Preliminary Saturn Atmospheric Density Results from Cassini's Final Plunge

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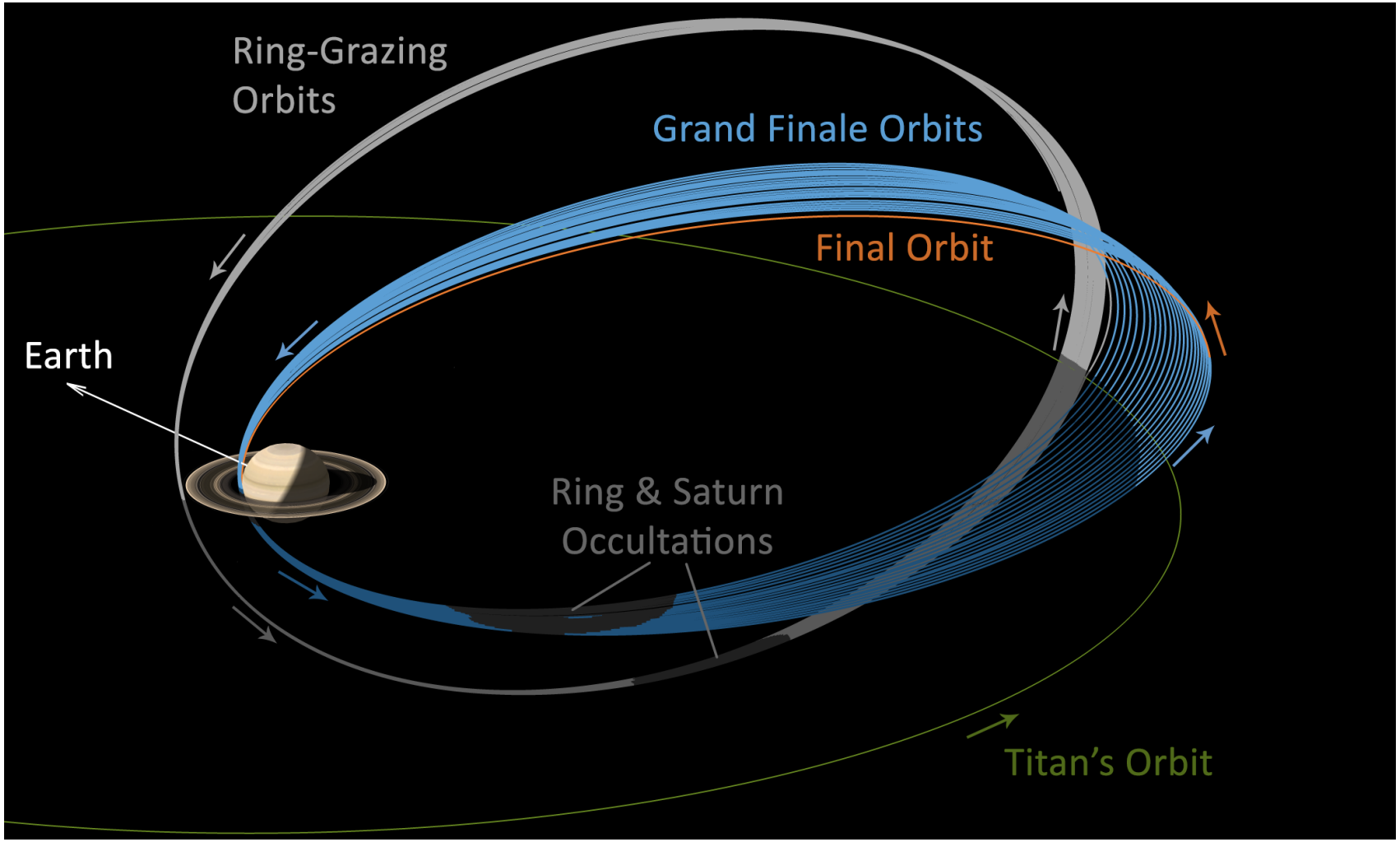
Motivation

Cassini End of Mission

- Ballistic trajectory, final five Saturn periapses flying between rings and atmosphere
- Final untargeted, distant flyby of Titan places spacecraft on impacting trajectory
- Plunge into atmosphere with High-Gain Antenna on Earth-point
- Collect Doppler data until drag torques antenna off Earth
- Line of sight velocity change information used to fit correction to Saturn atmospheric density profile
- Only chance for navigation team to directly investigate Saturn atmosphere
- One of the Cassini Mission's final science investigations

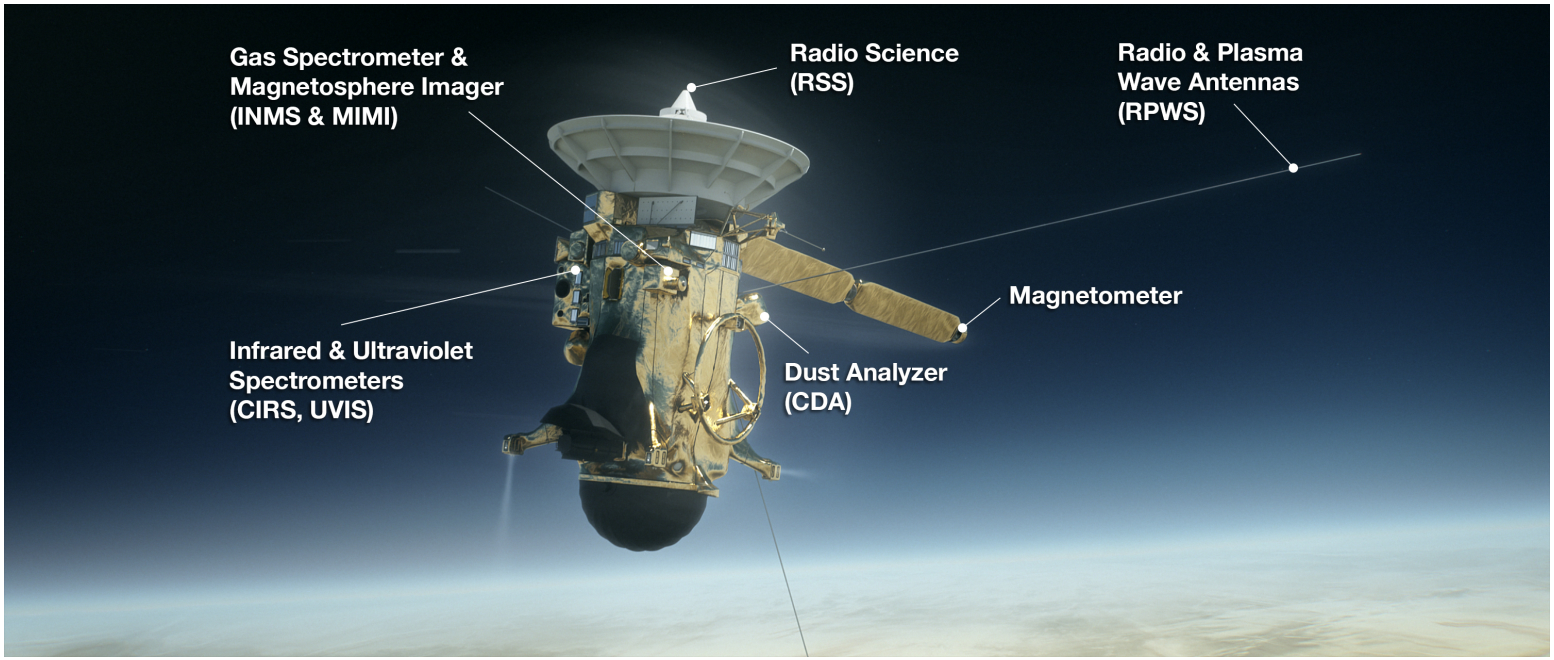
Geometry of final Cassini orbits



Source: https://saturn.jpl.nasa.gov/galleries/graphics/

Plunge characteristics

- Cassini's Rev293 final plunge into Saturn
  - 15-SEP-2017 10:33:17 ET (last tracking data point)
  - +10.7° N latitude, -54.31° E longitude
  - Saturn in Northern Summer, line-of-sight Earth visibility for impact
  - 63.3 mm/s drag ΔV accumulated prior to loss of signal
  - Coherent two-way tracking on 70-m station DSS43
  - Spherical frontal area model equal to 20.5 m^2, fixed drag coefficient C_D=2.1



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Atmospheric Density Models

Prediction Model

- Project Atmospheric Density Model
  - Based on occultation measurements from Koskinen et al.
  - Produces number density, convert to mass density assuming H_2 atmosphere
  - Used for mission planning predictions
  - Dependence on altitude and latitude
  - Predict updated based on experience flying last 5 Saturn periapses

$$n\left(r,\theta\right) = n_0 \cdot e^{\lambda_0\left(\frac{R_t}{r}-1\right)} \cdot e^{-43\sin\left(\frac{\theta^2}{\Delta\theta^2}\right)} + 0.1 n_0 \cdot e^{-\left(\frac{r-R_t}{H}\right)} \cdot e^{-200\sin\left(\frac{\theta^2}{\Delta\theta^2}\right)}$$

Table 1. 2017 Cassini Project Saturn Atmosphere Model

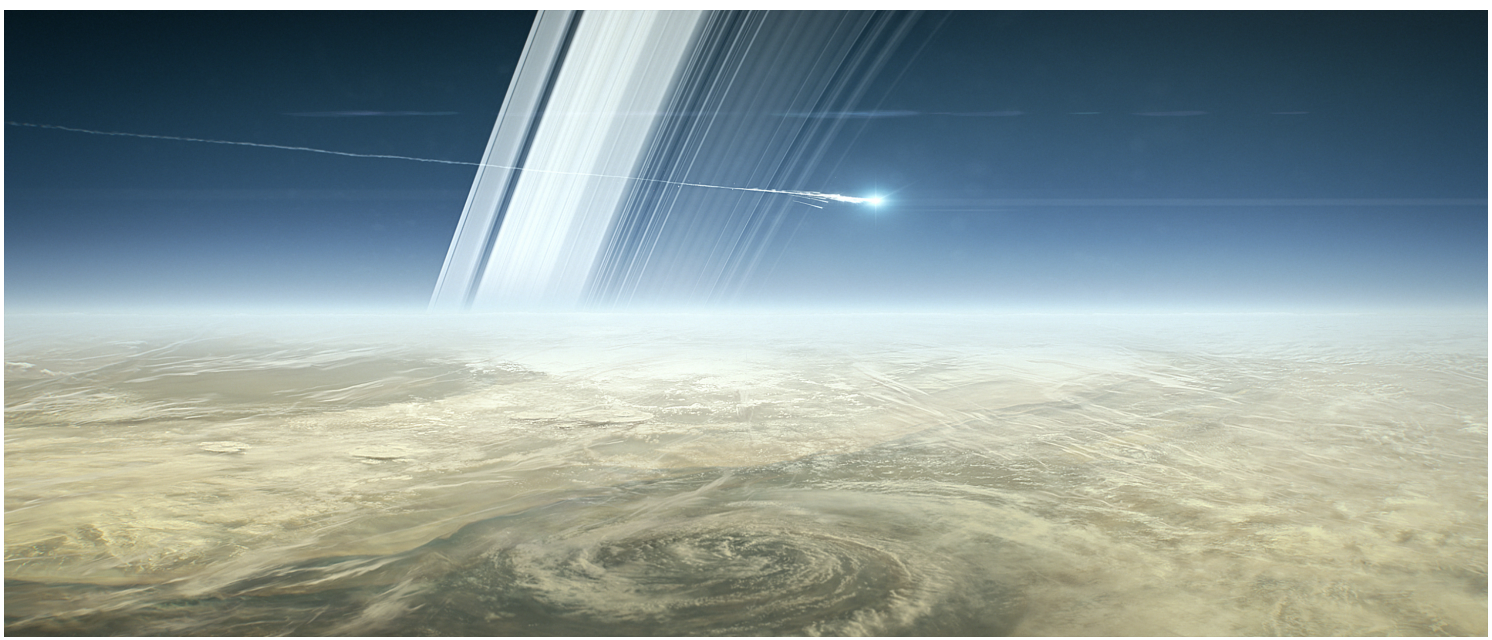
Parameter	Symbol	Units	Value
Number Density (Output)	n	cm^{-3}	
Radius (Input)	r	km	
Latitude (Input)	θ	rad	
Reference Number Density	n_0	cm^{-3}	1.26e10
Unitless Constant	λ_0		352.1
Altitudinal Constant	H	km	65
Reference Radius	R_t	km	61700
Latitudinal Constant	$\Delta\theta$	rad	1.05

Atmospheric Density Models

Estimation model

- Exponential Atmospheric Density Model
  - Base densities estimated in layers, lowest layer encompassing loss of signal
  - Layer transitions when accumulated drag acceleration is 10x Doppler noise
  - Scale height computation enforces continuity between layers
  - Altitude-dependent only, specific to plunge latitude

$$\rho = \rho_i \exp\left(\frac{h_i - h}{H_i}\right) \qquad H_i = \frac{h_i - h_{i+1}}{log\left(\rho_{i+1}/\rho_i\right)}$$



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Orbit Determination Process

Estimation arc setup

- Data arc:
  - Want to minimize number of parameters in filter
  - Arc focused on plunge, begin near apoapsis of final orbit:
  - 12-SEP-2017 12:00 ET to 15-SEP-2017 10:35 ET
  - Three tracks of 60-sec X/X Doppler prior to experiencing atmosphere
  - One-sec X-band up/down Doppler tracking during atmospheric entry
  - Range data not used

- Force Modeling
  - DE435 planetary ephemeris
  - Correction to SAT389 Saturn system ephemeris from rev271 reconstruction
  - Layered exponential atmosphere for drag modeling
  - Saturn zonal spherical harmonic gravity field J2-J8
  - Impulsive burn models spindown of reaction wheels
  - Spacecraft telemetry for thrusting to counter drag torque
  - Stochastic accelerations estimated for mis-modeled forces

Filter Setup

Filter configuration in JPL's Monte software

- 100% *a priori* uncertainty on base density layers
- Considered parameters don't have uncertainty reduced in filter
- Zonal gravity field updated from reconstruction of last 5 revs

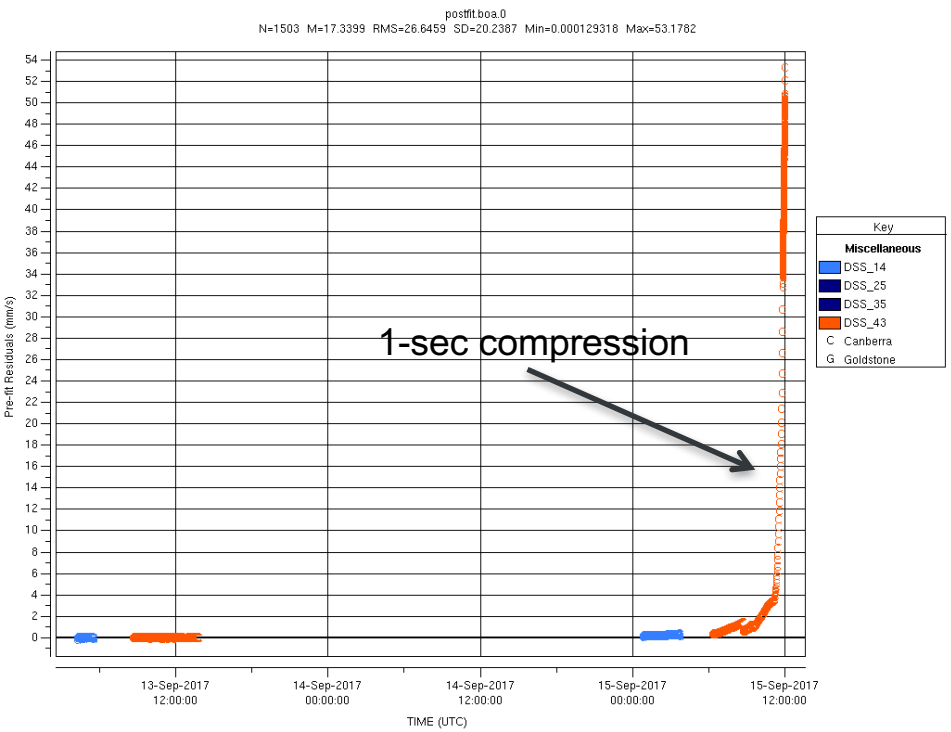
Table 2. Filter parameter setup

Parameter	Unit	Estimated/Considered	a priori σ
Epoch state S/C position - X/Y/Z	km	Estimated	0.46/0.08/0.03
Epoch state S/C velocity - X/Y/Z	mm/s	Estimated	0.52/0.14/0.49
Inbound Density Layer [0]	kg/km^3	Estimated	2.44E-01
Inbound Density Layer [1]	kg/km^3	Estimated	1.93E-01
Inbound Density Layer [2]	kg/km^3	Estimated	1.52E-01
Inbound Density Layer [3]	kg/km^3	Estimated	1.07E-01
Saturn gravity zonal harmonics	unitless	Estimated	Reconstructed values
Earth pole motion - X/Y	deg	Considered	8.594E-07
UT1 bias	sec	Considered	2.5E-04
DSN station locations	km/deg	Considered	2003 covariance[6]
Troposphere path delay - wet/dry	km	Considered	1.0E-05/1.0E-05
Ionosphere path delay - day/night	km	Considered	5.5E-04/1.5E-04
Drag scale factor	unitless	Considered	0.105

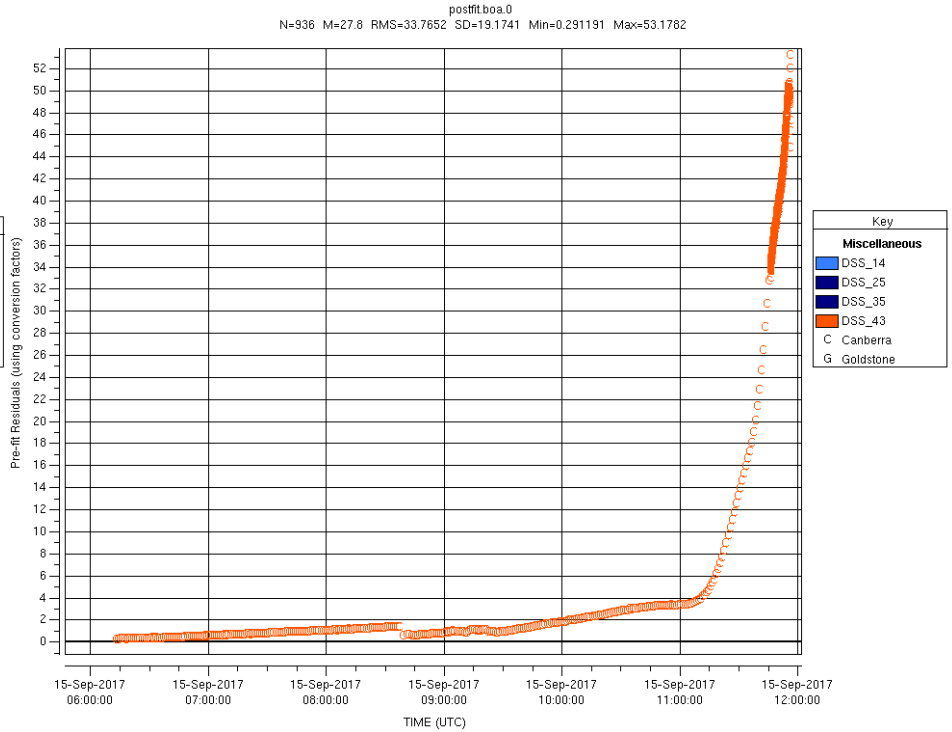
Estimation results

Prefit Doppler residuals for atmospheric entry (mm/sec)

Full arc prefit residuals



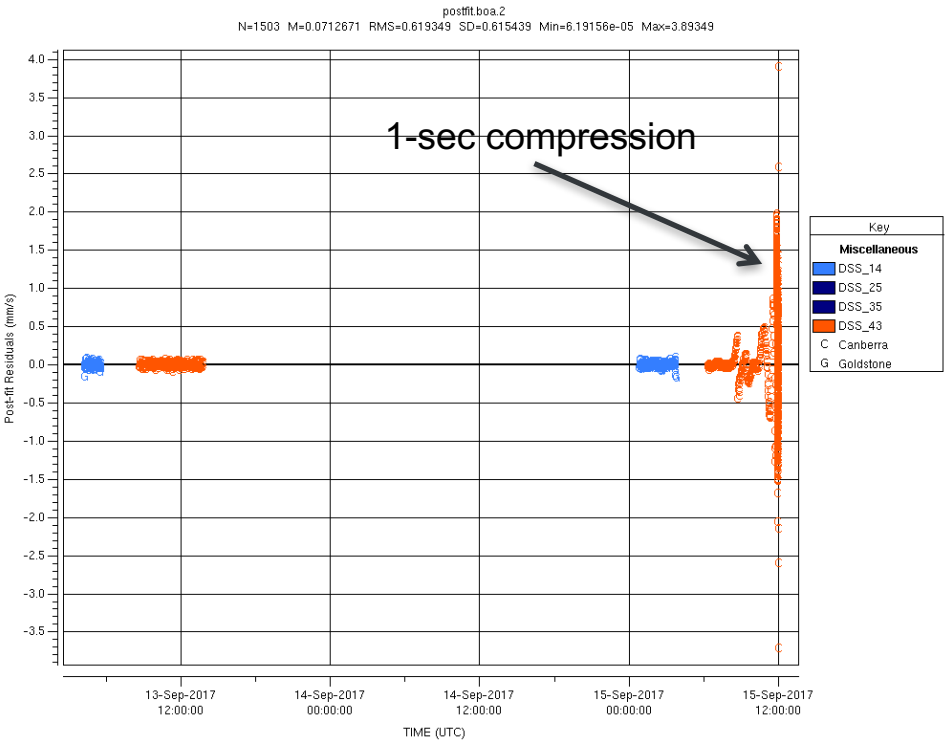
Prefit residuals zoomed on plunge



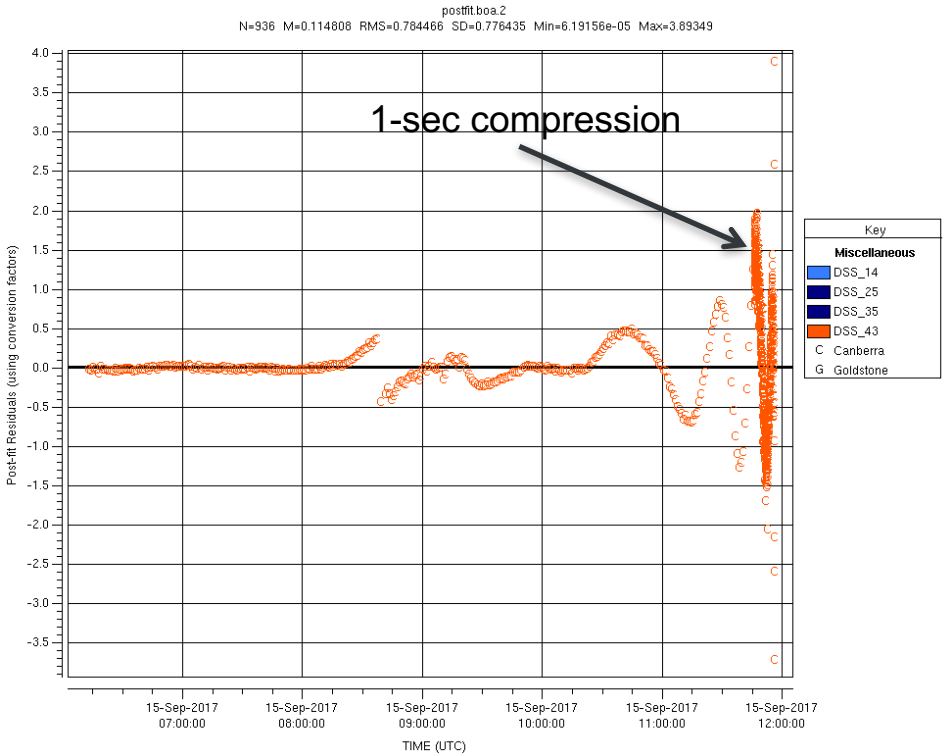
Estimation results

Postfit Doppler residuals for atmospheric entry (mm/sec)

Full arc postfit residuals



Postfit residuals zoomed on plunge



Estimation Results

Base Density Layer Estimates

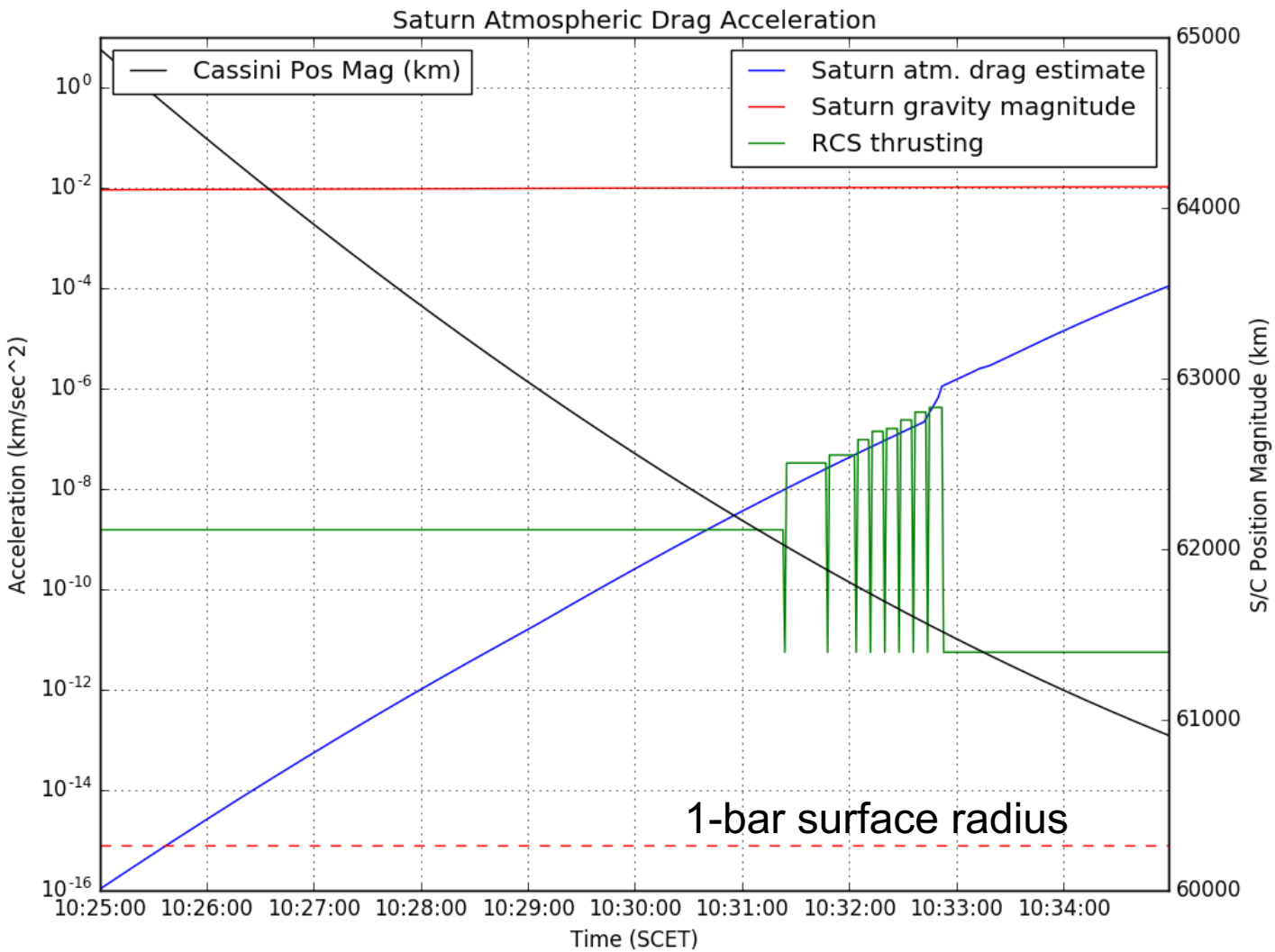
- Uncertainties reflect number of data points in each layer
- Doppler points in lowest layer start exhibiting greater noise
- Scale height on final layer capped at 200 km
- Final Doppler point accumulated 10:33:17 ET (11:55:35 UTC ERT)
- Uncertainties in density estimates 40%-50% of values
- Compare to Titan density experiment, 10%-25% uncertainty

Table 3. Base density layer estimation results

Base altitude (km)	Base Density (kg/km^3)	1σ uncertainty (kg/km^3)	Scale Height (km)
1304.4	2.59E-01	1.06E-01	418
1341.6	2.11E-01	9.44E-02	381
1379.3	1.68E-01	7.42E-02	383
1436.6	1.19E-01	5.77E-02	200

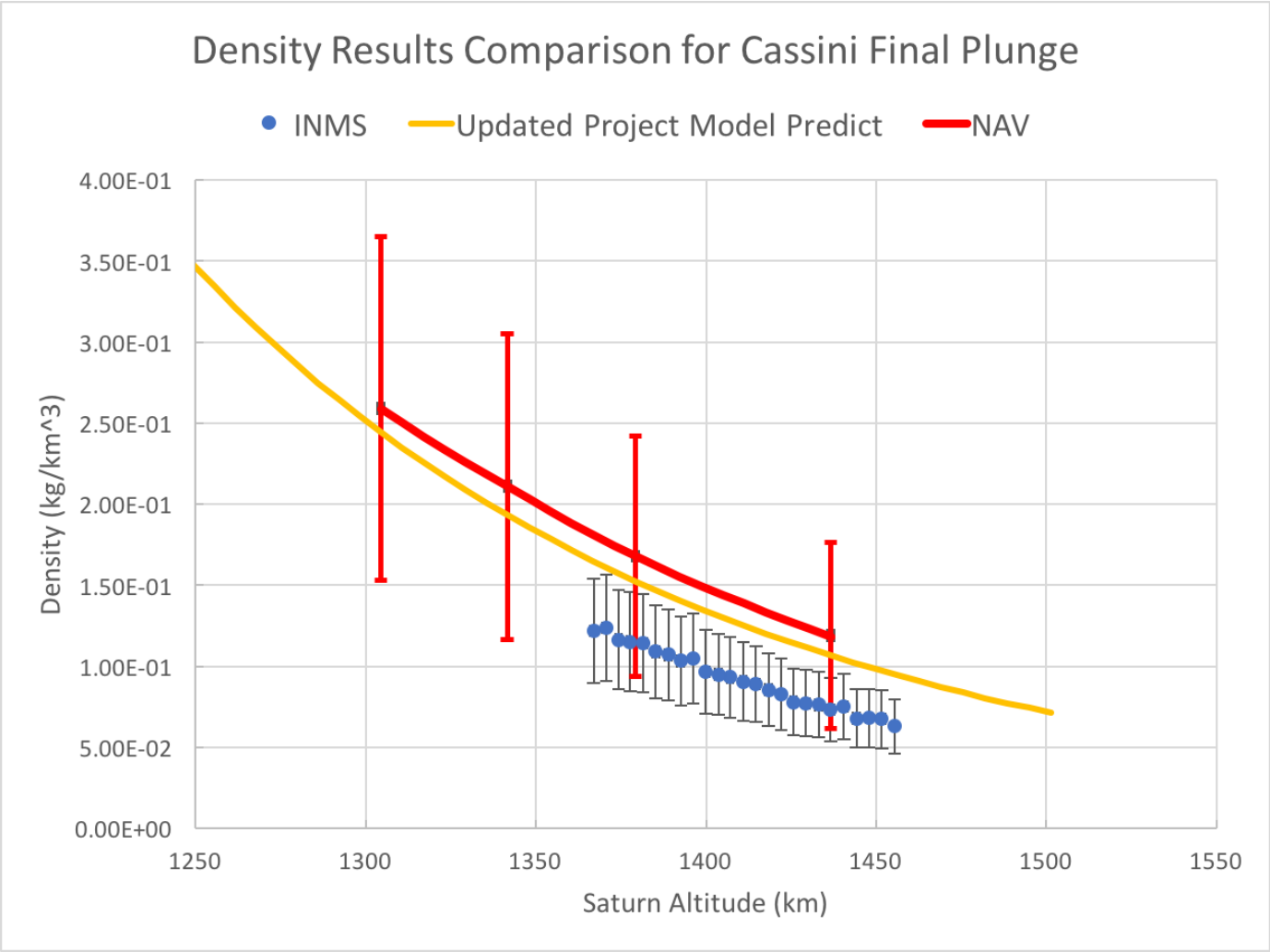
Estimation Results

Atmospheric drag estimated profile during plunge, 15-SEP-2017



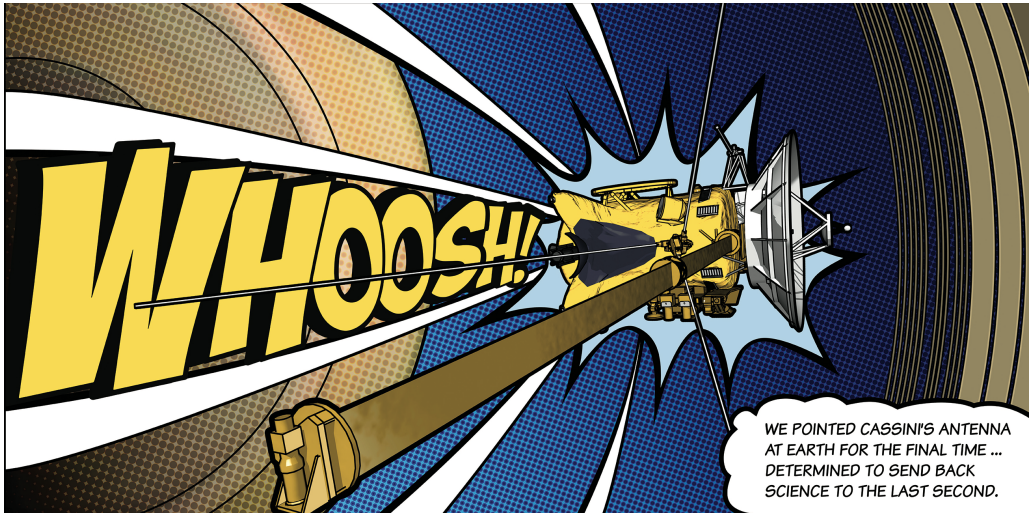
Comparison to results from other sources

- Error bars plotted as +/- 1σ
- Predicted atmosphere based on data from last five Saturn revs, scaled up from nominal project atmosphere model
- INMS counts converted to mass density assuming H2 atmosphere



Summary

- Final plunge was only opportunity for NAV team to estimate a Saturn atmospheric density profile
- Layered exponential atmosphere fit using Doppler data
- Doppler fit to an RMS noise level of less than 1 mm/s
- OD modeling changes cause only small differences in density values
- Uncertainties in density estimates 40%-50% of values
- INMS measurements agree with NAV at 2σ level
- AACS working on adapting torque estimation method for plunge



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