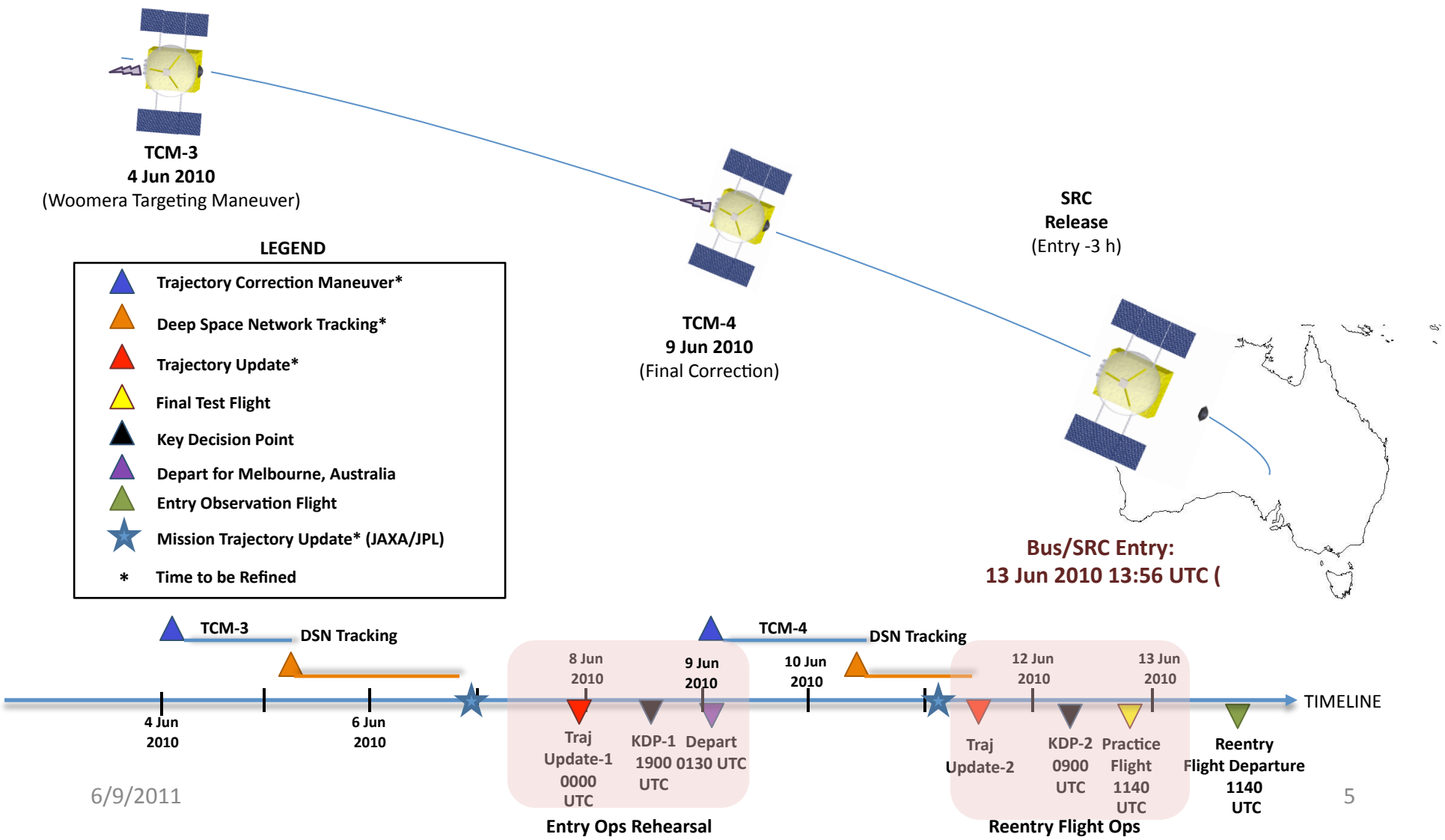
Entry Probe





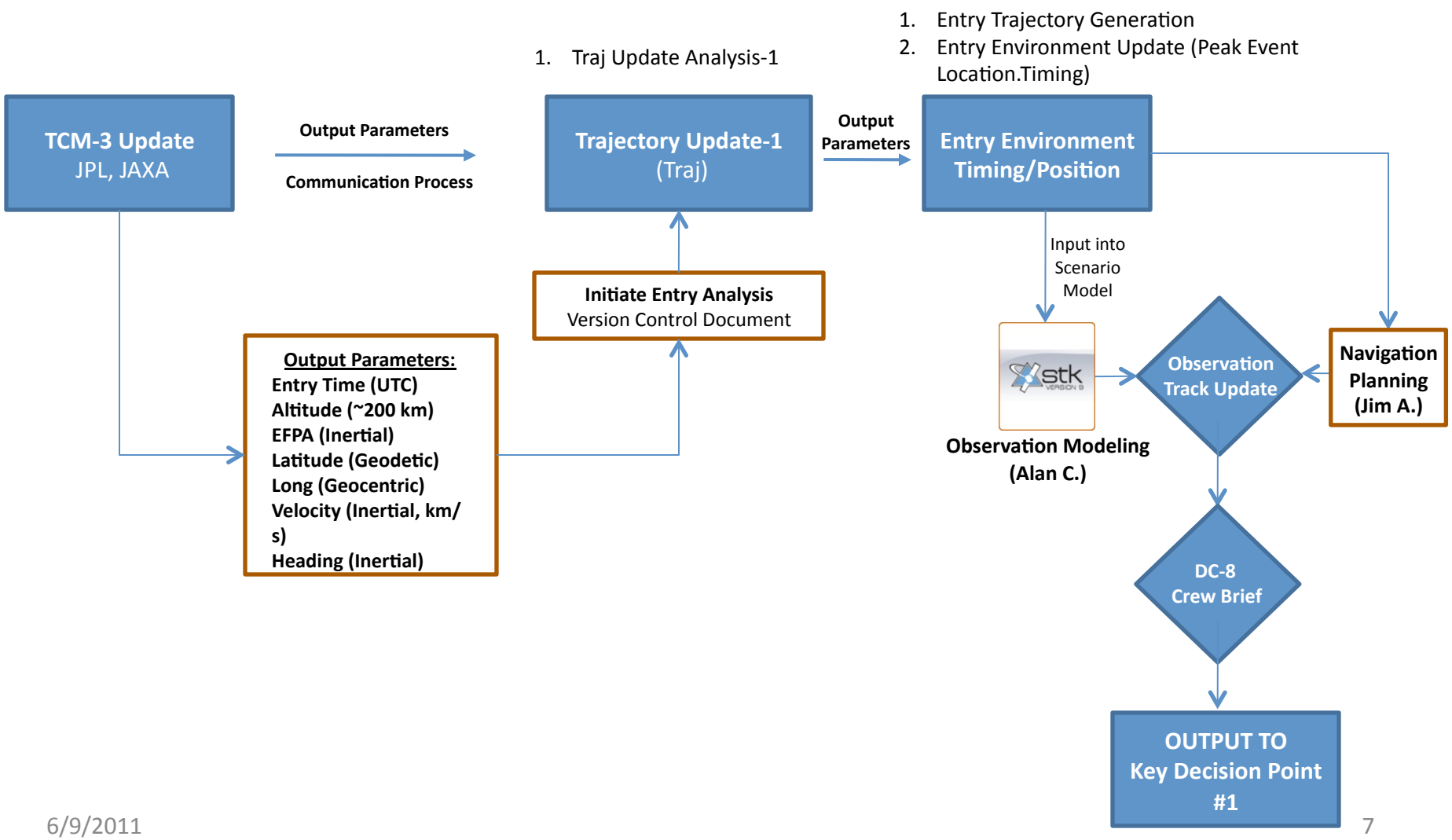
Cross sectional view of aeroshell

Hayabusa Terminal Approach Key Events

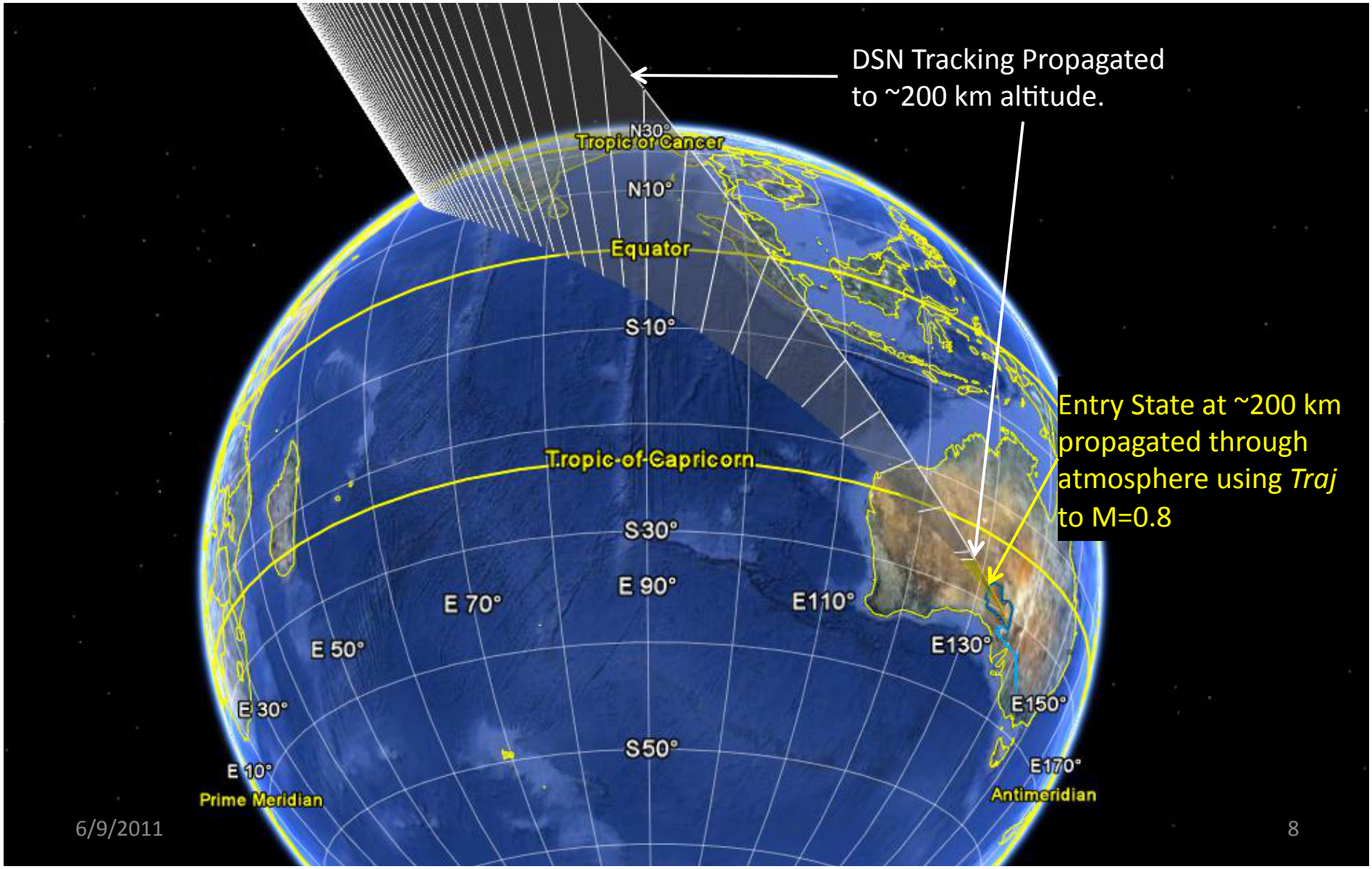


Observation Mission Design and Planning

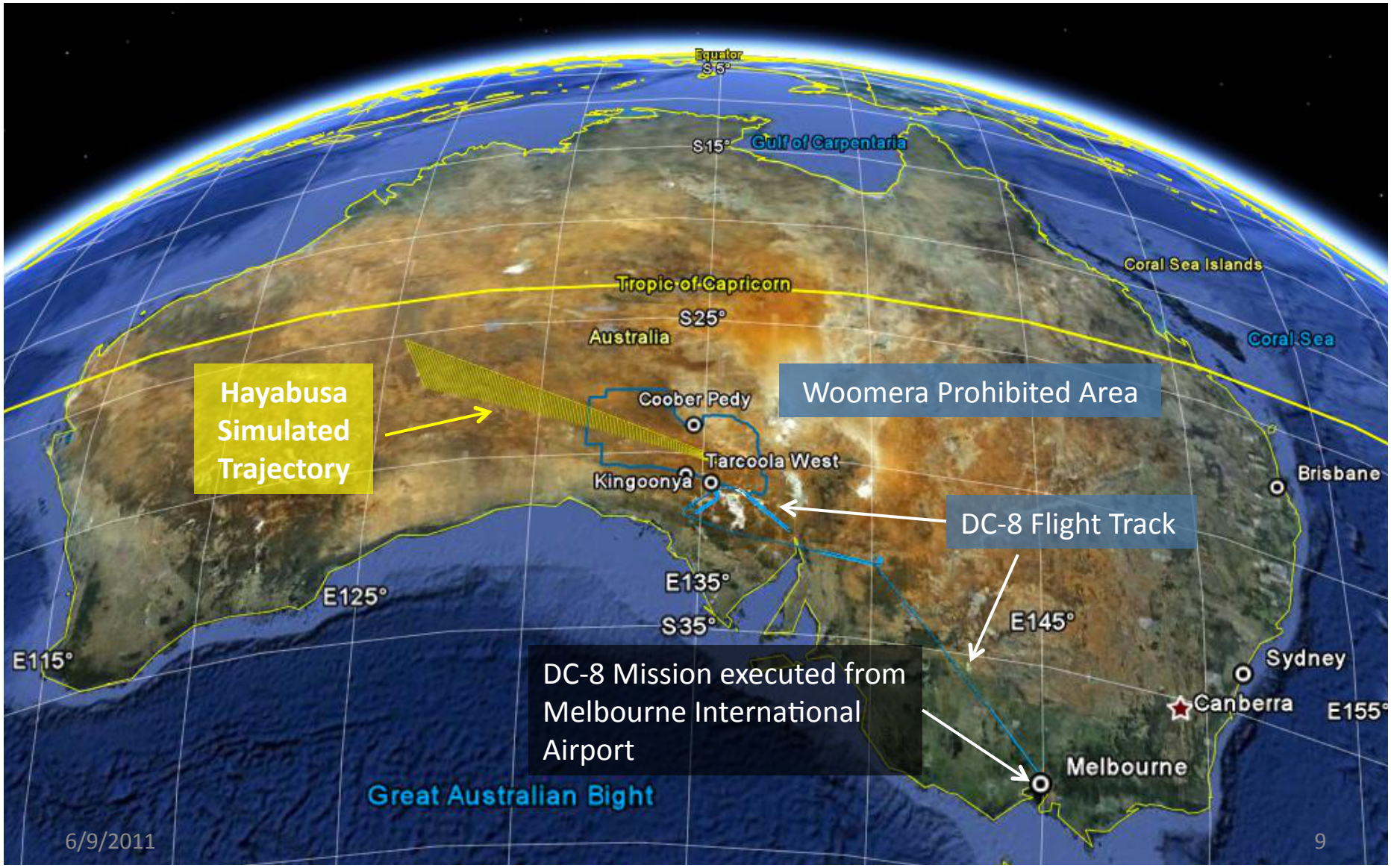
Observation Mission Planning Process



Hayabusa Tracking to Entry Interface



Hayabusa Observation Mission Overview



Analysis Tools

Traj -Atmospheric Entry Simulation Tool (v. 12.0)

- Outputs 3 DOF trajectory simulation
- Provides Aerothermodynamic heating prediction (Stagnation Point)
- Provides thermal protection material response (embedded FIAT)

STK (ver 9.0.0) Satellite Tool Kit

- Scenario Modeling and Visualization Tool
- Detailed analysis and comparison between trajectories
- Calculates Azimuth, Elevation and Range Data from Observer locations

Custom Observation Simulation Tool (Jim Albers)

- Used for ATV reentry observation
- Analysis of Key Observation Metrics
- Quick flight track updates, wind compensation script

Hayabusa Reentry- Entry State, Environments and Design

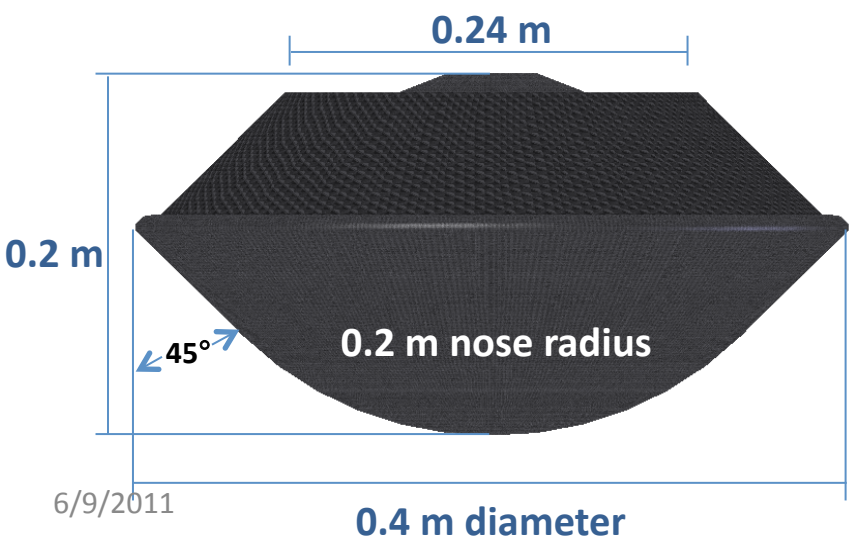
Entry State

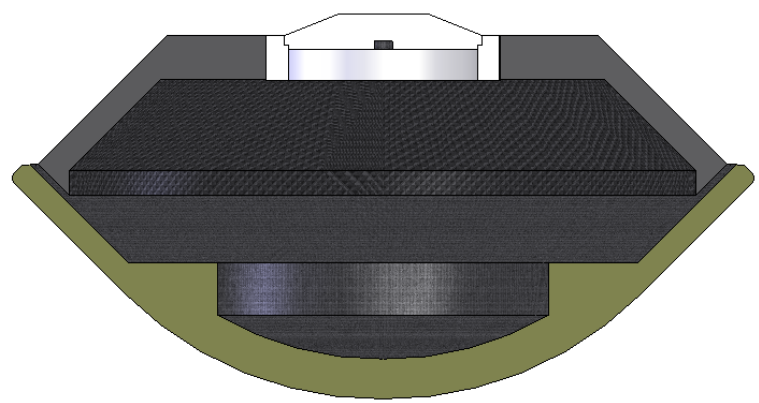
Parameter	Value (JPL OD Update 6/11/10, v2)
Flight Path Angle (Inertial)	-12.35 deg
Altitude	201.992 km
Heading	112.06 deg
Inertial Velocity	12.035 km/sec
Latitude (Geodetic)	-27.36 deg
Longitude	126.38 deg

Entry Environments*

Parameter	Value
Peak Heating	1112 W/cm^2
Peak Convective	949 W/cm^2
Peak Radiative	185 W/cm^2
Peak Deceleration	49 g
Peak Dynamic Pressure	53 kPa
Ballistic Coeff. (40 km)	110 kg/m^2
Total Heat Load	21.2 kJ/cm^2

* Generated within Traj using JPL OD 100611v2 Entry State





Cross sectional view of aeroshell

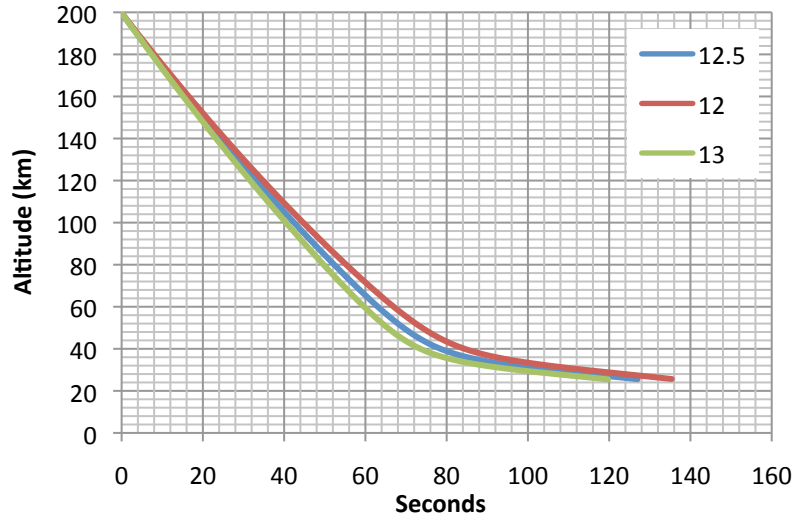
Entry Environment-Sensitivities

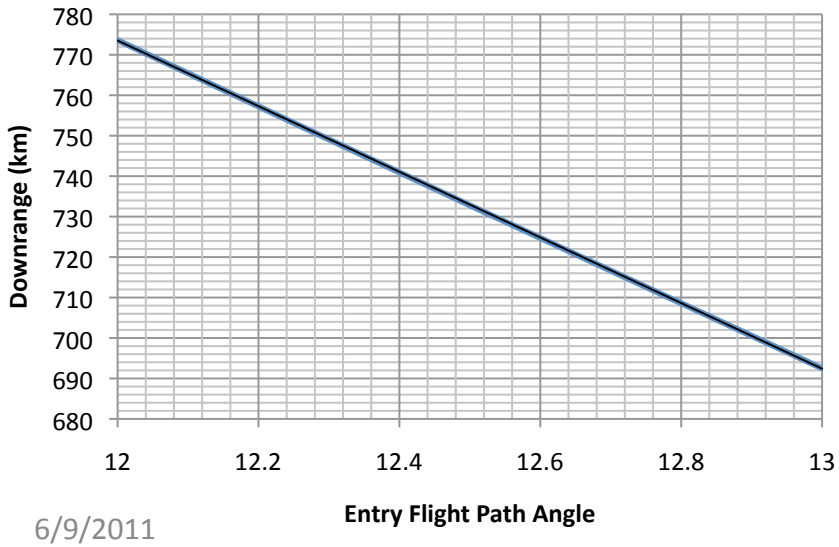
Based upon updated trajectory after TCM-4
Version-OD-100611v2

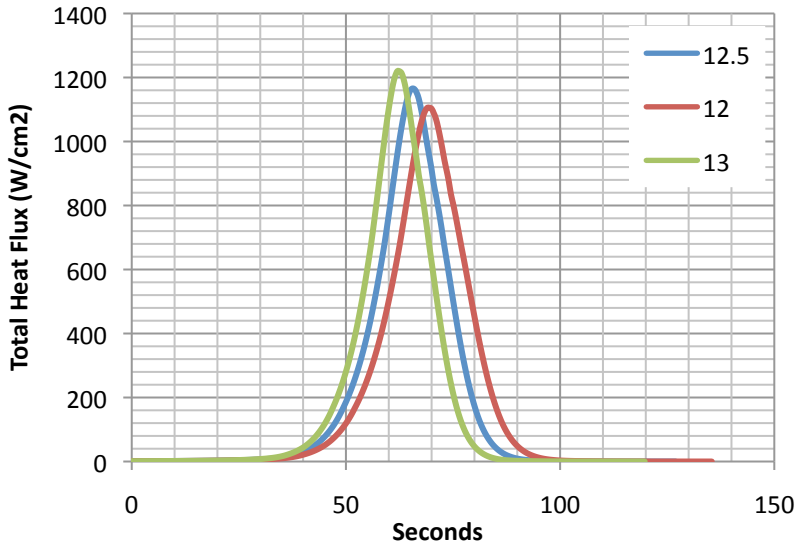
Atmospheric model:	US_1976
Geometry	45 deg sphere cone
Nose radius:	0.2 m
Base radius:	0.202 m
Entry mass:	18 kg
Entry Velocity:	12.022 km/sec (inertial)

Assumes same entry interface point for each case

Entry Gamma	Final (geocentric) Lat.	Long.	Peak Decel	Peak Heat	Total Flux	Peak Pressure
deg.	deg.	deg.	g	W/cm^2	J/cm^2	Pa
-12	-30.19	135.75	46.3	1106.5	22258.04	1.03E+05
-12.5	-30.03	135.17	51.07	1165.51	21494.94	1.13E+05
-13	-29.89	134.67	55.67	1221.45	20845.12	1.23E+05

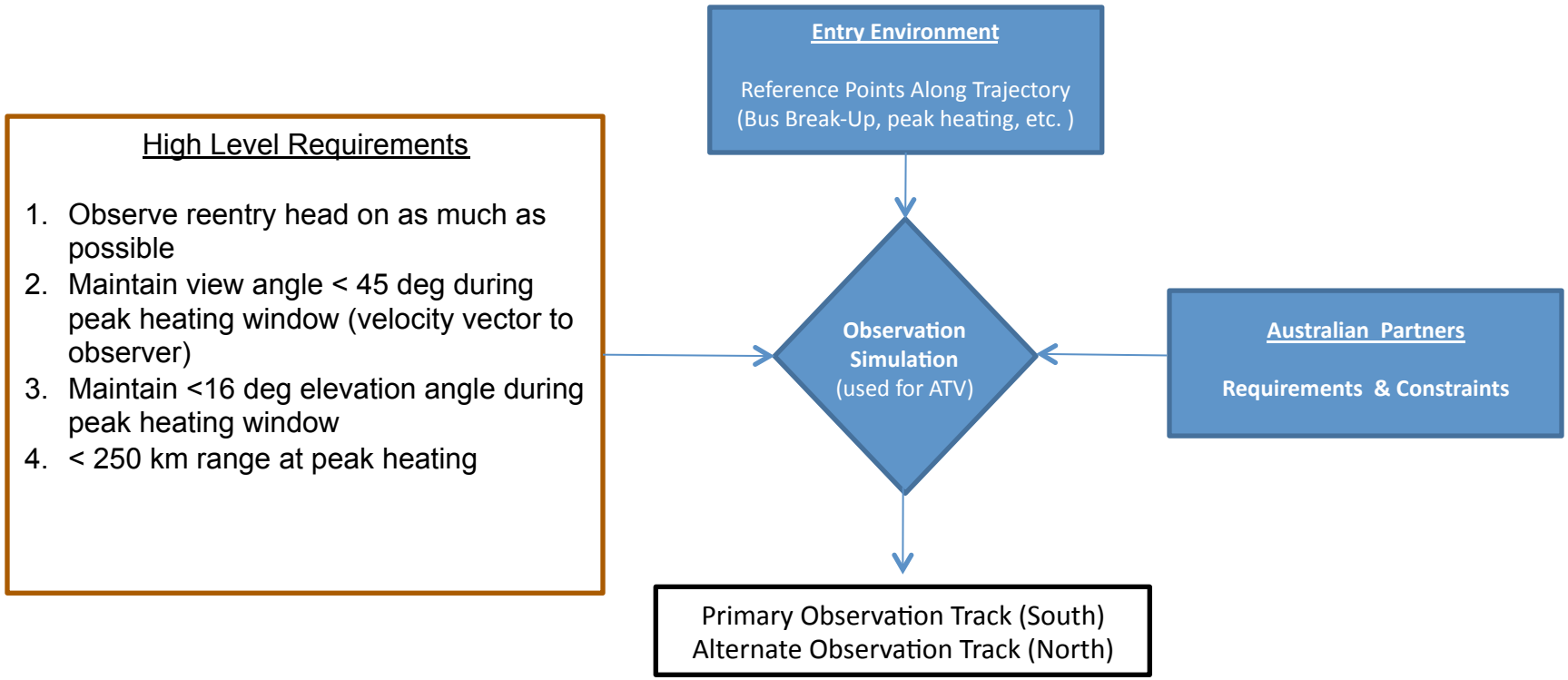




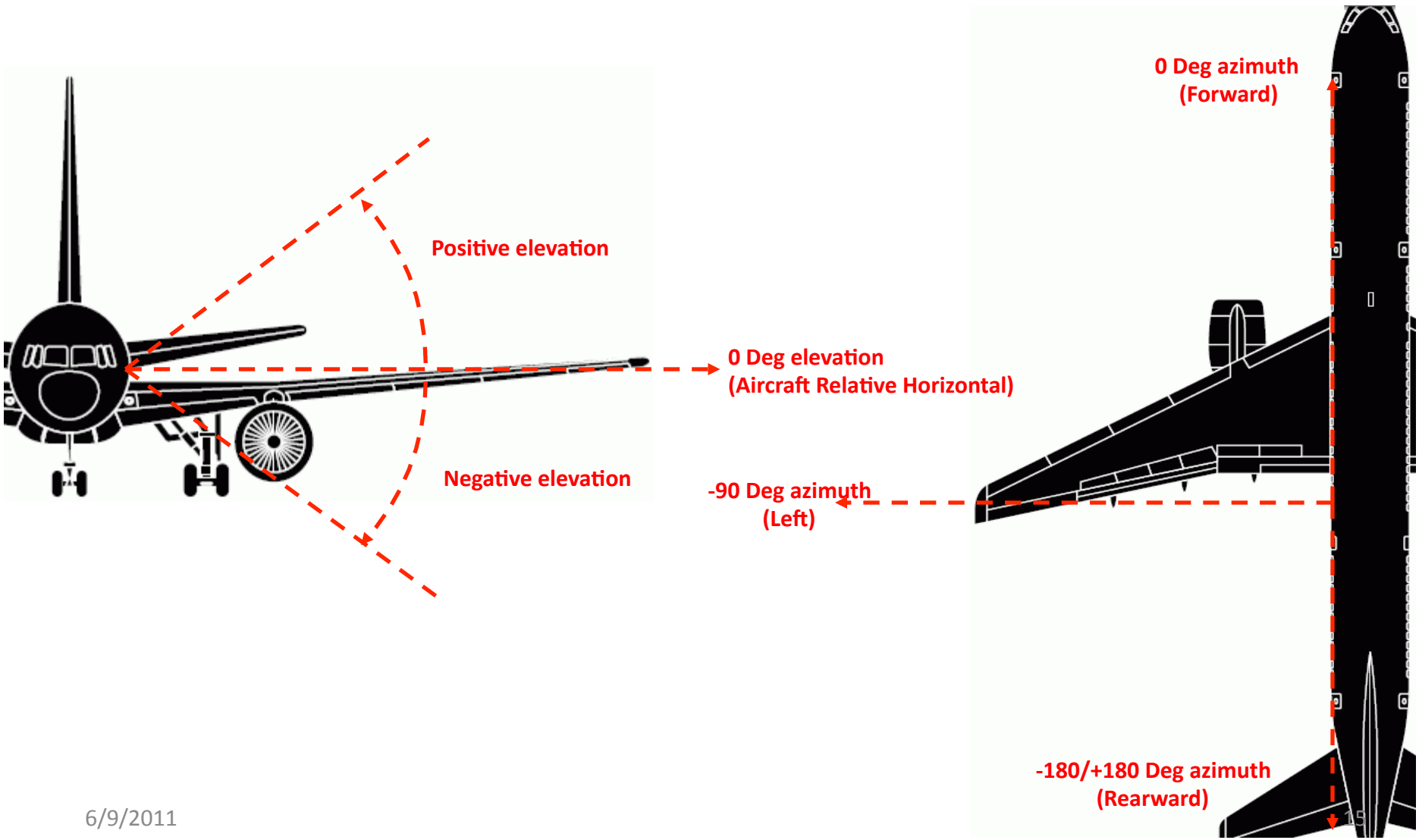


STK: 3-d Animation of Reentry

DC-8 Observation Track Planning Process



Azimuth and Elevation (Az/El) Relative to Aircraft



Observation Simulation Tool

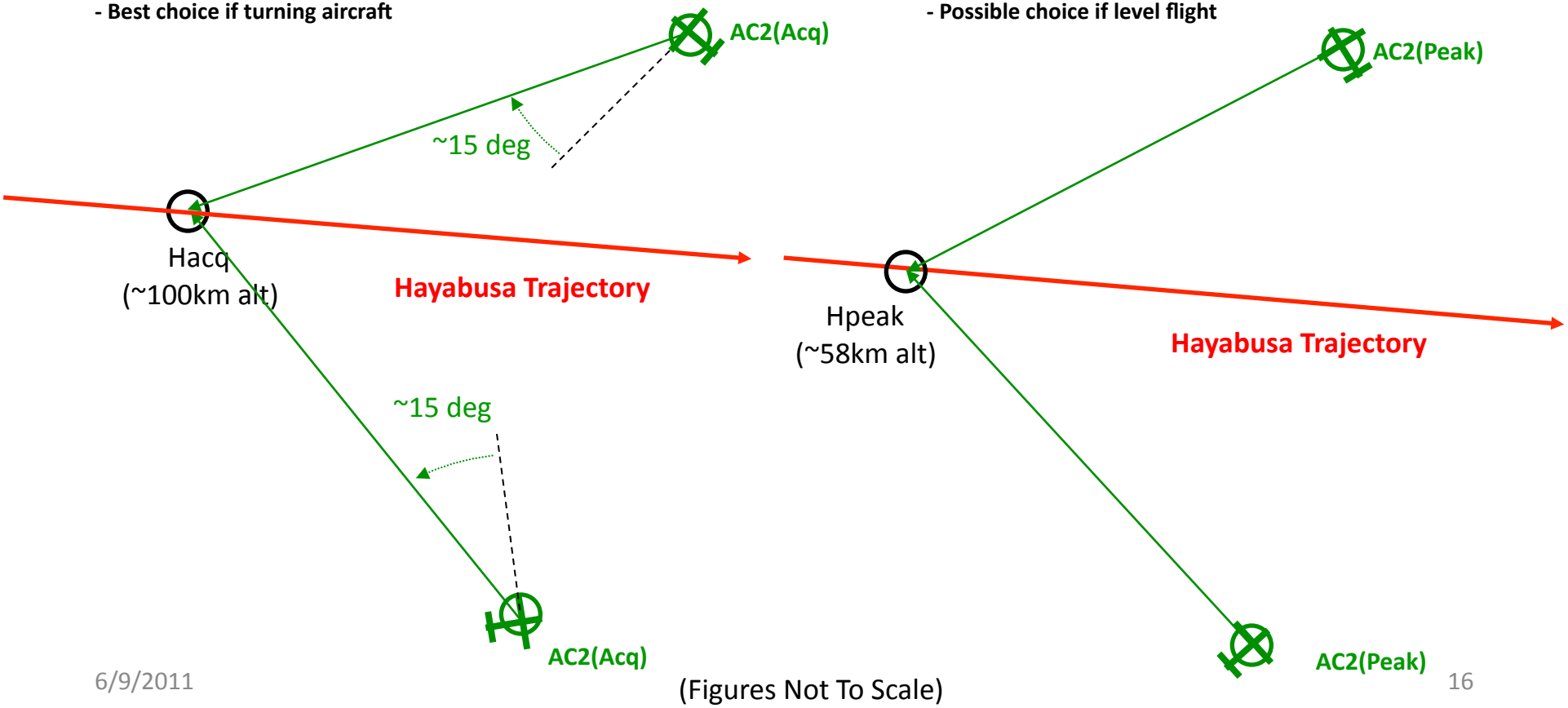
Utilized in Detailed Observation Track Design Trades

Jim Albers/Peter Jenniskens

~30 Observation Flight Track Options Explored in Detail

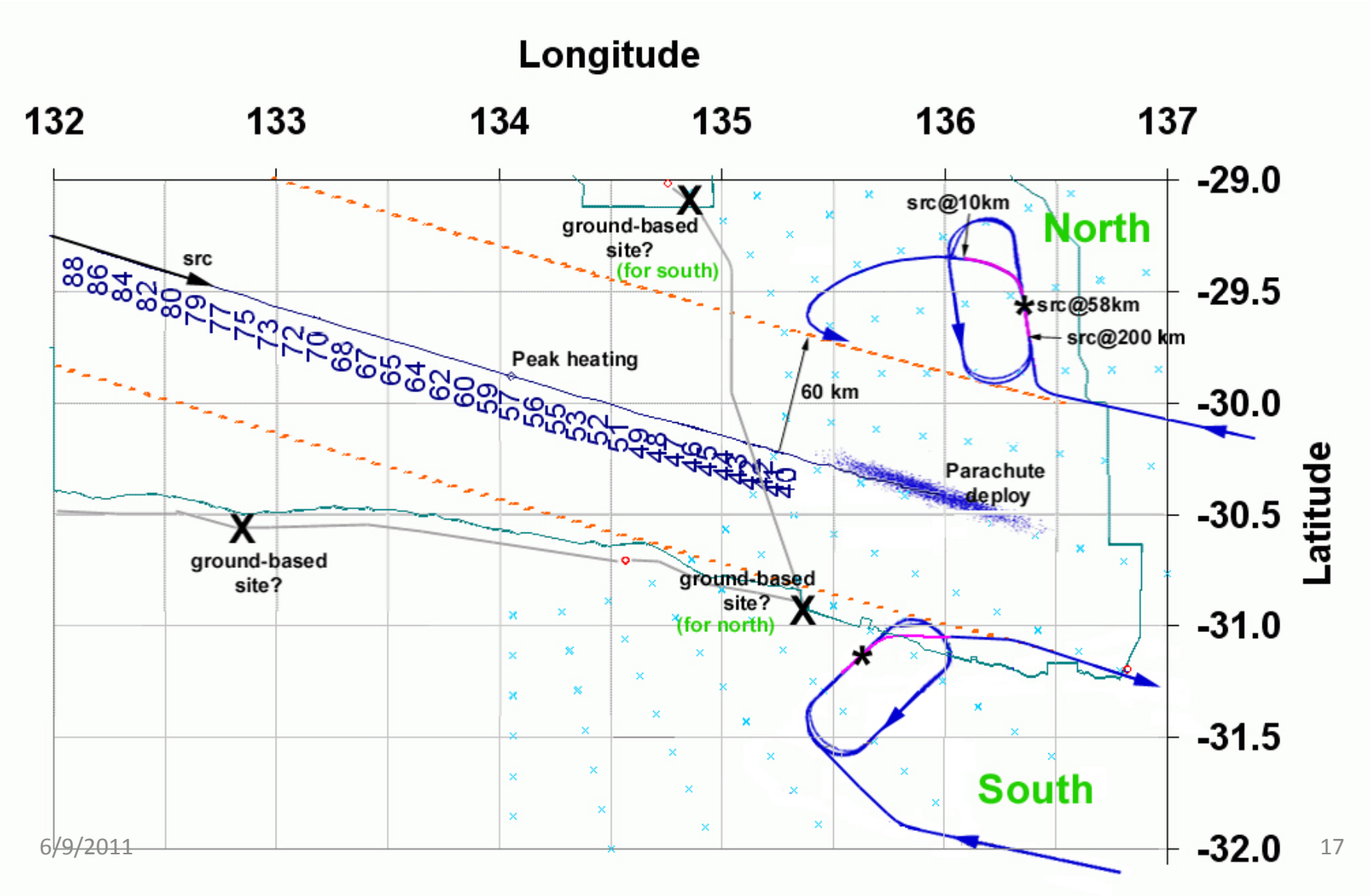
1) Relative to first brightening of Hayabusa (~100km alt)
- **15 deg forward from perpendicular for North position**
- **15 deg rearward from perpendicular for South position**
- **Keep desired portion of trajectory within +/- 15 deg of perpendicular**
- **Best choice if turning aircraft**

2) Relative to Hayabusa peak heating point (~58km alt)
- **Peak heating perpendicular to aircraft**
- **Select aircraft position for desired observation time before and after peak heating (+/- 15 deg of perpendicular)**
- **Possible choice if level flight**

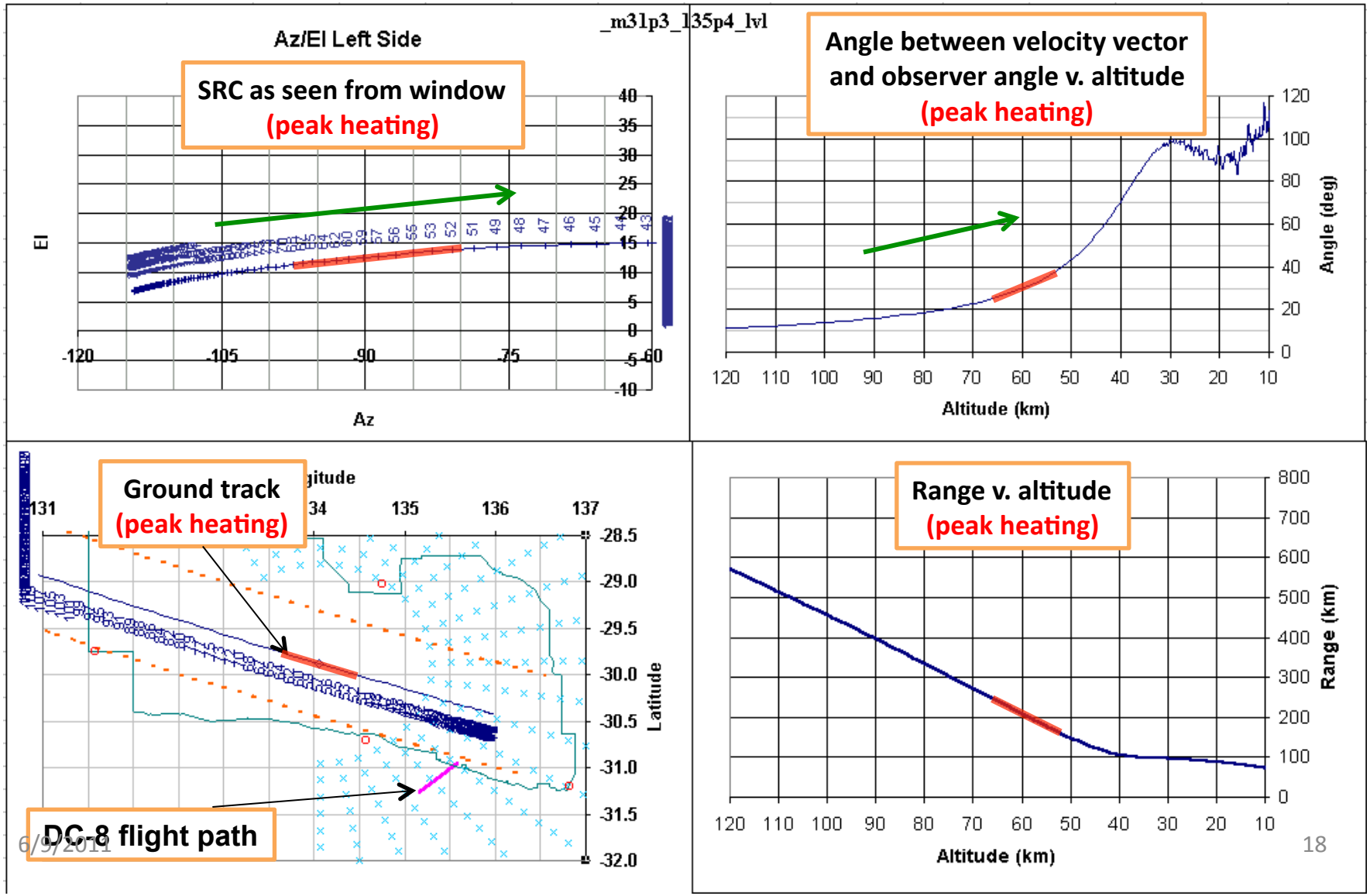


(Figures Not To Scale)

South (Primary) and North (Secondary) Flight Path Examples from Initial Trades

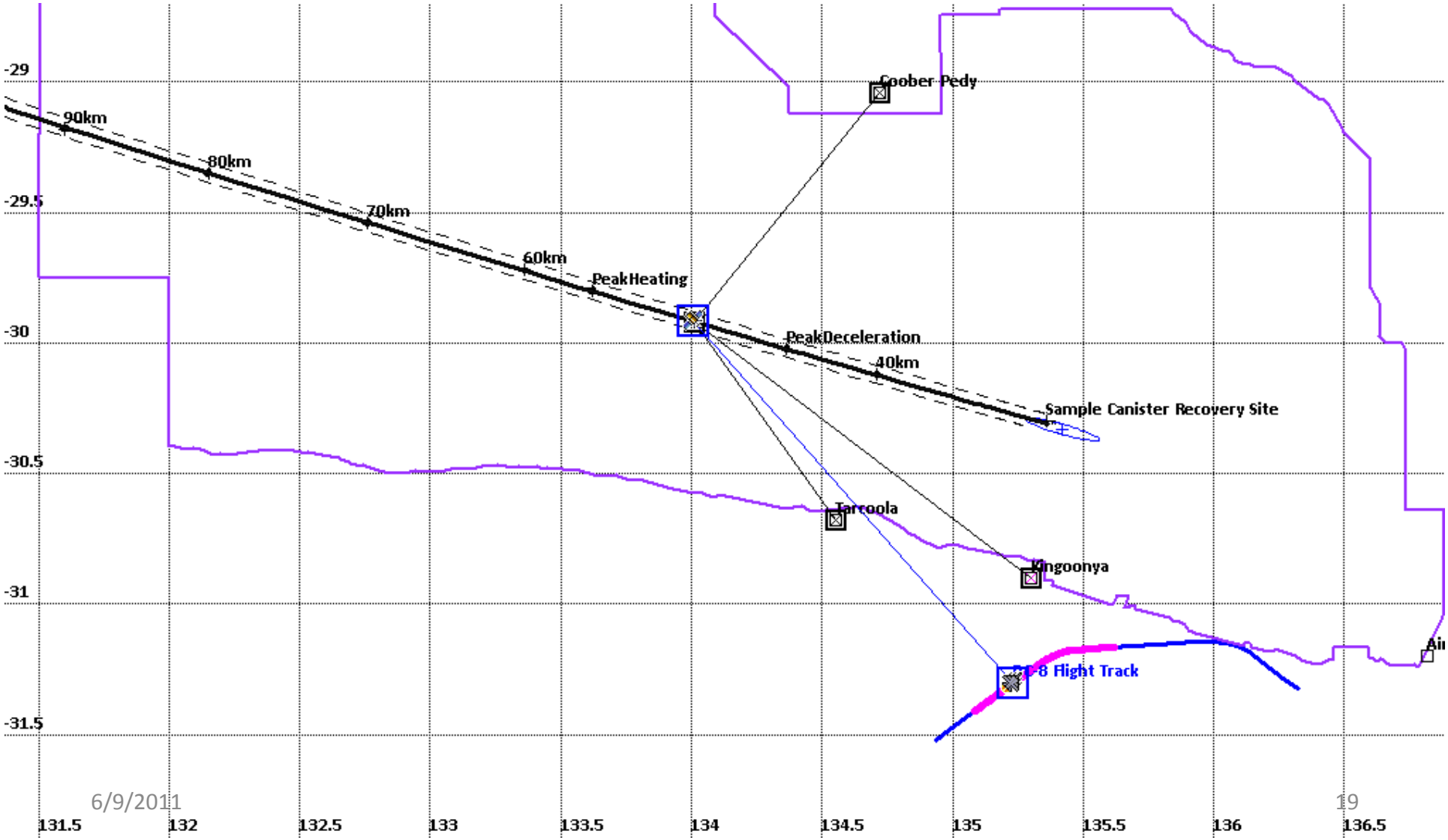


South Flight Path Option Observation Parameters

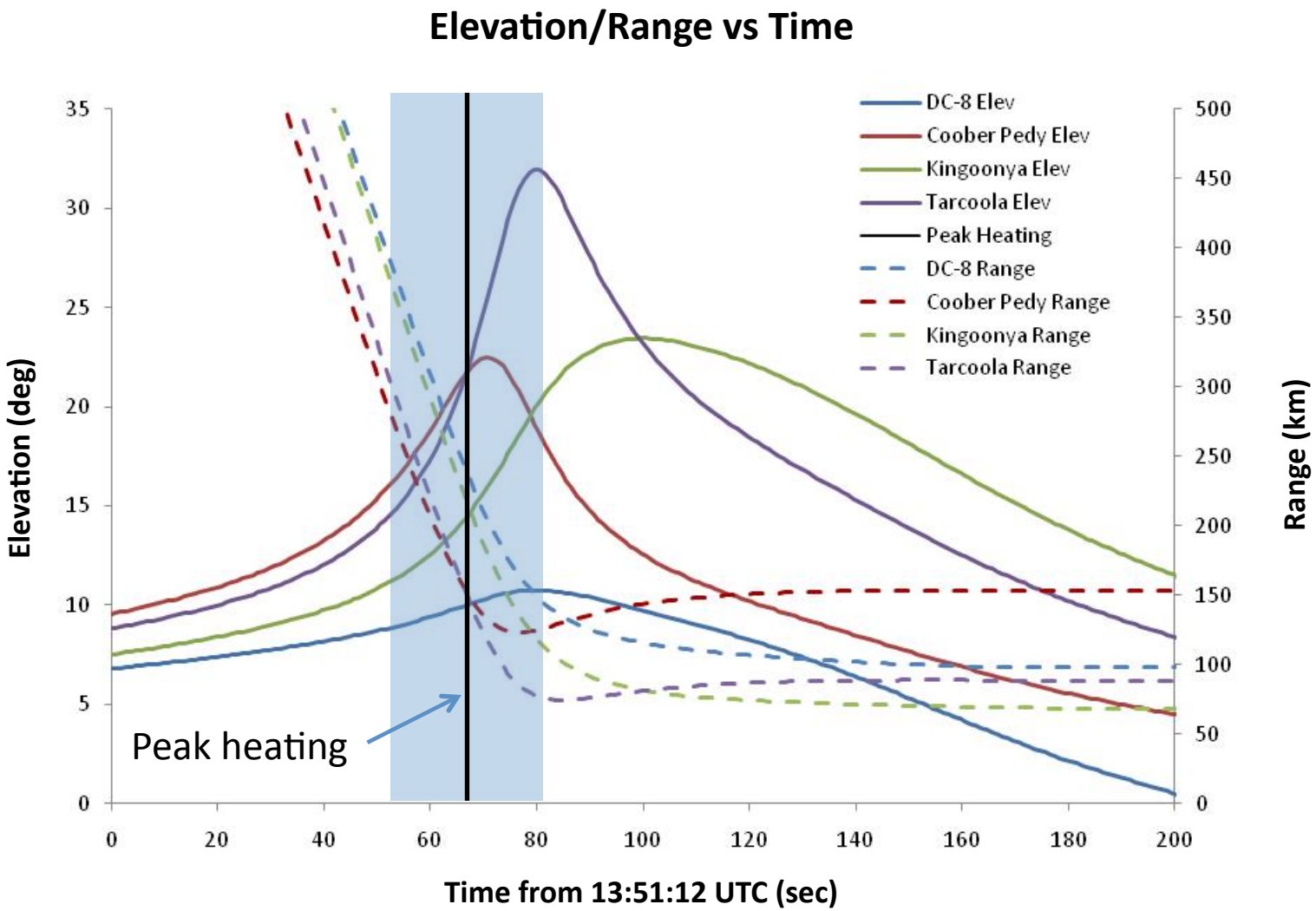


Hayabusa Reentry Observation Locations

2-d Scenario Overview- Observation Locations

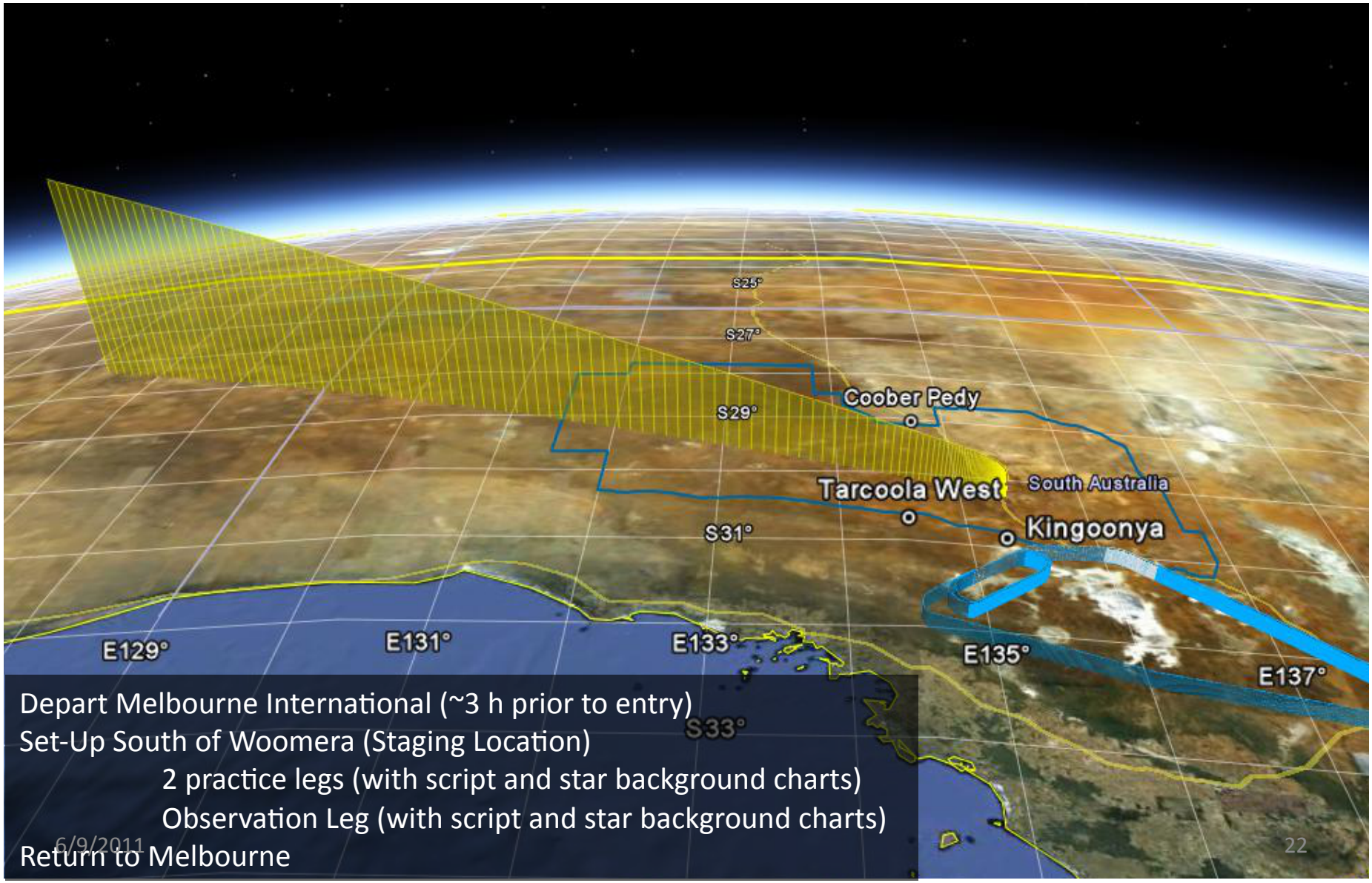


Observer Elevation and Range to Predicted Trajectory



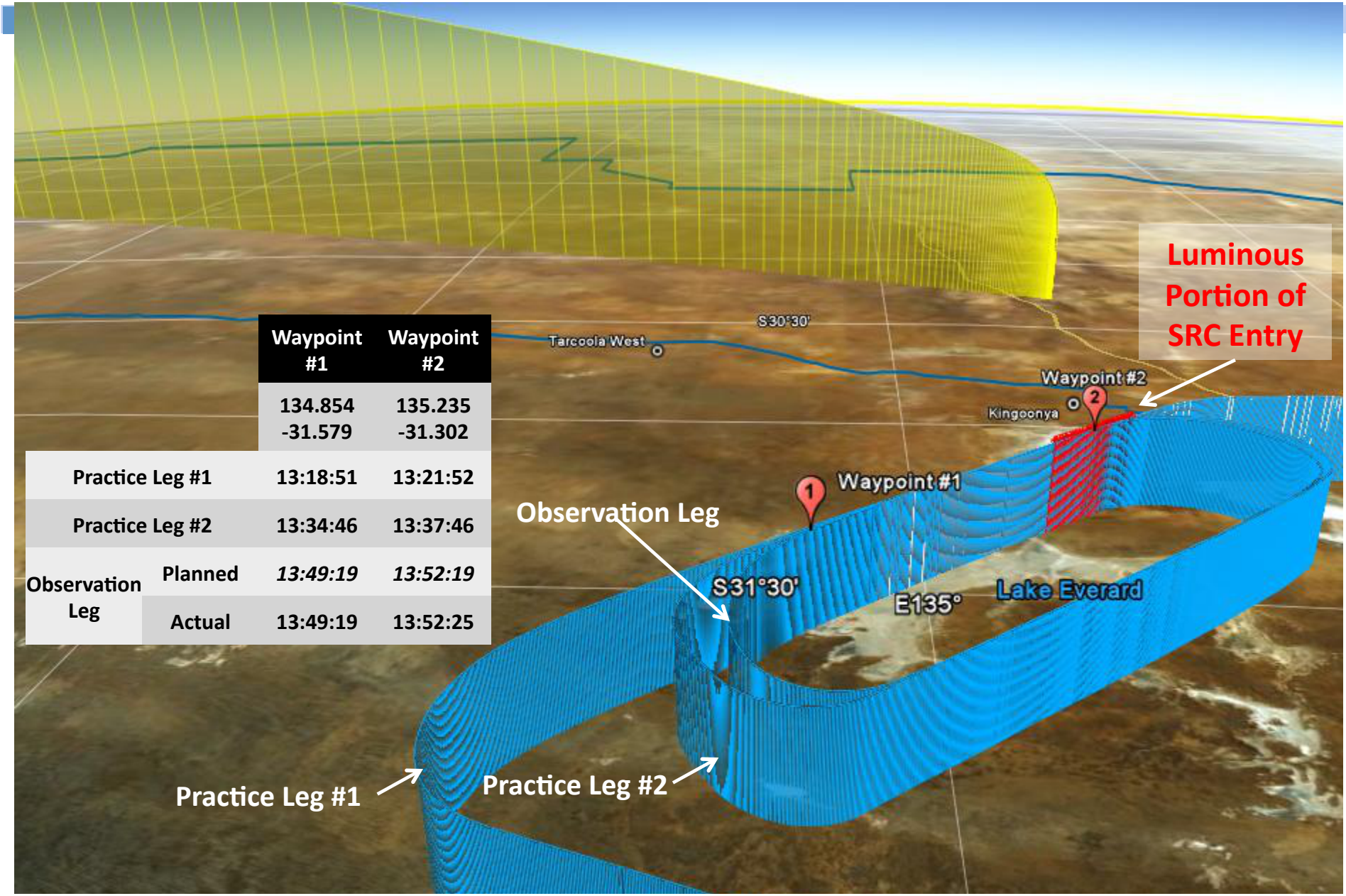
Mission Execution

Observation Mission Execution



Depart Melbourne International (~3 h prior to entry)
Set-Up South of Woomera (Staging Location)
2 practice legs (with script and star background charts)
Observation Leg (with script and star background charts)
Return to Melbourne

DC-8 Observation Mission Track



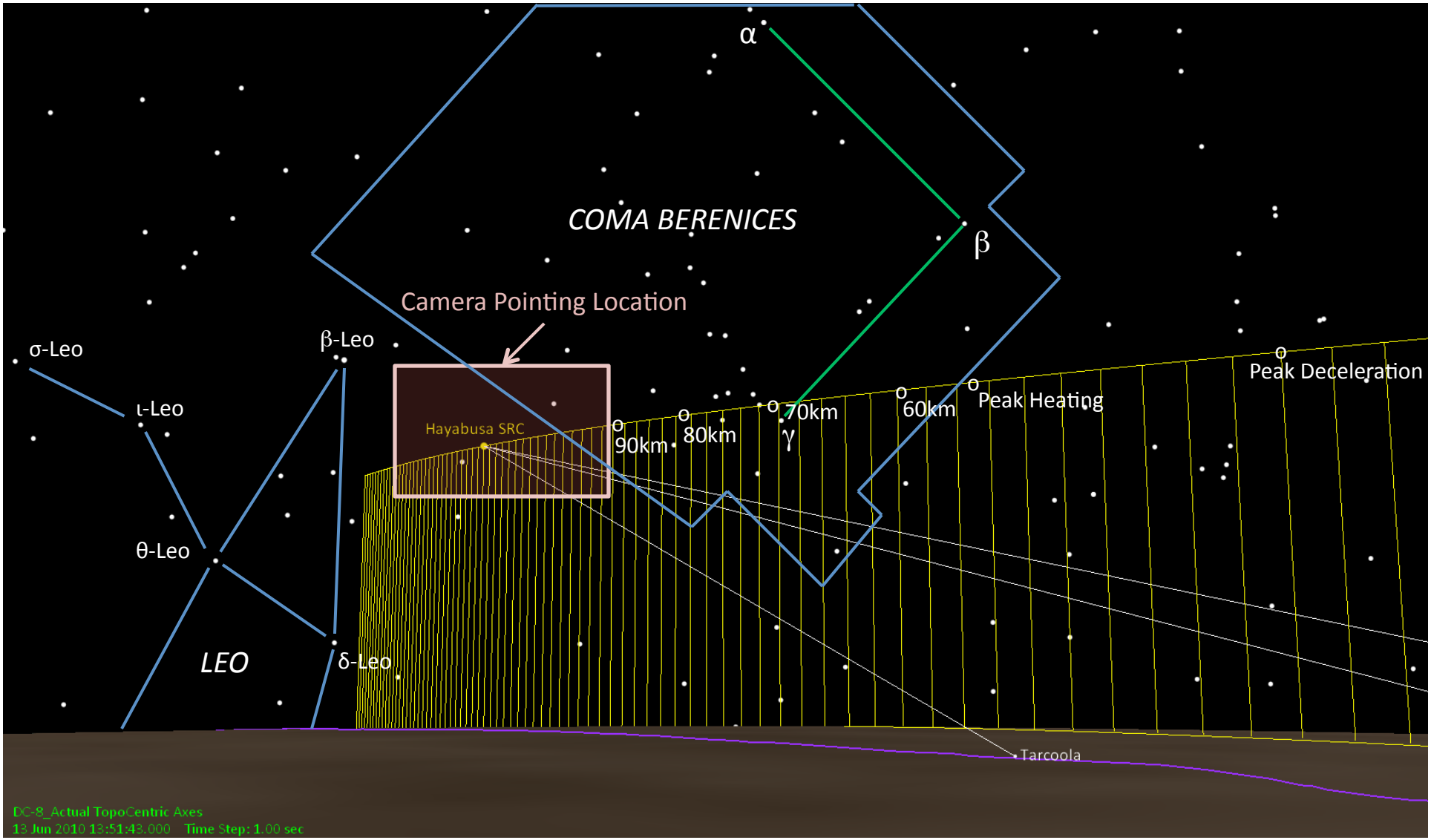
		Waypoint #1	Waypoint #2
		134.854 -31.579	135.235 -31.302
Practice Leg #1		13:18:51	13:21:52
Practice Leg #2		13:34:46	13:37:46
Observation Leg	Planned	*13:49:19*	*13:52:19*
	Actual	13:49:19	13:52:25

Mission Execution- Observation Leg Script

- 13:50:***XX*** - “Wings level”
- 13:50:42 – “30 seconds to interface
- 13:50:52 - 20 seconds
- 13:51:02 - 10 seconds
- 13:51:12 - “200 km”
- 13:51:47 – “100 km”
- 13:51:59 - “In Coma Berenices“
- 13:52:05 - “Bus Break-up“
- 13:52:19 - “Peak Heating“
- 13:52:26 - “Peak Deceleration”
- 13:52:34 - “ 40 km“
- 13:52:44 - “35 km”

Star Background with Trajectory Overlay

Simulated View from NASA DC-8



Minimum magnitude 6 stars displayed

High Definition Video from NASA DC-8

DIM Camera Description

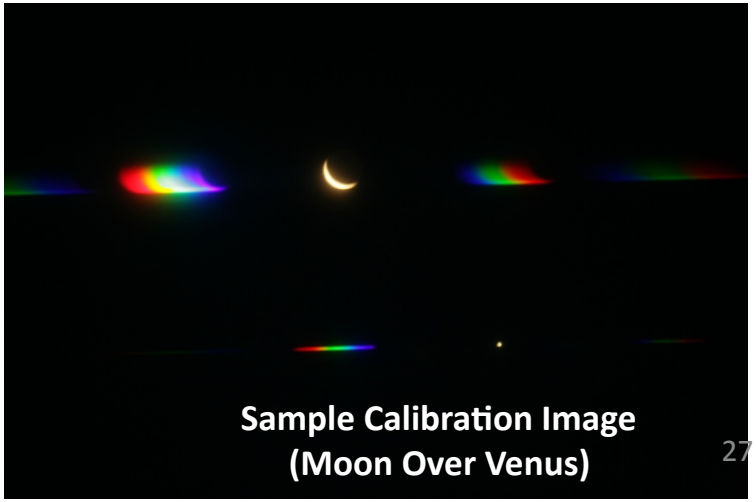
DIM Set-Up

Canon 1ds-Mark II

Lens 200 mm, f 2.8
Sensor 35.8 x 23.9 mm, 4992 x 3328 Pixels
Transmission Grating 75 lines/mm
Exposure 1/10 sec shutter speed
ISO 800
Aperture 2.8

Mount and Interfaces

Platform Tripod Ball Mount attached to plexiglass
Camera Interface Custom Adjustable Mount
Shutter Release Remote Trigger
Memory 16 GB High Speed Compact Flash RAM

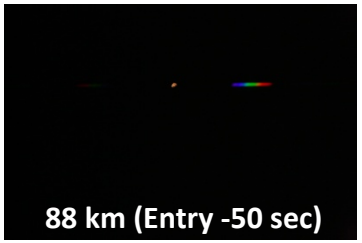


Sample Calibration Image
(Moon Over Venus)

DIM Data

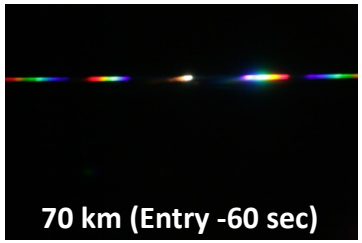
Hayabusa Re-Entry MAC

Bus Visible



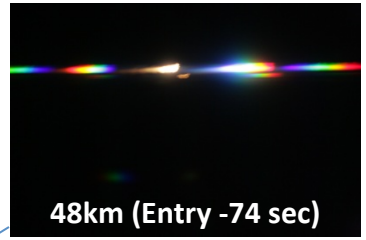
Bus Break-Up

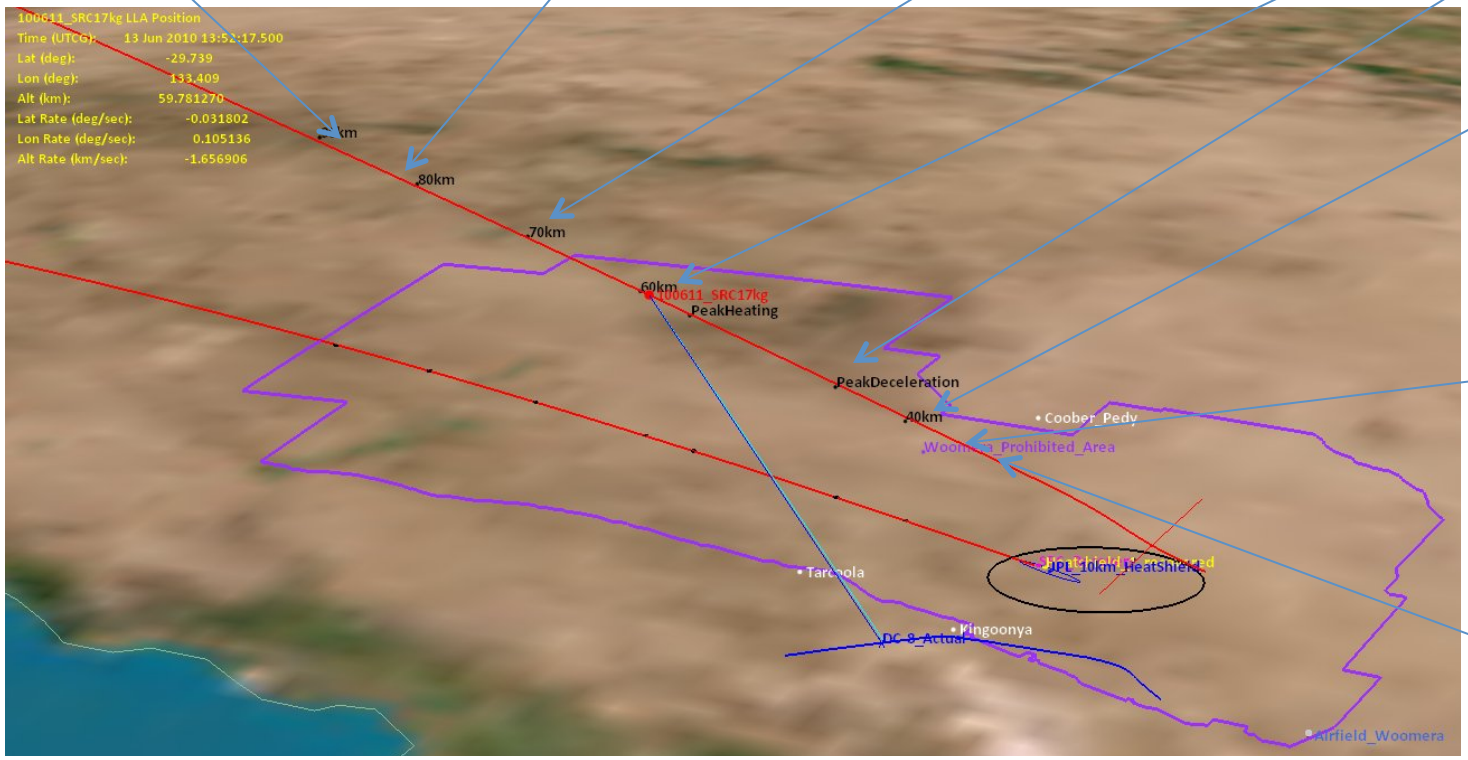
Capsule Visible

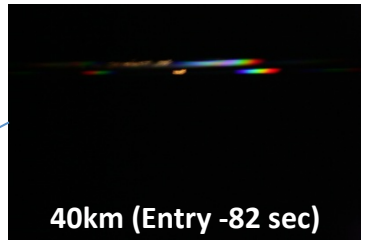


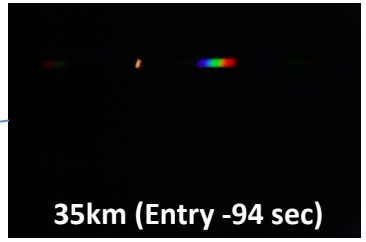
~ Peak Heating

Peak Deceleration

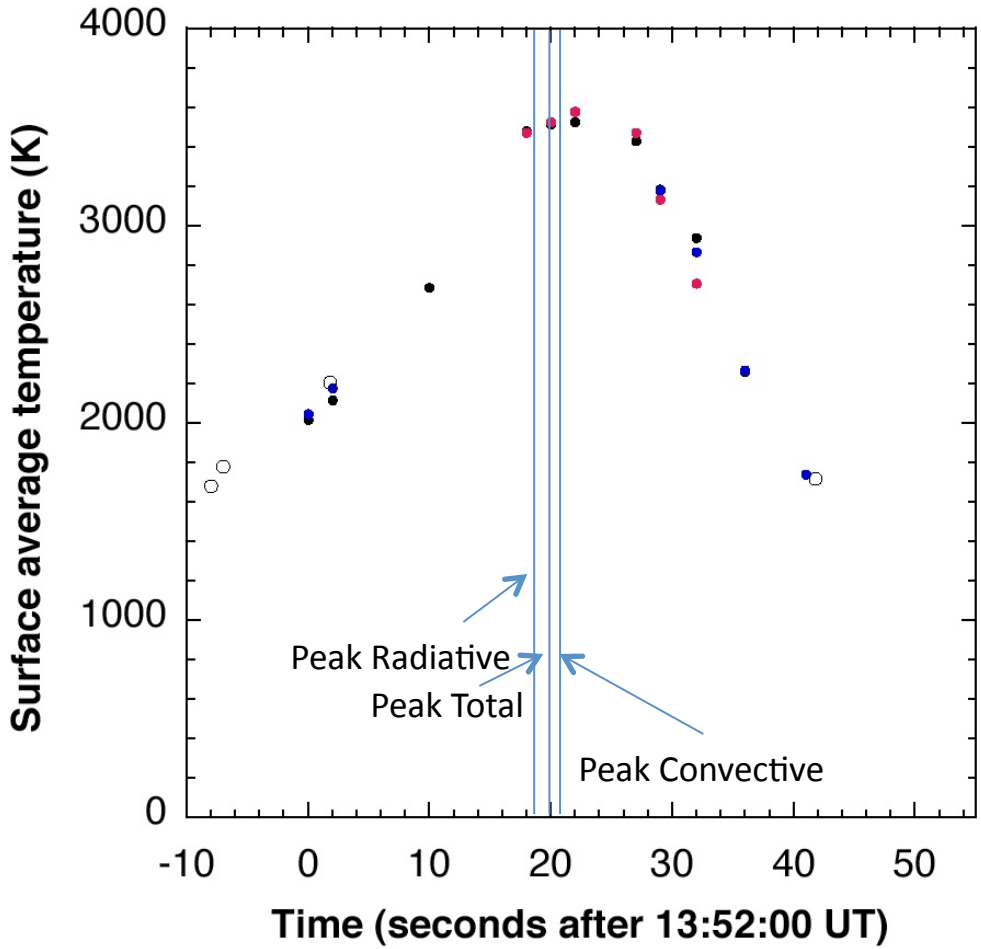








Capsule Surface Temperature (preliminary)



- DIM/A. Cassell, analysis by P. Jenniskens
- Derived from broadband (green) flux, time uncertain by ±1 s.
- Black circles refer to zero order , blue to first order (right) and pink to first order (left). Open symbols are data from Xybion video.
- Much more data available, pending careful calibration
- Projected surface areas should also be factored into the surface temperature calculations.

Post-Flight Trajectory Analysis

Sources of Uncertainty Entry State Vector

	OD 100611_v2*	Final Update (13:13 UTC)	Difference
Time (UTC)	13:51:11.47	13:51:12.00	0.53 sec
Altitude	201.9223 km	202.0308 km	0.1085 km
Latitude (geodetic)	-27.3614 deg	-27.3606 deg	+0.008 deg
Longitude	126.3783 deg	126.3857 deg	+0.0074 deg
Velocity (inertial)	12.0350 km/sec	12.0348 km/sec	-0.002 km/sec
Flight Path Angle (inertial)	-12.3545 deg	-12.3501 deg	+0.0044 deg
Heading (Inertial)	112.0557 deg	112.0676 deg	+0.0119 deg
Entry Interface Uncertainty (Spacecraft Bus, 1-sigma)	OOP = 1203 m CT = 720 m DT = 22.48 msec	OOP = 57.8 m CT = 45.1 m DT = 1.34 msec	

***Based upon entry state of S/C Bus , probe released 3 h prior to entry with 0.17 m/s ΔV, S/C attitude unknown.**

Comparison Between Predictions

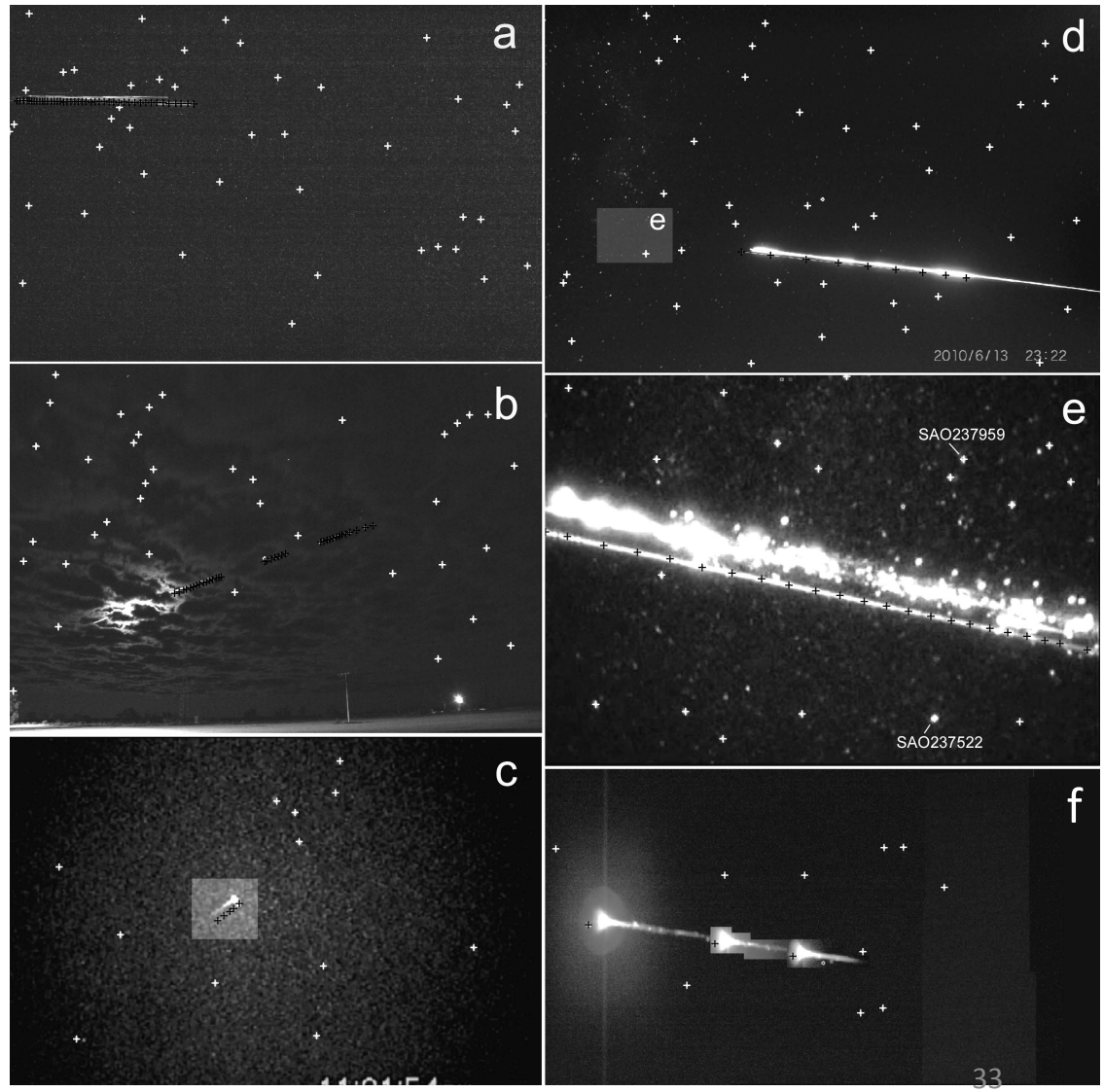
	Predicted Trajectory Used in Mission Planning*			OD049v2_16.27kg			OD049v2_17 kg		
Parameter	**Value**	**Lat, Long (deg) Altitude (km)**	**Time from Entry**	**Value**	**Lat, Long (deg) Altitude (km)**	**Time from Entry**	**Value**	**Lat, Long (deg) Altitude (km)**	**Time from Entry**
Peak Radiative	185 W/ cm^2	-29.77, 133.51 58.1	66.5	174 W/ cm2	-29.77, 133.53 58.2	66.6 sec	184 W/ cm^2	-29.78, 133.56 57.7	66.9
Peak Heating	1112 W/cm^2	-29.80, 133.62 56.5	67.5	1081 W/ cm2	-29.81, 133.64 56.4	67.7 sec	1111 W/ cm^2	-29.81, 133.63 56.5	67.6
Peak Convective	949 W/ cm^2	-29.85, 133.77 54.2	69.0	929 W/ cm2	-29.84, 133.75 54.7	68.8 sec	948 W/cm^2	-29.84, 133.76 54.5	68.9
Ballistic Coeff. (40 km)	110 kg/m^2			105.3 kg/m^2			110 kg/m^2		

*17 kg entry mass assumed

For the key observation events, the observation prediction is very close to the final updated OD solution prediction.

Trajectory Reconstruction- Ground Observations

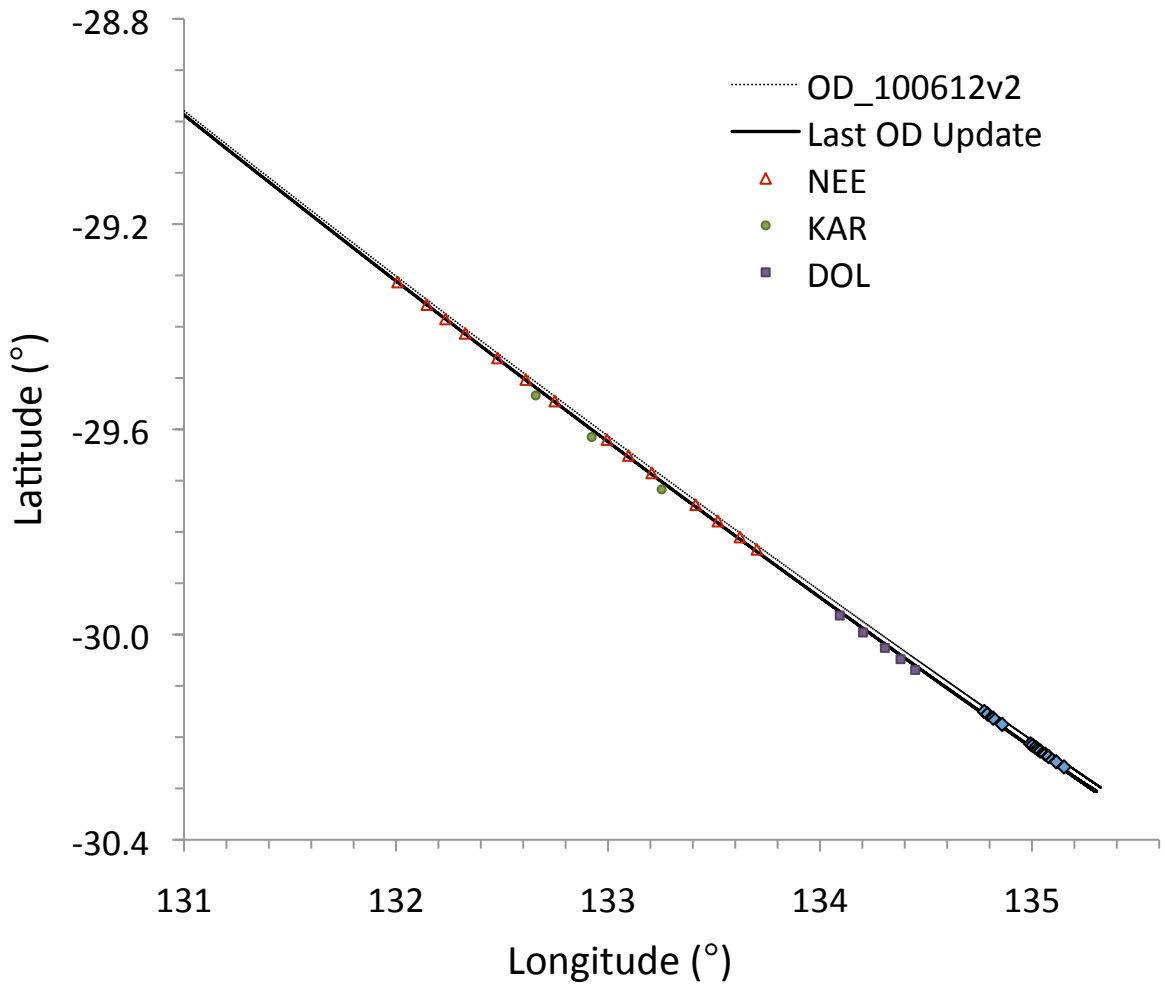
Panel	Location	Operator	Affiliation
a	Tarcoola West	Bill Dolson	SETI
b	Kingoonya	Ed Schilling	NASA ARC
c	Tarcoola West	Julie Bellerose	NASA ARC
d	Coober Pedy	Andrew Neeley	UNSW
e	Coober Pedy	Paul Maley	NASA JSC
f	Coober Pedy	Yiannis Karavas	CCO



Trajectory Reconstruction- Ground Observations

Comparison to Predicted Trajectory

Analysis of reconstructed trajectory shows good agreement with prediction.



FIRBAL Analysis By Peter Jenniskens

Acknowledgements

- **NASA DC-8-** Crew- Frank Cutler
- **Dryden Ground Support**
- **Science Team-** Too numerous to list
- **JPL Tracking-** Robert J. Haw, Powtache Williams
- **JAXA**- Tanno Hideyuki, Tetsuya Yamada
- **Woomera Prohibited Area-** Ian Tuohy, John McKevett
- **JSC Spaceflight Meteorology Group-** Timothy Oram
- **Funding**- NASA In Space Propulsion Technology Program