My Experience as Huygens Project Scientist

Jean-Pierre LEBRETON
ESA's Cassini Study Scientist (1984-1989)
Huygens Project Scientist (1989-2011)
Huygens Mission Manager (2002-2011)

Chercheur associé au CNRS/LPC2E, Orléans
jean-pierre.lebreton@cnrs-orleans.fr

Chercheur associé au LESIA, Observatoire de Paris-Meudon
jean-pierre.lebreton@obspm.fr

OUTLINE

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- My first contact with Cassini & Titan
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- The Huygens SWT
- Chronology of Cassini
- The role of the Project Scientist during the 7-year development
- Huygens Boom story
- Radar Altimeter Story
- The Doppler problem
- The Day Before
- The Day
- Channel A Story
- The Spin Story
- Study Scientist Advices

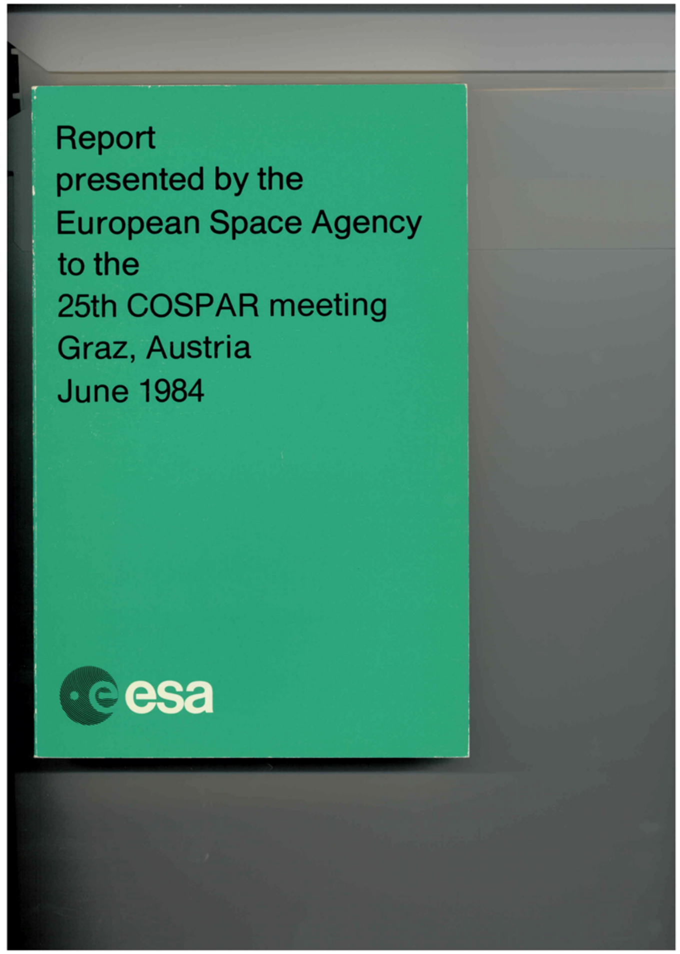
My Career at ESTEC

- PhD in Orléans (laboratory space plasma physics)
- 1978-1980: Postdoc (laboratory space plasma physicist)
- 1980-1984: STS-9/Spacelab-1 (Instrument Projet Manager, 1ES020)
- 1984-2011: Cassini Study Scientist (-‘89), then Huygens Project Scientist (’89-2011); Huygens Mission Manager (’02-’11)
- 2000-2001: Venus Express Study Scientist:
- 2007-2011: EJSM (Europa Jupiter System Mission) et TSSM (Titan Saturn System Mission) Study Scientist
- 1980-2012+: Space instrumentation development: Spacelab-1, TSS, TSS-1R, Rosetta, Demeter, Proba-2, JUICE ?
- 1978-2011: Lab Work

My First Contact with Cassini and Titan

- Details may not be accurate
- My Boss: Hi Jean-Pierre, do you want to become Study Scientist for Cassini ? Your are free of « duties » ; this is the job you have been recruited for; Your Study Manager would be Georges Scoon
- First task: ½ page in 1984 COSPAR Report !

COSPAR 1984 Report(1)



COSPAR 1984 Report(2)

FIRST (Far Infrared and Submillimetre Space Telescope)

The far-infrared and submillimetre space telescope (FIRST) is foreseen as an orbiting telescope, radiatively cooled to a temperature of 150 K, with an aperture of 8 m, operating at wavelengths between 100 μm and 1 mm. At 100 μm, FIRST would have a spatial resolution of 3.5 arc sec and is expected to achieve a sensitivity of 10 mJy. Three main instruments are planned for the focal plane: an imaging multiband photometer with four bands between 100 and 800 μm and a high-resolution (10^4) spectrometer operating between 100 and 200 μm. Both of these would be cooled to about 20 K. The third instrument is a cooled superheterodyne instrument package, with four front ends covering the wavelength range of 300–650 μm, and with a resolving power of 10^6.

The foreseen sensitivity, spatial resolution and spectral resolution of FIRST is unprecendented for this largely unexplored wavelength range. It would permit the study of the physical processes that take place in quasars, at the nuclei of active galaxies and in the disks of peculiar and normal galaxies. It would allow the study of major aspects of the evolution of our own galaxy, contributing substantially to studies of the manner in which diffuse matter in dark clouds turns into stars and planetary systems, or the manner in which stars of advanced age resupply the interstellar medium with processed matter rich in heavy elements. In addition to this, and perhaps even more importantly, FIRST could enable observers to study the early evolution of the universe, and the origin of the galaxies and clusters of galaxies.

The Saturn-Orbiter/Titan-Probe Mission

This mission will address questions of the origin of the solar system and such subjects as:

- planetary internal structure;
- dynamo theory and magnetic field generation;
- fluid dynamics;
- atmospheric physics of both Saturn and Titan;
- ring structure and dynamics, and relation with the satellite system;
- internal configuration, surface morphology and surface processes of the icy satellites;

- nature of the surface of Titan and its atmospheric composition;
- physicochemical processes in Titan's atmosphere leading to the formation of prebiotic molecules;
- configuration and dynamics of the magnetosphere of Saturn and its interactions with the solar wind, the satellite and the rings.

The European Science Foundation/National Academy of Science Joint Working Group on Planetary Exploration recommended this mission at the end of their study in 1983, based on the use of a second Galileo spacecraft. In the meantime the use of the Galileo spacecraft has been replaced by a new and more cost-effective spacecraft concept, the Mariner Mash II (MM II).

NASA and ESA have agreed to undertake a joint assessment study of a Saturn-Titan mission aiming for a launch around 1993. The study will be of 6–8 months duration and will be initiated in September 1984. The mission will be based on a US-provided MM II orbiter and Shuttle/Centaur launch with ESA developing the probe. The payload on both the orbiter and probe will be shared as will be tracking/mission operations. A jointly chaired Science Study Team will be established.

The Cassini Study Milestones

- Mid’84-Mid’85: ESA/NASA assessment study
- 1986: Selected by ESA for competitive phase-A
- Start of Phase-A study delayed by one year to allow programmatic adjustement with NASA
- Nov’87-Sep’88: ESA/NASA Phase A study
- Titan Probe selected by ESA in Nov’ 88.. and named Huygens
- 1989: CRAF/Cassini New Start approved
- 1992: CRAF cancelled; Cassini-Huygens proceeds.. But restructured… all articulations gone.

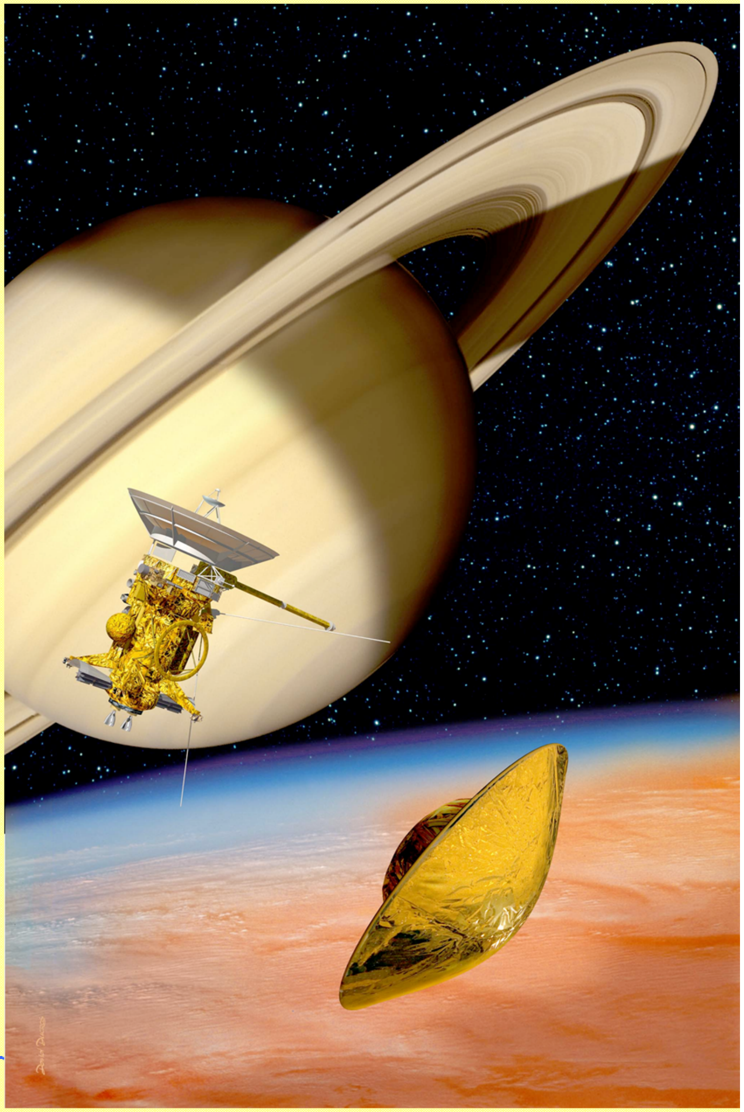
Cassini and Huygens

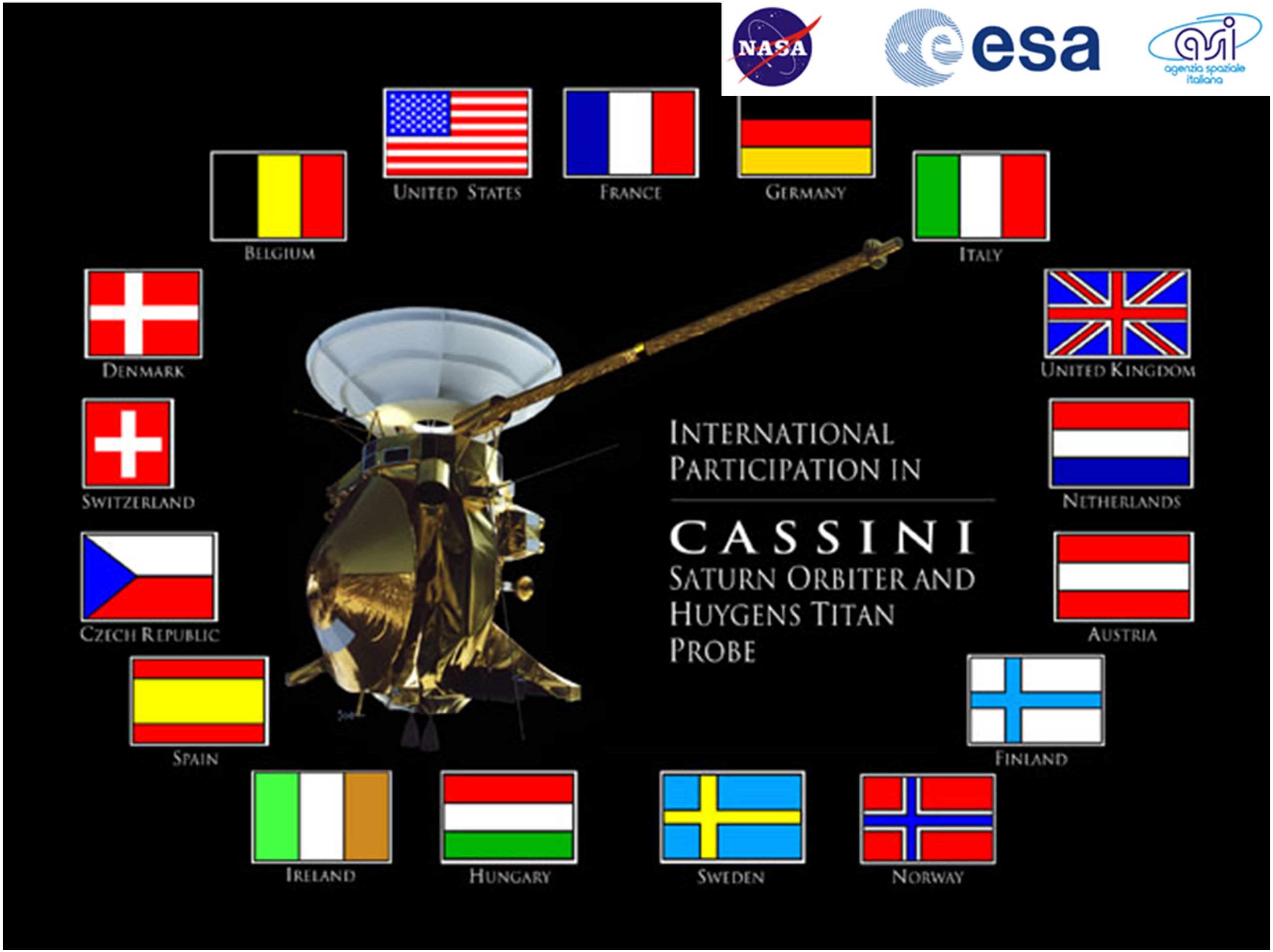
Christiaan Huygens

Giovanni Domenico Cassini

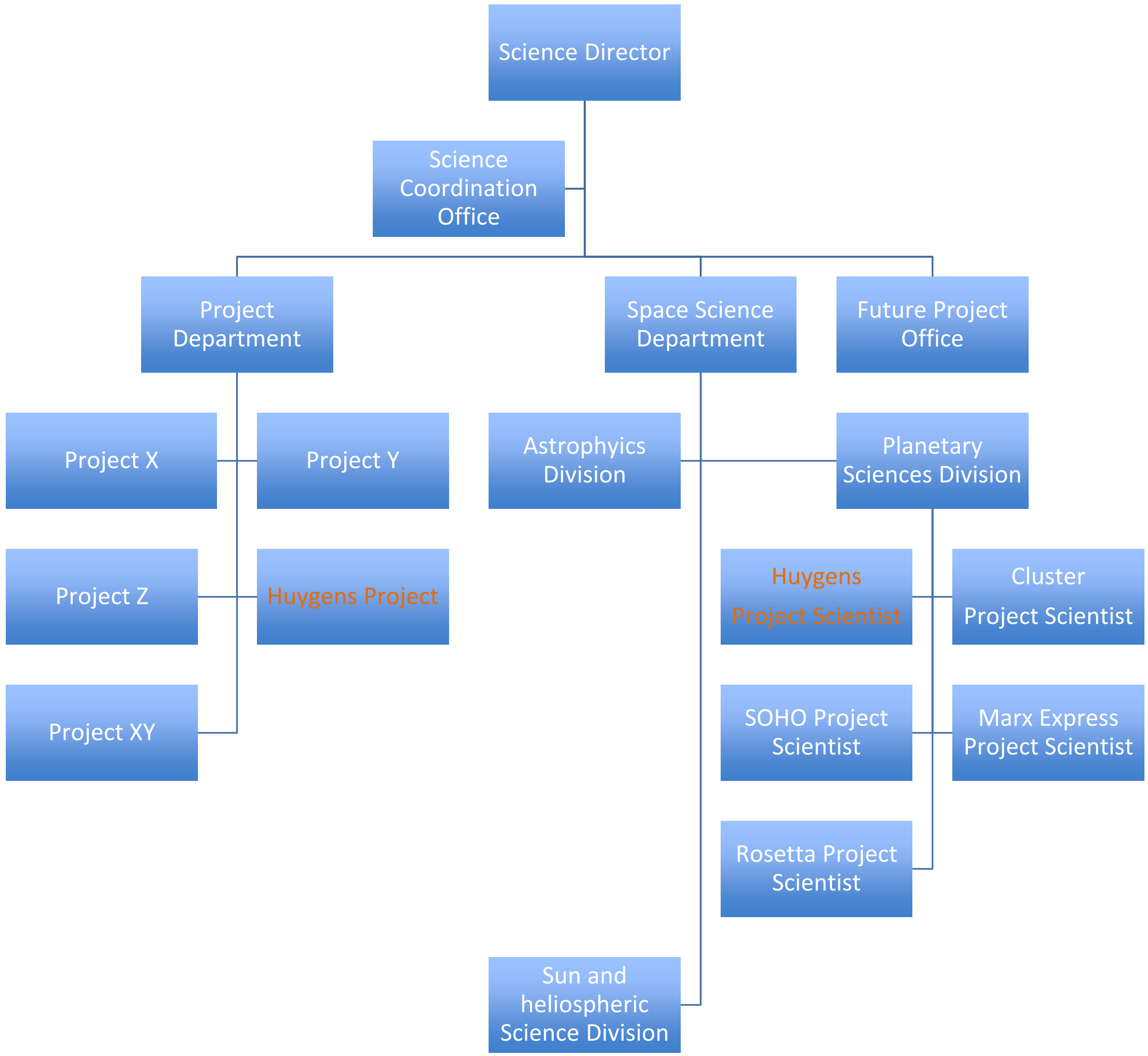
Christiaan Huygens (1629-1695) Dutch scientist, who discovered the true nature of Saturn's rings, and in 1655, Titan

Giovanni Domenico Cassini (1625-1712), Italo-French astronomer, who discovred several of Saturn's satellites: Iapetus, Rhea, Tethys and Dione. In 1675, he discovered what is today called "Cassini Division" the gap in-between the two main rings of Saturn




NASA
esa
asi
agenzia spaziale italiana
United States
France
Germany
Belgium
Italy
Denmark
United Kingdom
International
Participation in
CASSINI
Saturn Orbiter and
Huygens Titan
Probe
Switzerland
Netherlands
Czech Republic
Austria
Spain
Finland
Ireland
Hungary
Sweden
Norway

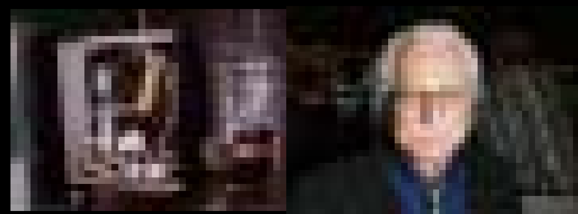
ESA Science Directorate Organigramme
(in the '80s and '90s)



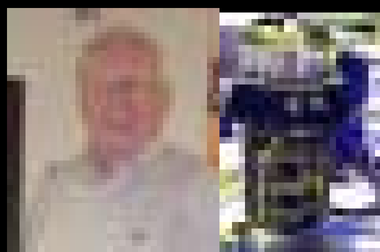
Cassini & Huygens Project Managers

Huygens probe experiment(er)s

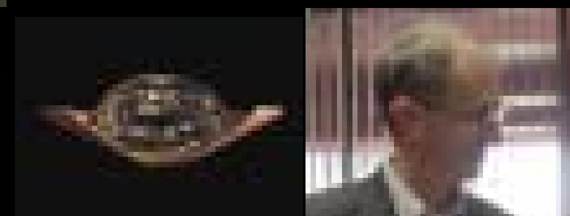
ACP



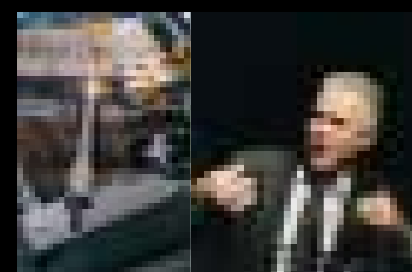
GCMS



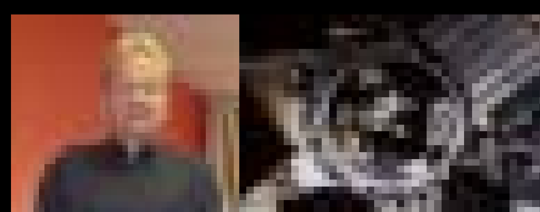
DWE



DISR



HASI

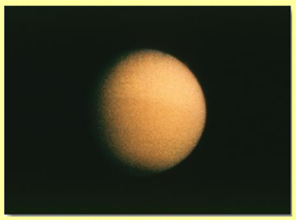


SSP

1st HSWT Meeting, JPL, 1990-1991 ?

Chronology of the Cassini-Huygens mission

11/1980 — 1984-86 — 1987-88 — 1991-97 — 1997-2004 — 2004-2008



Voyager Titan flyby

1982: Proposal submitted to ESA (D. Gautier et al.) to return to Titan in the framework of an ESA-NASA Collaboration

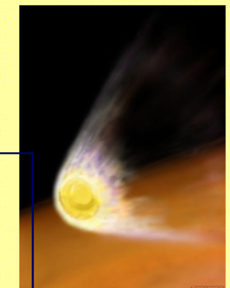
Joint feasibility study ESA-NASA

Industrial Study of the Titan Probe

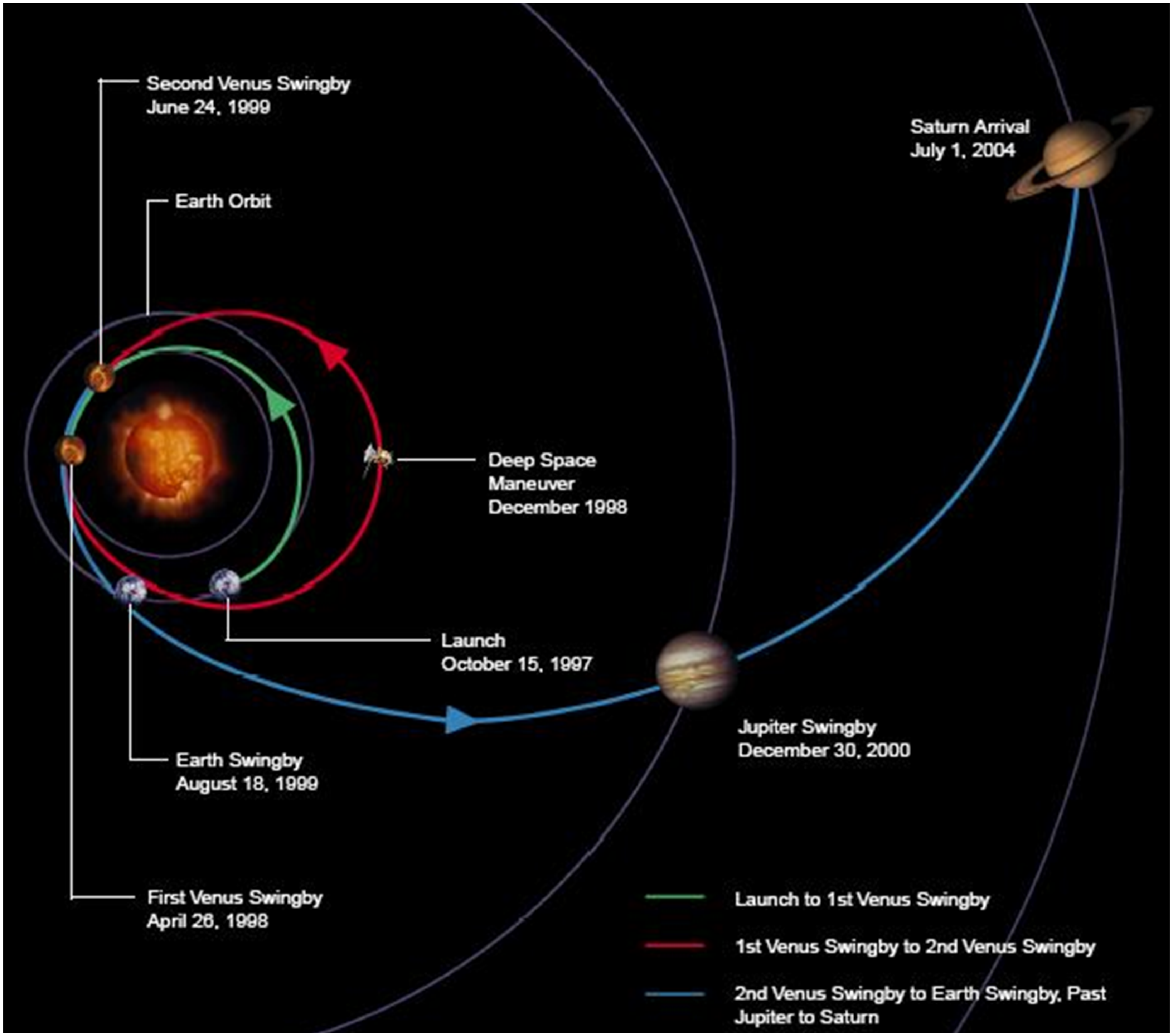
Development

7 year of Travel

01/2005



1 Jul-2004: SOI
14 Jan 05: EDL on Titan
2004-2008: Saturn Tour (77 orbits; 45 flybys of Titan)
2008-2010: 1st extension
2010-2017 2nd extension


Second Venus Swingby
June 24, 1999
Earth Orbit
Saturn Arrival
July 1, 2004
Deep Space
Maneuver
December 1998
Launch
October 15, 1997
Jupiter Swingby
December 30, 2000
Earth Swingby
August 18, 1999
First Venus Swingby
April 26, 1998
Launch to 1st Venus Swingby
1st Venus Swingby to 2nd Venus Swingby
2nd Venus Swingby to Earth Swingby, Past
Jupiter to Saturn

Gravity Assist Propulsion

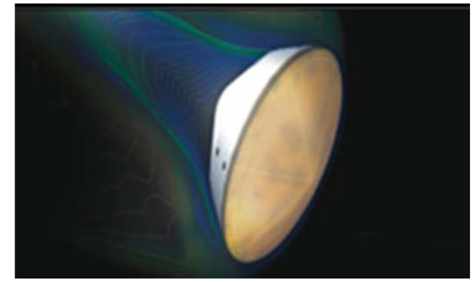
- http://www.sciences.univ-nantes.fr/sites/genevieve_tulloue/Meca/Planetes/assist_grav.html

PS Role during Project Development

- Maximize science within the project constraints and ressources !
- Chair Huygens SWT and vice-chair of the Cassini-Huygens PSG
- Be part of the Huygens Project team but keep your independancy role; always be ready to be the science return advocate. Fight for science.
- Attend all project progress meetings with industry; be alert for science impact of any decision that may be taken
- Monthly Reporting to Science Director
- Support all communications activities
- Specific examples illustrating PS role
  - Help make the unknown environment sufficiently known to allow designing for the unknown: Titan engineering models
  - The Huygens HASI boom story
  - The Huygens Radar altimeter : RAS extension and testing

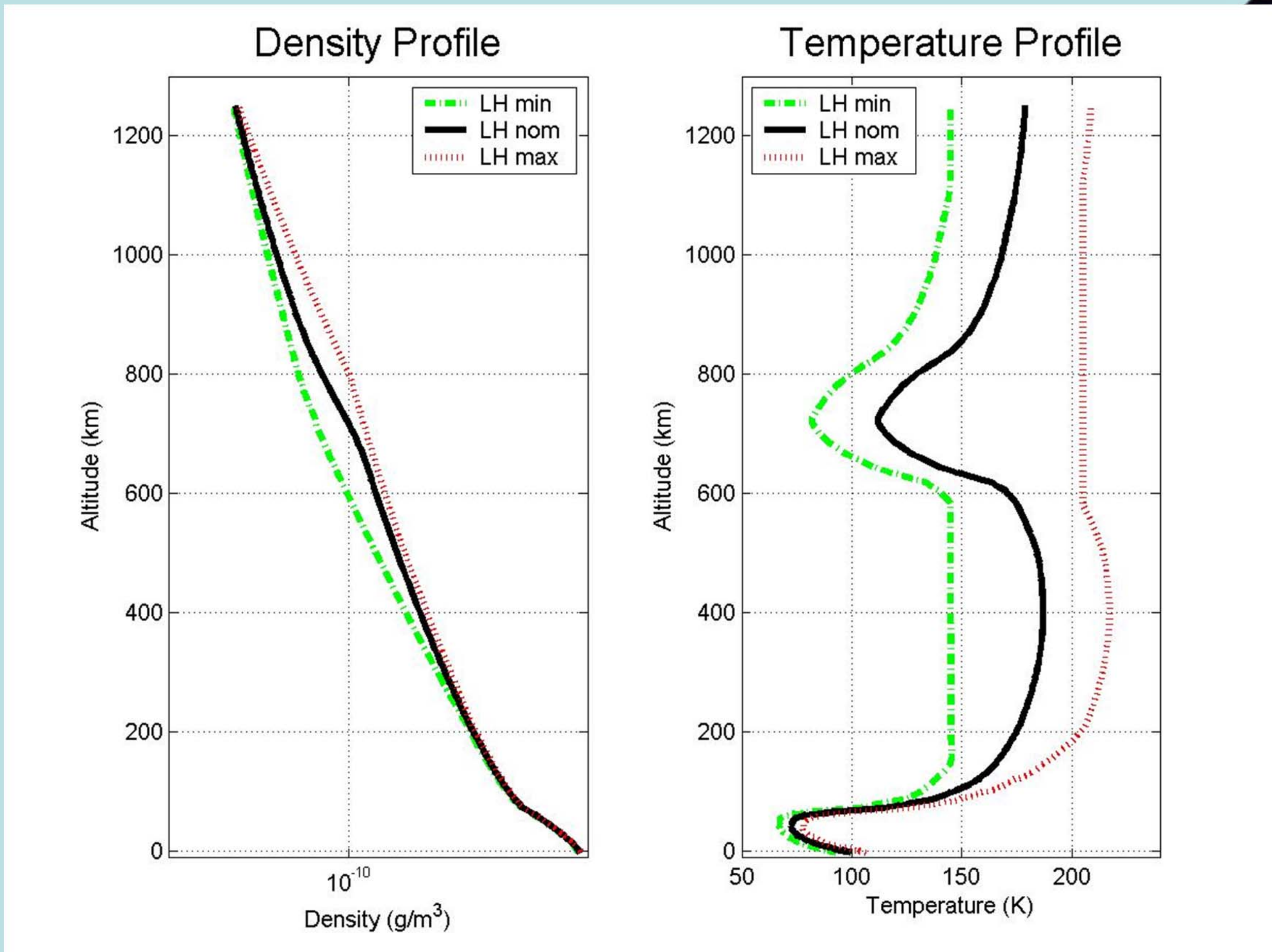
Titan Engineering Models

(ref. to ESA SP 1177)



- Atmosphere Structure Models (T,ρ, composition): Entry aerothermodynamics, Parachute performances (Lellouch-Hunten, Yelle)
- Zonal wind models: Parachute deployment loads, Probe drift effects (Flasar)
- Atmospheric Gravity Waves: effects of structure gradients, turbulence (Strobel, Sicardy)
- Lightning and triboelectric charging (Lorenz)
- Moist convection model (Lunine)
- Radar reflectivities of plausible Titan surfaces (Kirk)
- Atmospheric attenuation of Radio S-band signal (Bird)

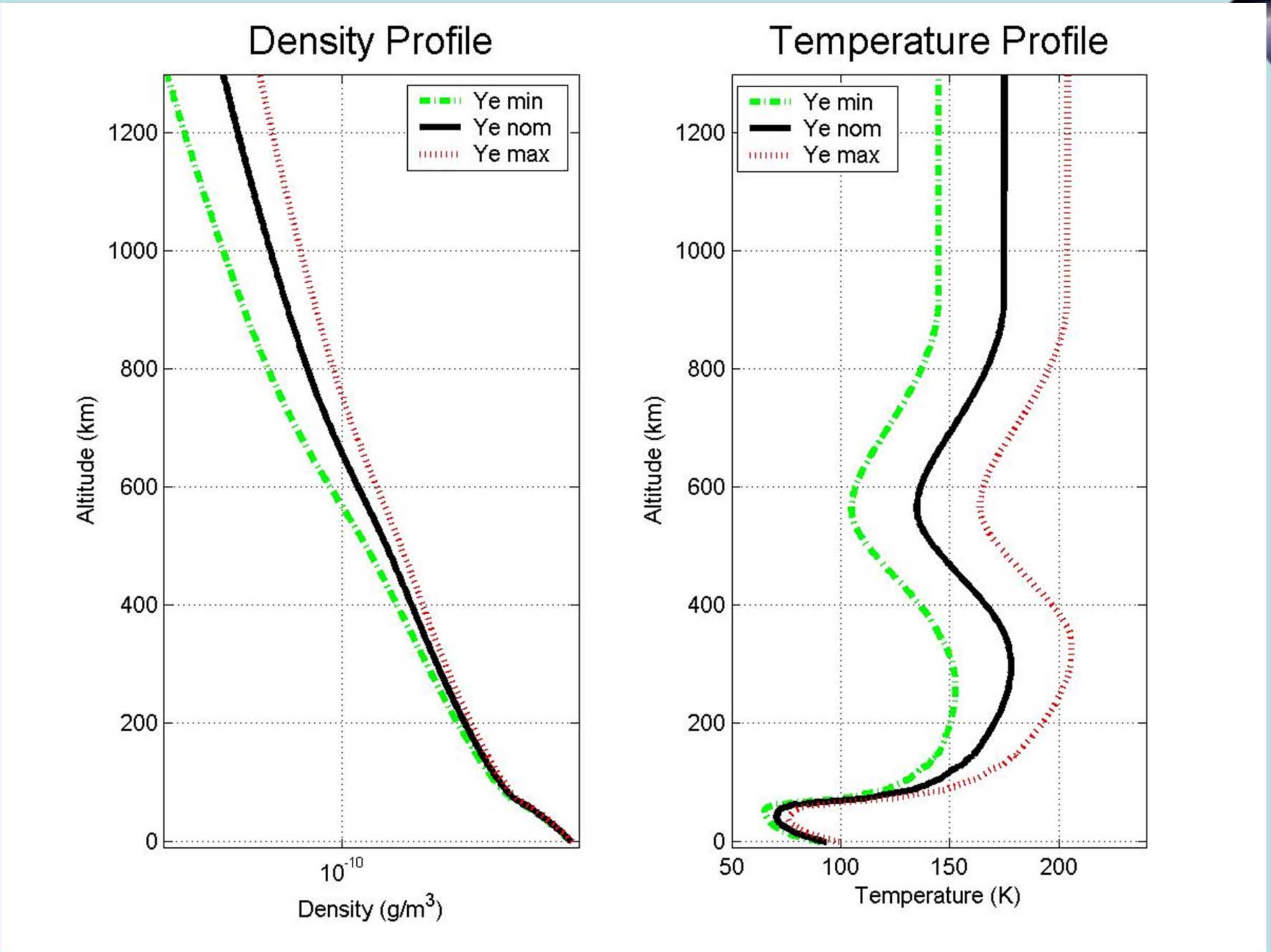
Lellouch-Hunten Model (1987)



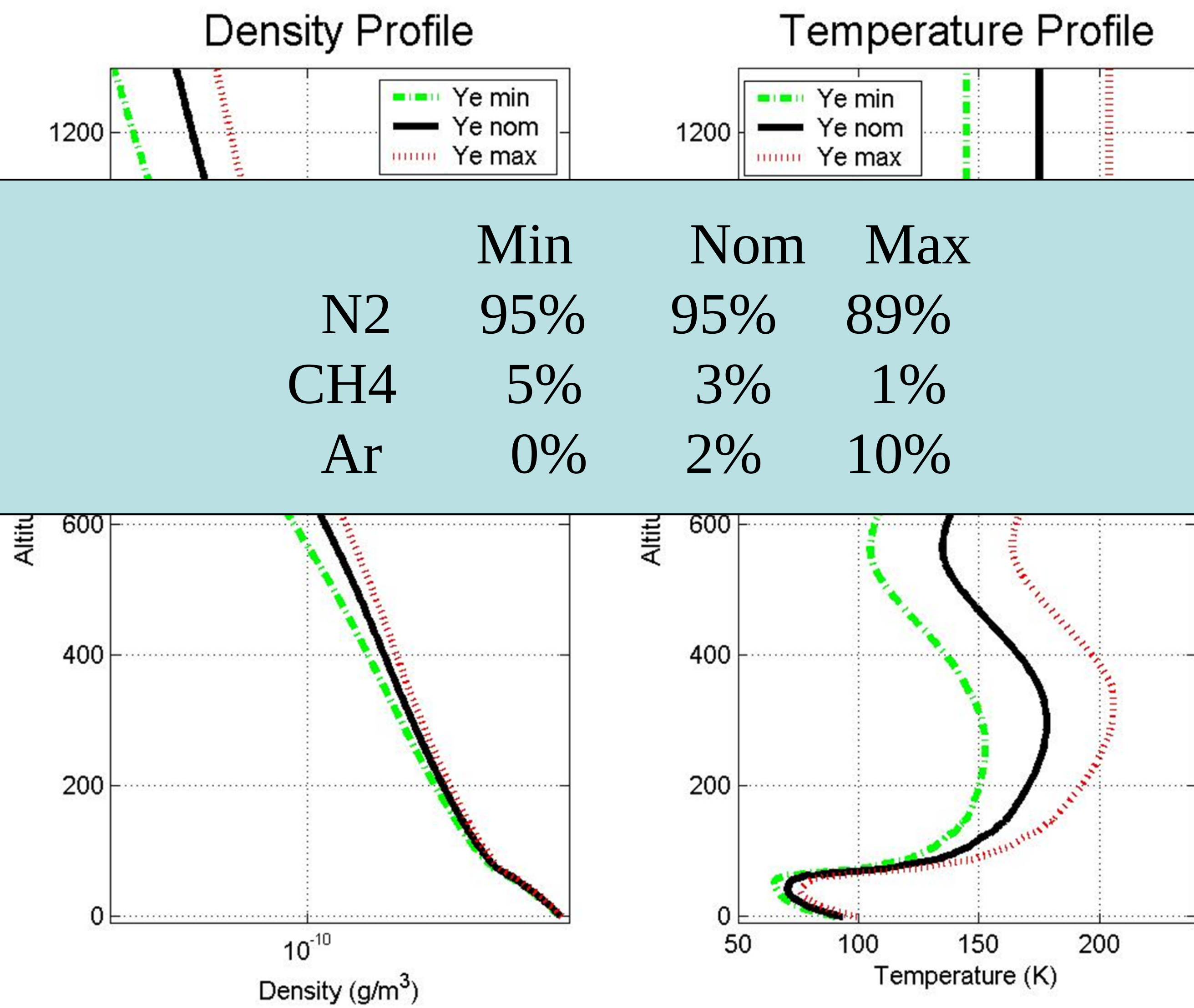
Three main components are Nitrogen (N2), Methane (CH4), and Argon (Ar).

0.5% < X_{CH4}/X_{N2} < 3.5 %; Relative molar abundance of Argon : 0 < X_{Ar}/X_{N2} < 27%.

Yelle Model (1994)

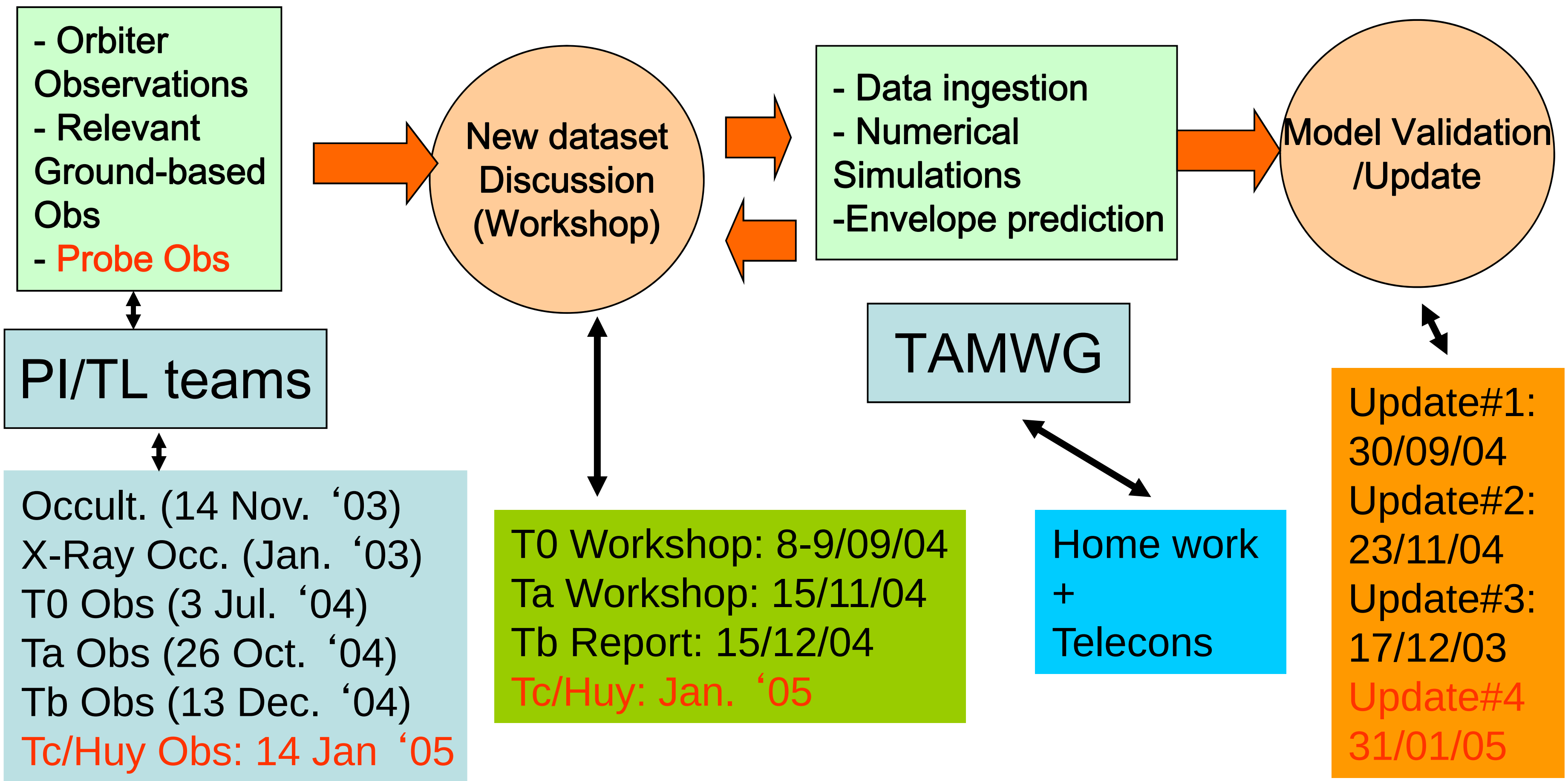


Yelle Model



	Min	Nom	Max
N2	95%	95%	89%
CH4	5%	3%	1%
Ar	0%	2%	10%

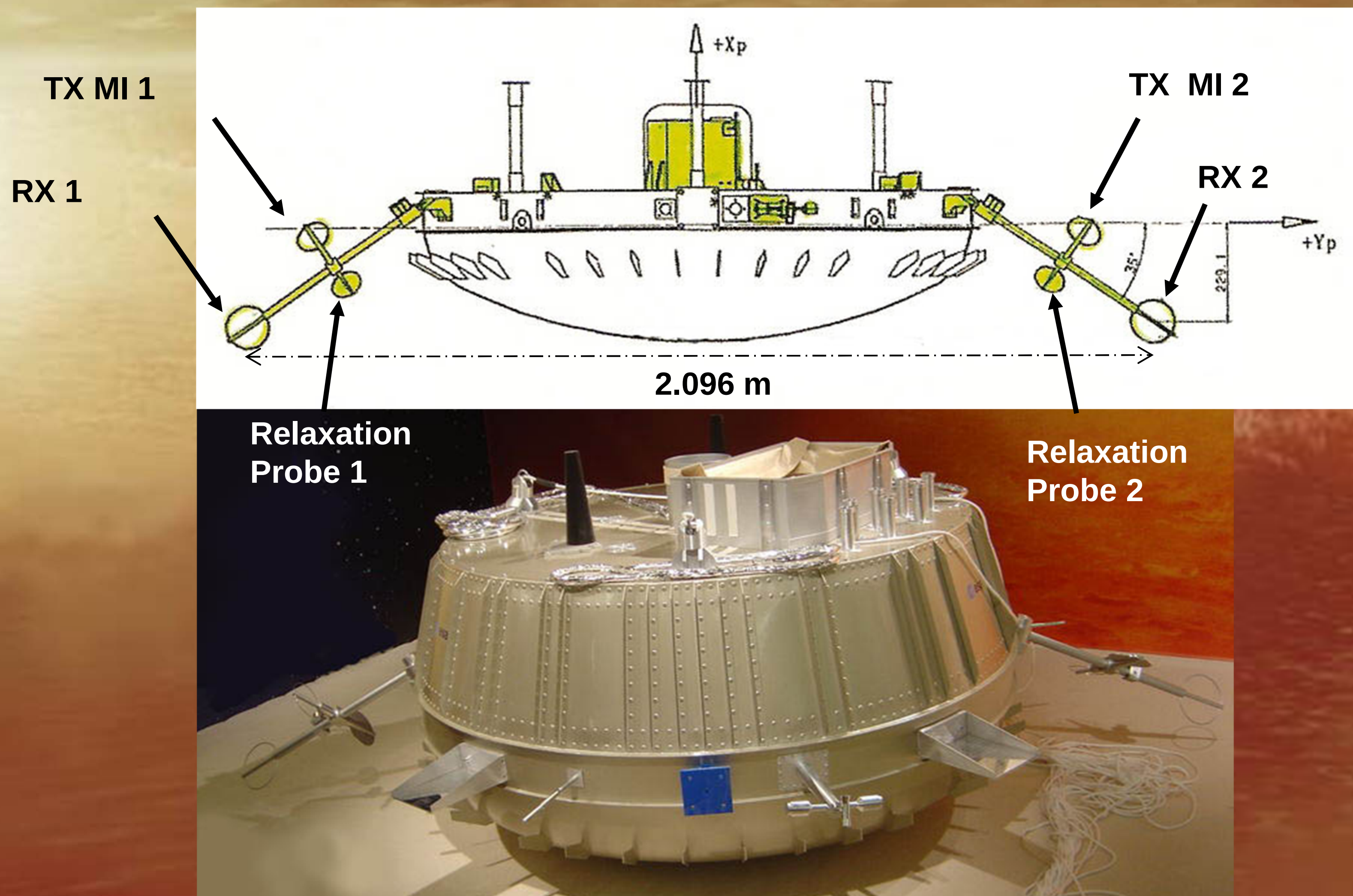
Titan Atmosphere: From Observations to Model Validation/Update



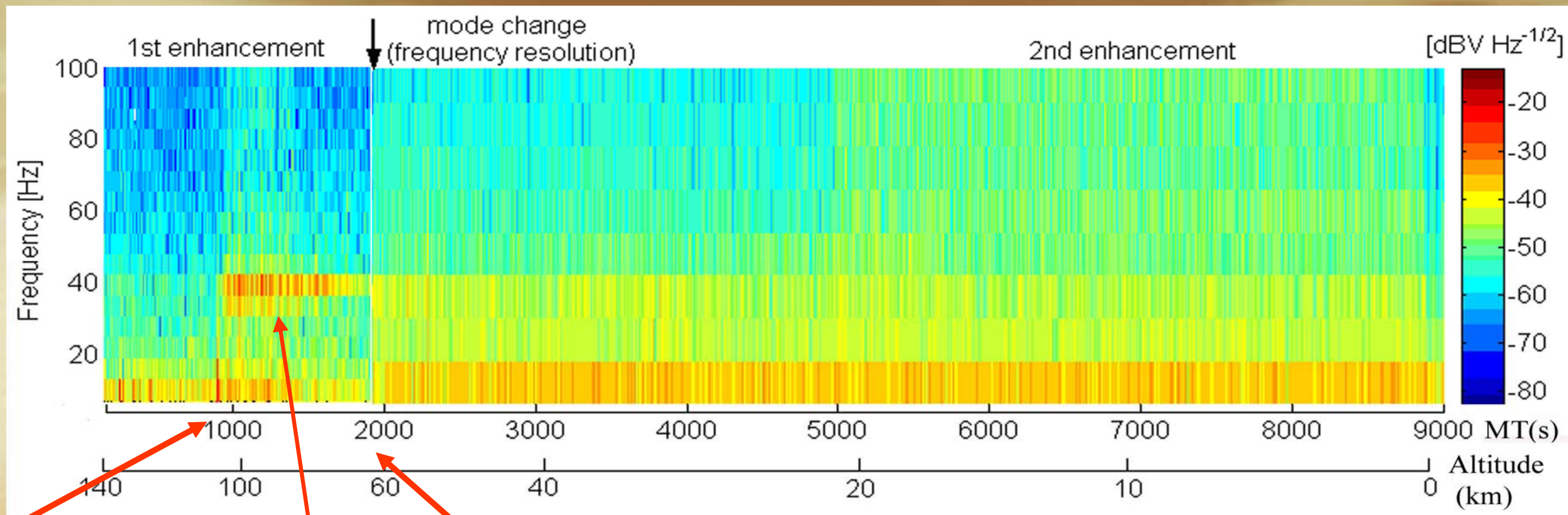
The Huygens HASI boom story

Huygens HASI/PWA Experiment

Objectives: Measure conductivity of atmosphere and surface (Solid or Liquid); Detect associated EM waves (and sound) associated to putative lightnings

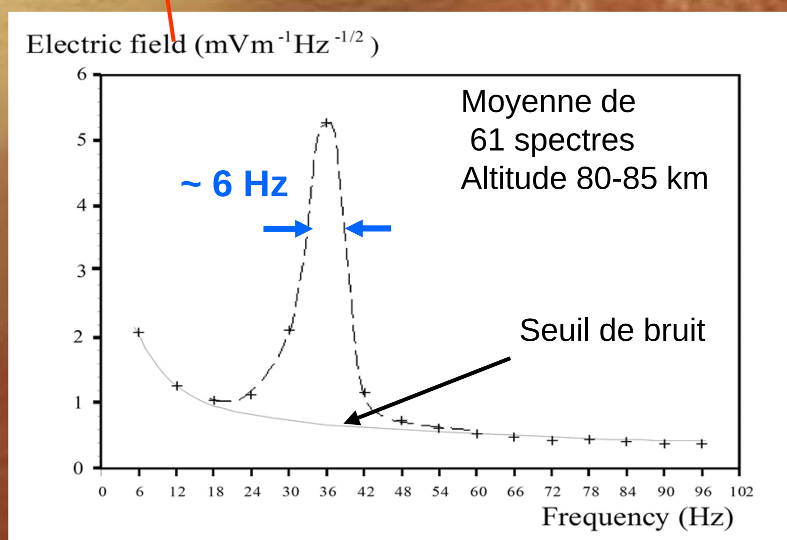


Narrow Band Signal with High Q Factor



MT ~ 900 s
Parachute
exchange

Mission Time 1930 s => Pre-programmed Mode Change

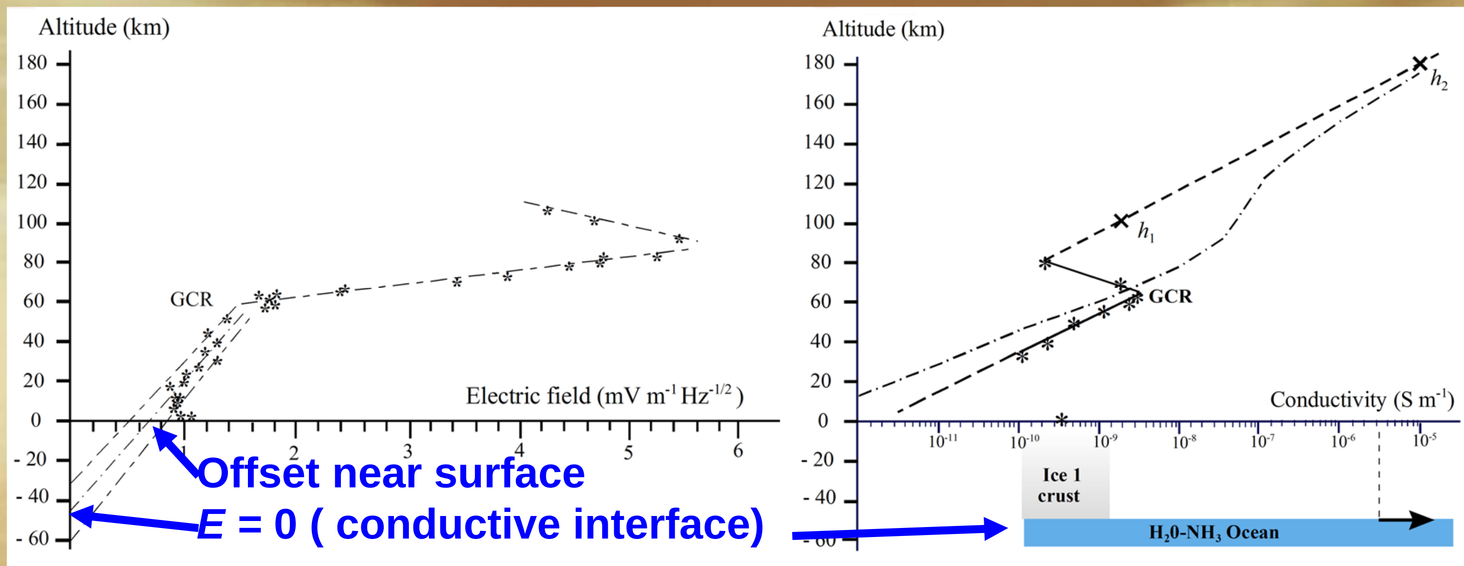


$$Q = \frac{f}{\Delta f}\bigg|_{\substack{\text{half}\\\text{power}}} \approx \frac{36}{6} = 6$$

Comparable To Earth SR Signal

Beghin et al. 2009; 2011

Titan Ocean: Huygens HASI/PWA Result

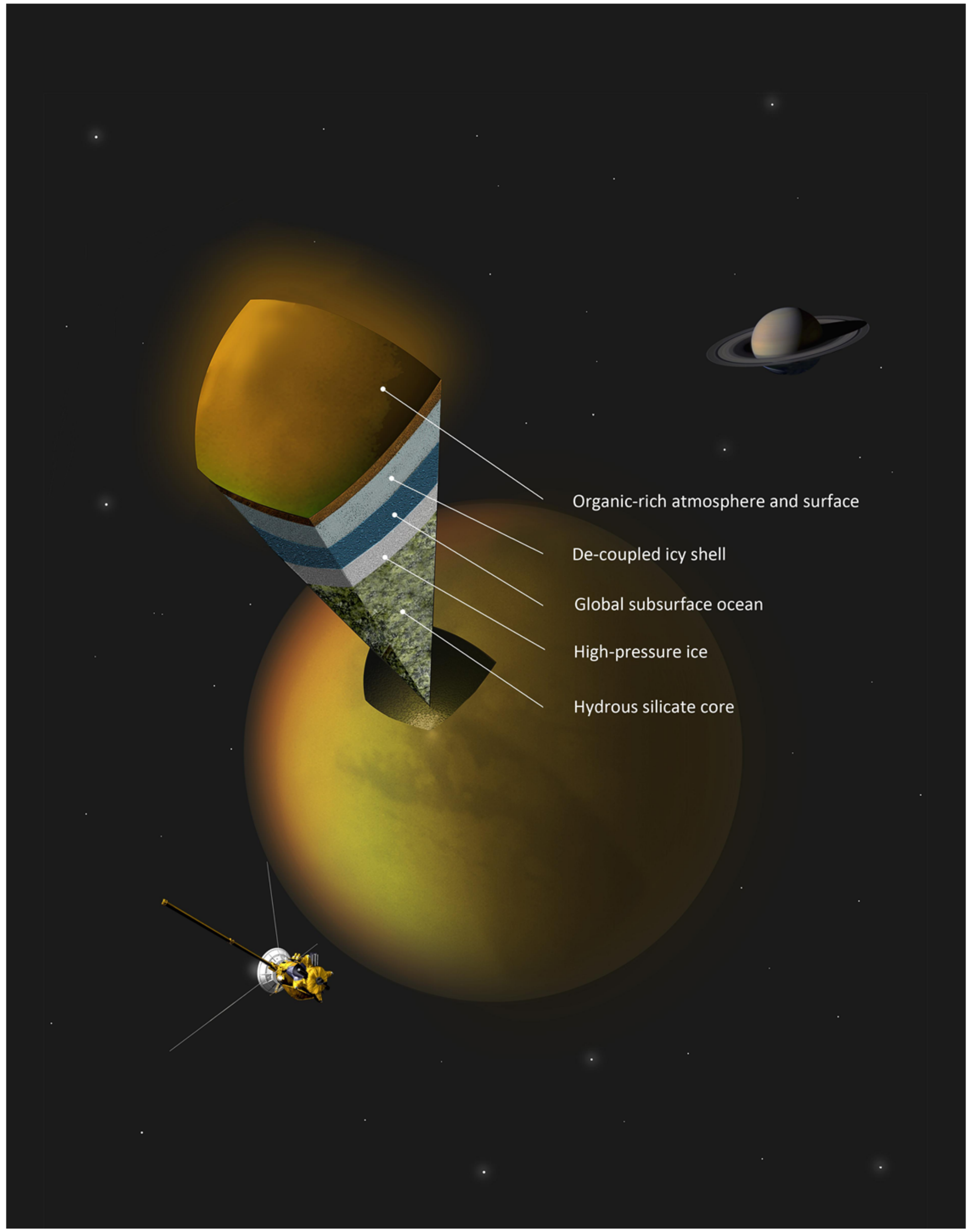


Top layer: Ionosphere

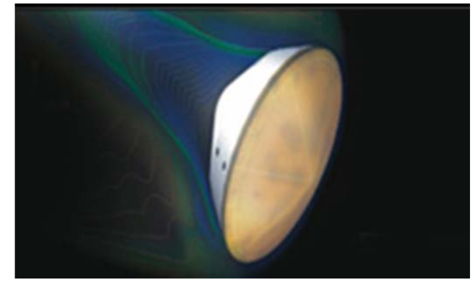
Bottom reflecting layer: Required for Schumann Resonance

Extrapolation of the *E* profile implies an ocean ~ 50-90 km under the ice

Titan interior structure

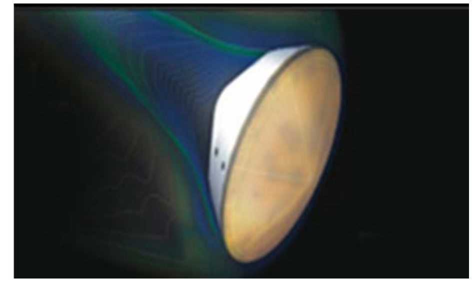


Descent Trajectory Reconstruction: DWTG



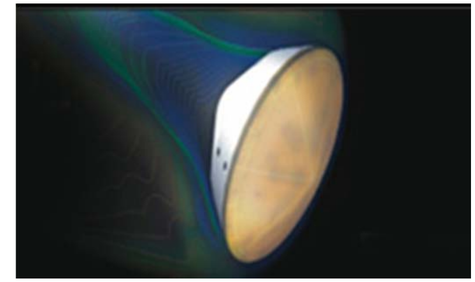
- DTWG set-up during Probe Mission development under DWE Co-I Dave Atkinson's leadership. Galileo's experience was brought in.
- Extracts from Minutes of HSWT#15 meeting (March 1997)
  - The HSWT emphasises the usefulness of the role of the DTWG. The HSWT recommends that this body be maintained at a low level during the cruise phase and at a full level of activity after the Probe descent during the early data analysis phase.
  - It was agreed by the HSWT that a low level of activity will be maintained during the cruise phase (R. Lorenz is setting up a Web page). The need for a DTWG co-chair was discussed. No decision was taken. A co-chair will be required for the data analysis phase.
- DTWG work led to IPPW series (Lisbon, 2000)
- Great opportunity for a Young Scientist materialised: Led to recruitment of Bobby Kazeminejad

Special thanks

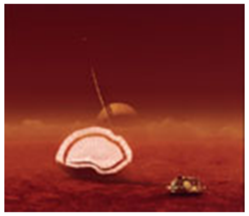


- Ralph Lorenz, (YGT’s Huygens Project Team, 2001-2002)
- Stephan Ott (YGT’s Huygens Project Team, 2001-2002); Mission analysis, ISO, Herschel
- Francesca Ferri :RF 1998-2000;Titan & Mars science, HASI Team, Netlanders, Exomars
- Roland Trautner (1999-2011), Huygens instrumentation, HASI team, Exomars
- Olivier Witasse (RF:2000-2002, Deputy PS 2003-2006), science support, Ground-based observation coordination, Data archive; Mars Express, Exomars/TGO
- Daniel Firre (Stagiaire 2001); HRTF; ESOC
- Bobby Kazeminejad (2001-2005); HRTF and DTWG; Galileo Project
- Miguel Perez (2002-2005), Sci Ops support, Venus Express Science Operations Team
- Alexandre Piot (RF: 2003-2005), Radar balloon flight; ATV Team
- Sandrine Maloreau (Stagiaire 2003); Balloon radar data processing,
- Thomas Civeit (Stagiaire 2003); Titan winds observation; SOFIA Science Operations Team
- Elias Roussos (Stagiaire 2004), Huygens mission scenario simu; Cassini MIMI Team
- Alain Sarlette (Stagiaire 2005); Comparative studies Huygens Drop-test & Huygens spin;
- Arnaud Magette (Stagiaire 2005); Comparative studies Earth &Titan lightning detection;

Radar Altimeter Story



- Included as a system sensor to provide altitude to payload operational reasons (10 % accuracy specs). FMCW radio altimeter.
- Worked a project agreement to provide echo signal to HASI. ➔ RADAR-HASI interface.
- Designed (and tested) for below 10 km Altitude. But switched on at 60 km.
- Provided erroneous altitude above 15 km, which was declared « true » despite a very robust algorithm. Confused DISR for a while. Recovered below 15 km.



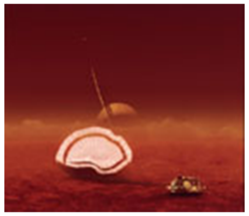
HRA tests on board of Planes, Balloons and Helicopters

Project tests

- Helsinki plane test 1994: 1 radar, funct. Tests, successful, low altitude
- Radar return simulator tests (up to 10 km), successful

Science Tests

- Comas Sola 1995: 1 radar, DM, successful, PWA + analogue data
- Arizona Helicopter test flights: 1 radar, successful, low alt, analogue+camera
- Trapani 2003: 1 radar, improved DM, partially successful
- Sky tests 2004: ground based interference tests
- Antarctica 2004: 2 FS radars, PWA + analogue, cancelled / delayed
- Teresina 2004: successful, 2 FS radars, analogue+digital data, camera



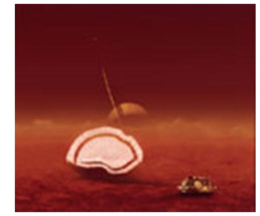
PEASMA Campaign – Teresina, Brazil

HRA Goals

- Flight of both HRA FS models, digital DAQ system, backup DAQ system, camera
- Verify correct concurrent operations of both radars
- Check performance at high altitude, collect data for supporting Huygens radar data analysis

PEASMA goals:

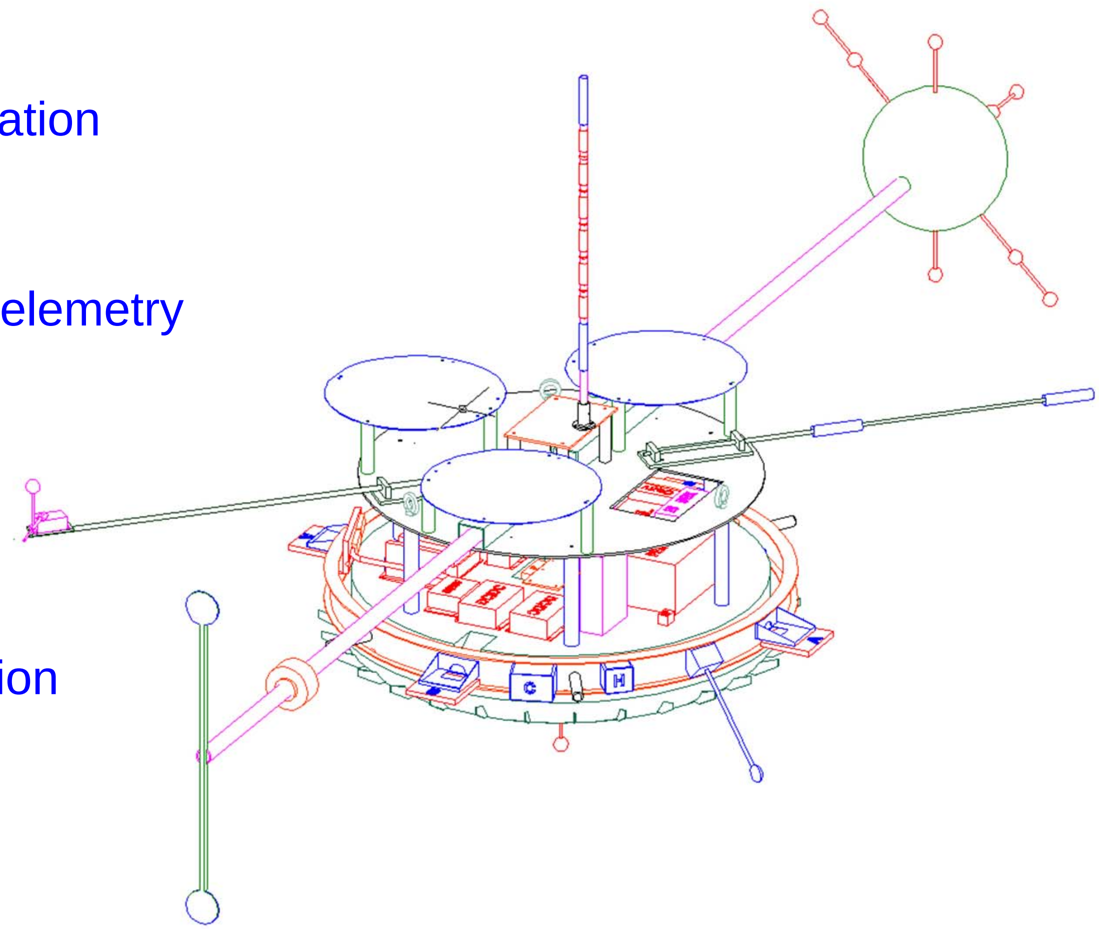
- Measurements of electric fields
- Measure perturbations due to presence and movement of Balloon / Gondola
- Measurements of atmospheric conductivity (RP)
- Test of instrumentation for future Mars lander applications



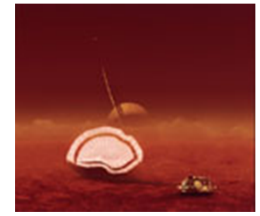
PEASMA flight

- CETP / ESTEC cooperation
- Gondola mass 158 Kg
- 5m x 2. 2m x 1.3m
- No commanding, only telemetry (recorded on board)
- 100 ZL balloon (100.000 m^3)

- 8 h nominal flight duration
- 35 km ceiling

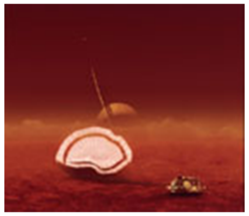


Operations

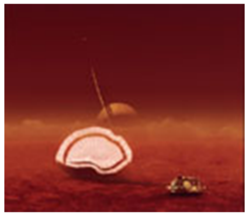


- Operations only via external panel
- Backup recorder: no access after airtight sealing
- DAQ PC: Access via LAN
- Audio verification of radar and backup recorder function
- Visual verification of PC power on, power status, and DAQ software activity
- Visual verification of backup recorder electronics activity
- Minimum of ca. 3 minutes required for startup and verification

Inertial calibration

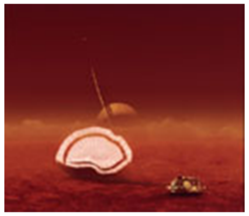


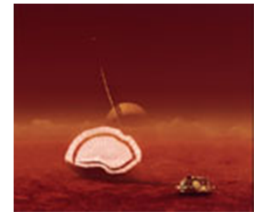
Launch & flight



- **Launch at 7:54 UTC (4:54 local)**
- **Flight duration ~ 6:10 hrs**

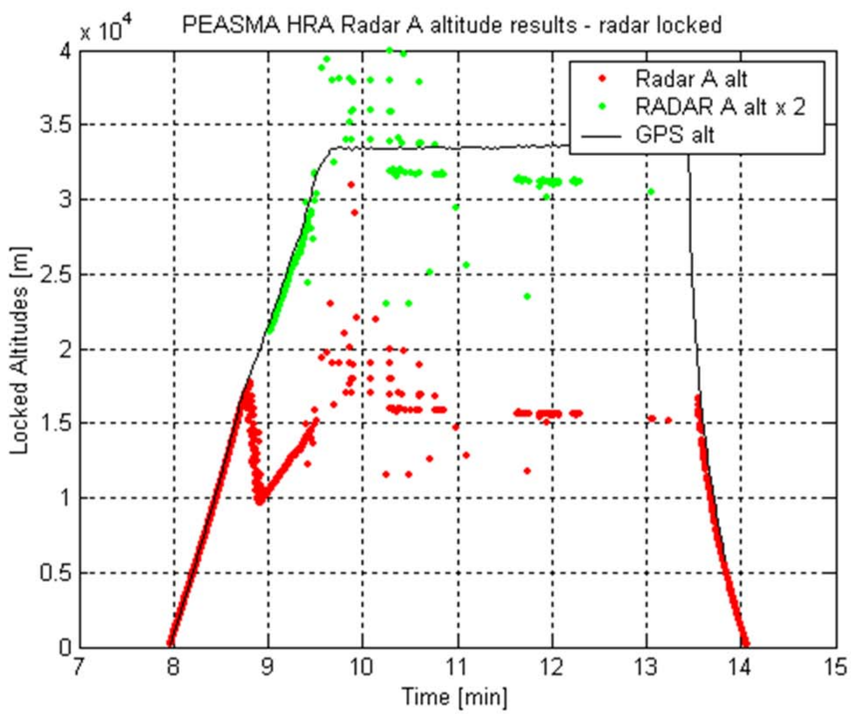
Recovery

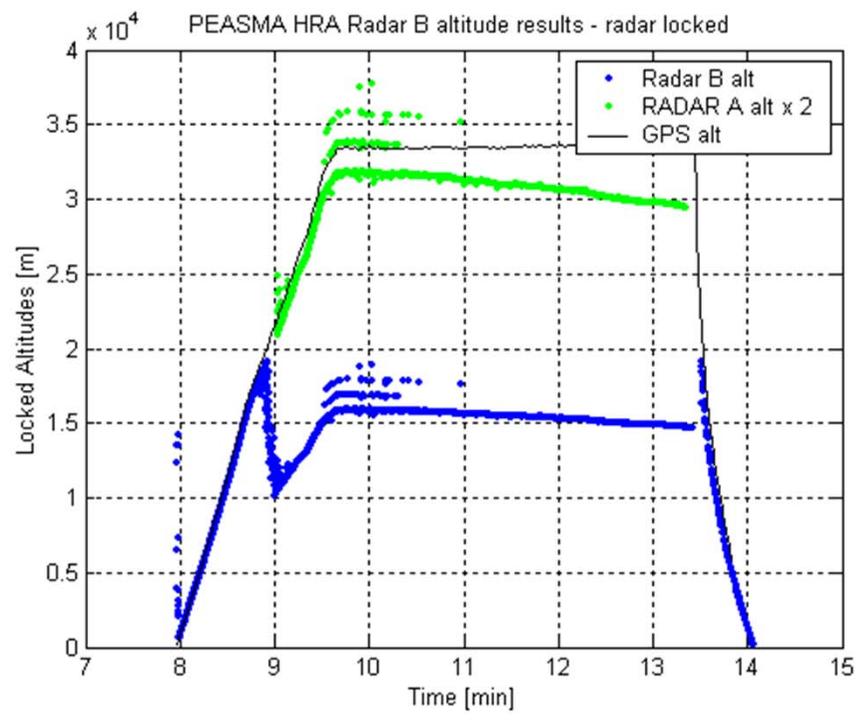




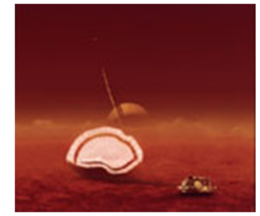
HRA , GPS and x2 Correction

- Digital data from HRA A / B recorded by PC DAQ shows identical behavior but at (slightly) different times and different altitudes
- MSB (bit 15) is zero at high altitude, bits 15-12 fluctuate during transient phase
- When multiplied by 2, alt reading at high altitude is correct (when temp error compensated)



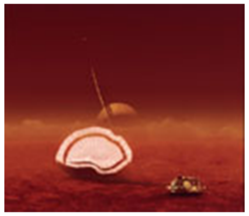


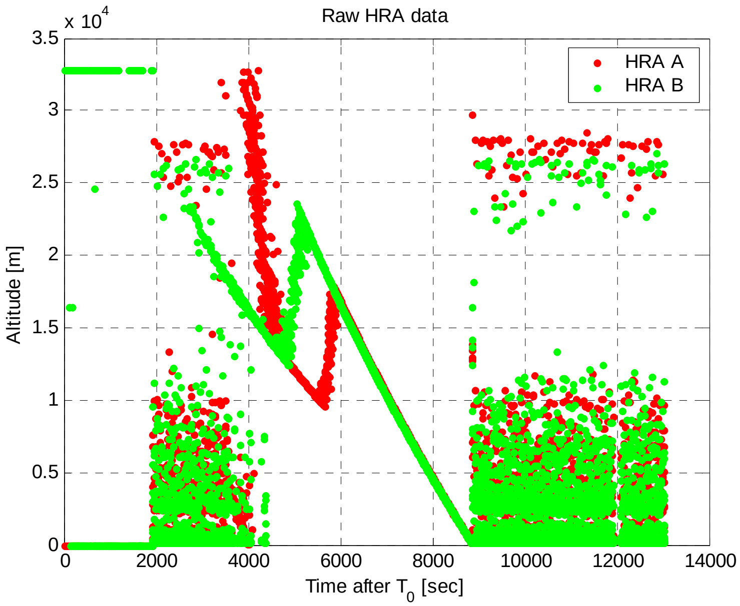
Post-flight assessment

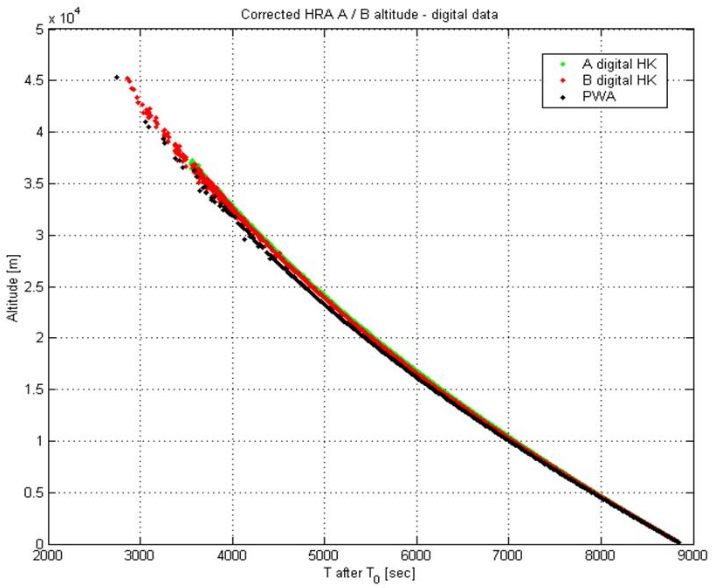


- Radar performance evaluation indicated that observed behaviour during balloon flight most likely expected on Huygens; algorithm robusteness unknown
- We are 10 days before probe separation
- Software table patch or no patch ?
- Decision: no patch

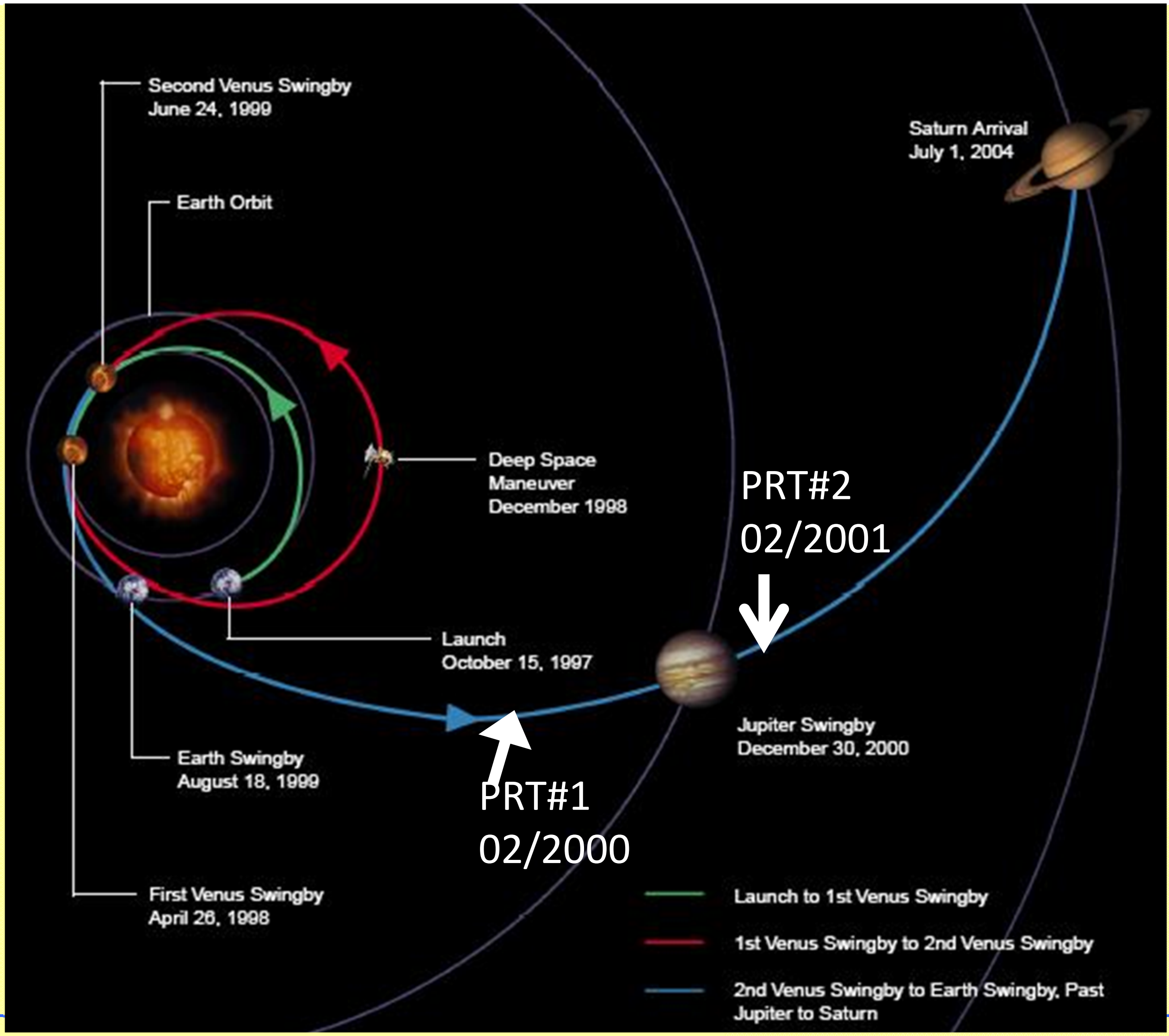
Raw and Reconstructed Altitude Data







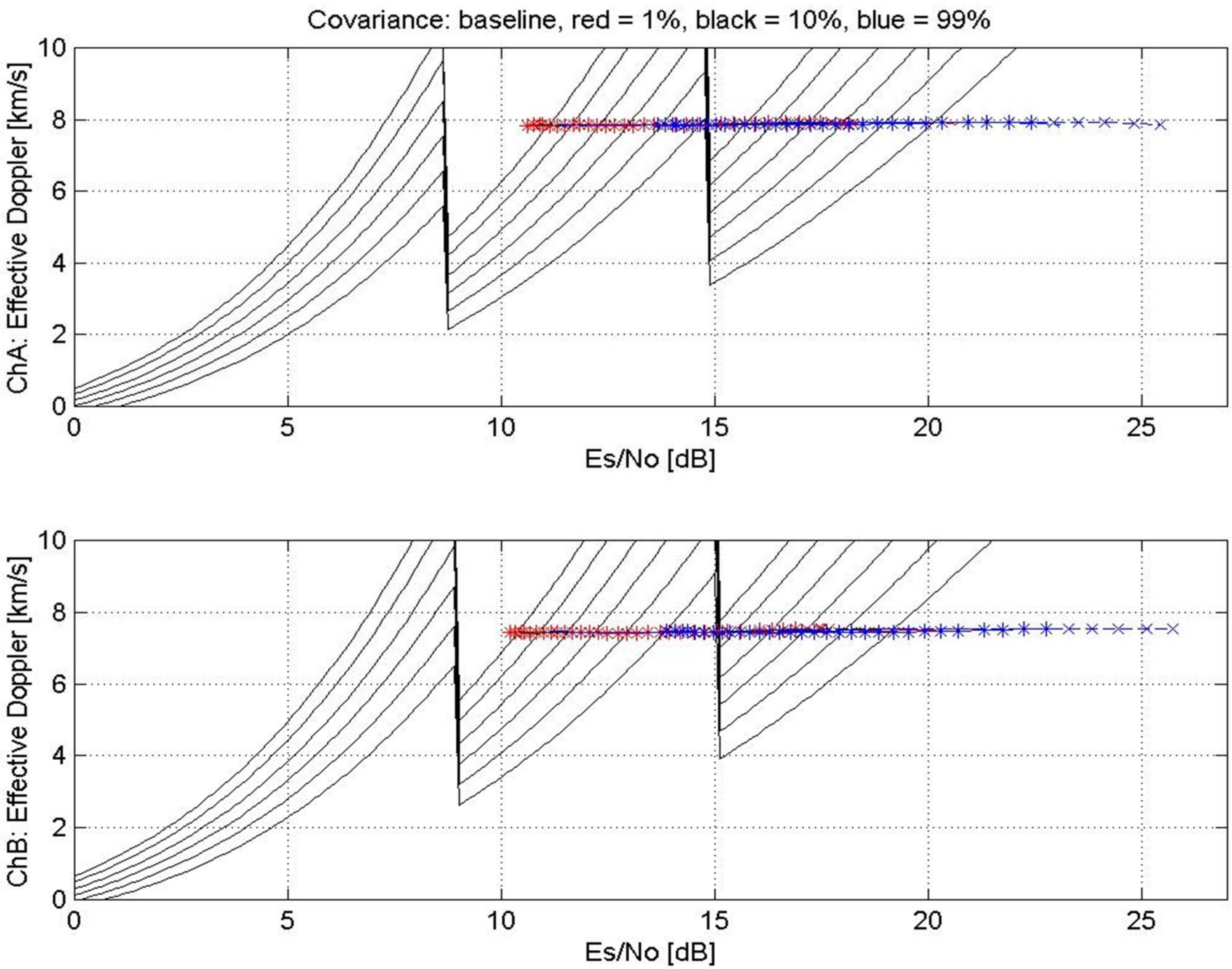
Discovery of Doppler Problem



Baseline Mission (Low flyby)

Input parameters (B-plane)

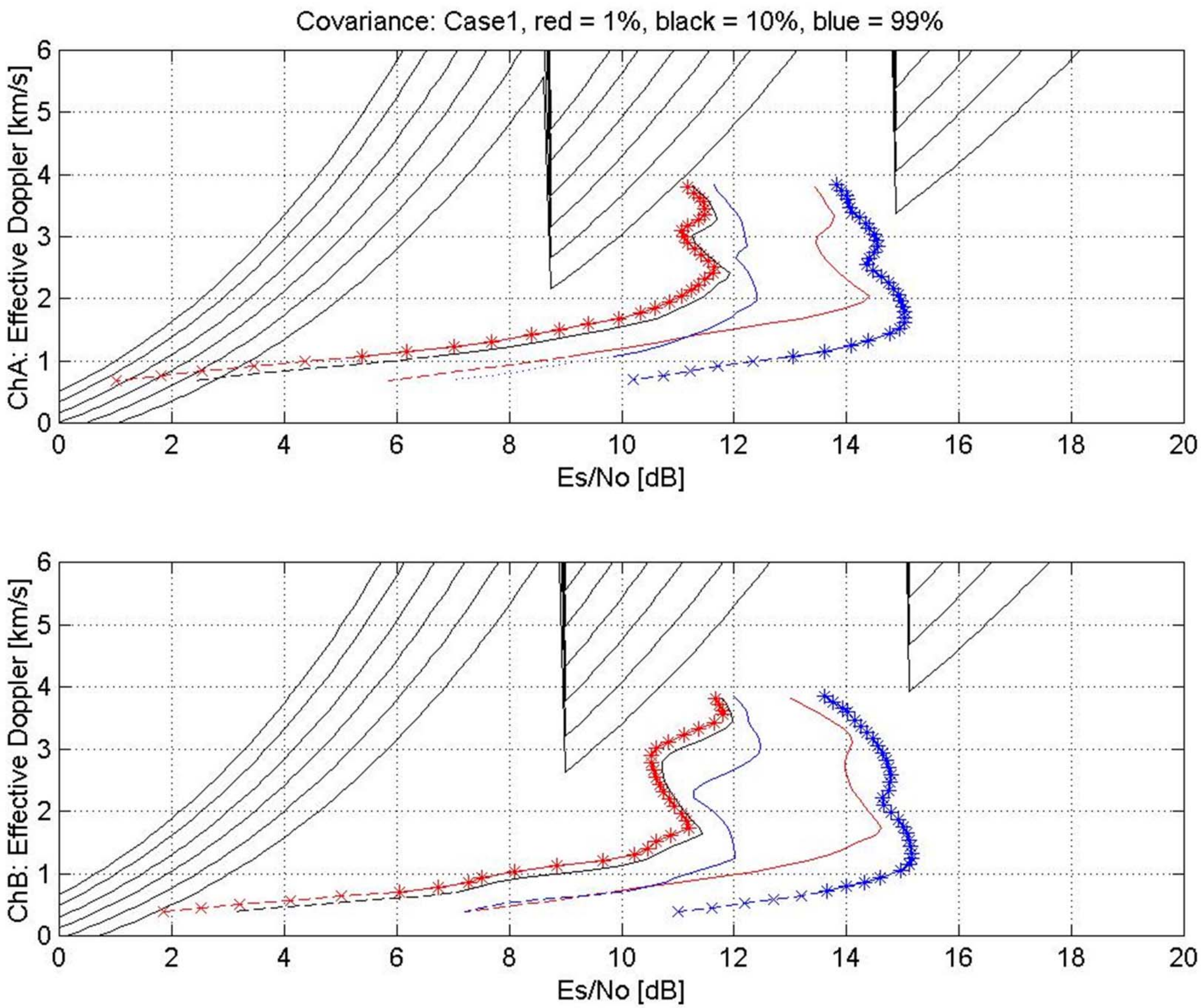
Parameter	Orbiter	Probe
B-Plane Angle (deg):	-22.5	-60.0
Flyby Altitude (km)	1228	
ODT	4.0	
Pre heating time (h)	-	0
Vinf (km/s) (α/δ in deg)	5.55 (-24.7/15.6)	5.75 (-26.3/15.0)
Entry angle (deg)	-	- 64
Wind model	HRTF - prograde	
Covariance Matrix	010406	
Reference Altitude (km)	-	1270
Initial epoch (JD2000)	1792.427084d (T1=27/11/2004 10:15:00)	


Covariance: baseline, red = 1%, black = 10%, blue = 99%
ChA: Effective Doppler [km/s]
Es/No [dB]
ChB: Effective Doppler [km/s]
Es/No [dB]
0
2
4
6
8
10
0
5
10
15
20
25

Case1

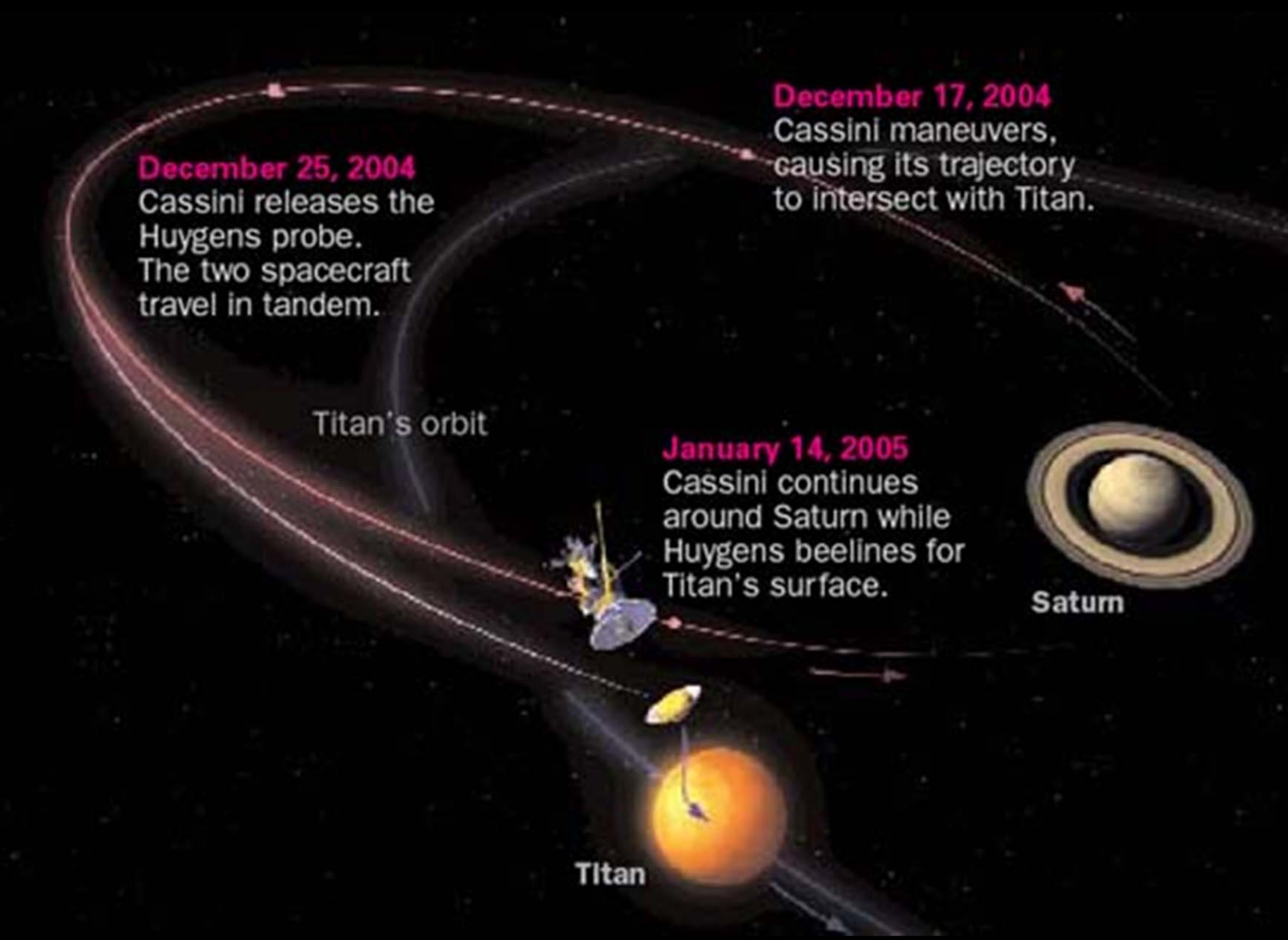
Input parameters (B-plane)

Parameter	Orbiter	Probe
B-Plane Angle (deg):	-180	-190
Flyby Altitude (km)	65 000	
ODT	2.1	
Pre heating time (h)	-	4
Vinf (km/s) (α/δ in deg)	5.33 (-11.4/5.88)	5.64 (-13.13/3.7)
Entry angle (deg)	-	- 64
Wind model	HRTF - prograde	
Covariance Matrix	010406	010406
Reference Altitude (km)	-	1270
Initial epoch (JD2000)	1840.3640742d(14/01/2005 08:44:16)	



Covariance: Case1, red = 1%, black = 10%, blue = 99%
ChA: Effective Doppler [km/s]
Es/No [dB]
ChB: Effective Doppler [km/s]
Es/No [dB]
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
18
20

Huygens released on 3rd orbit around Saturn



13 January 2005: The Day before

Huygens is well on its way!

Looking forward to an exciting day on the 14th of January, the Huygens Mission Team is pleased to invite you to the 'Huygens Dinner' that will take place on Thursday 13th January 2005 at

Hotel Jagdschloss Kranichstein in Darmstadt

The dinner will start at about 20:00. Transport will be arranged. Buses will leave from ESOC at around 19:15 and return to ESOC and selected hotels (list to be provided).

Please confirm your attendance by sending an email to

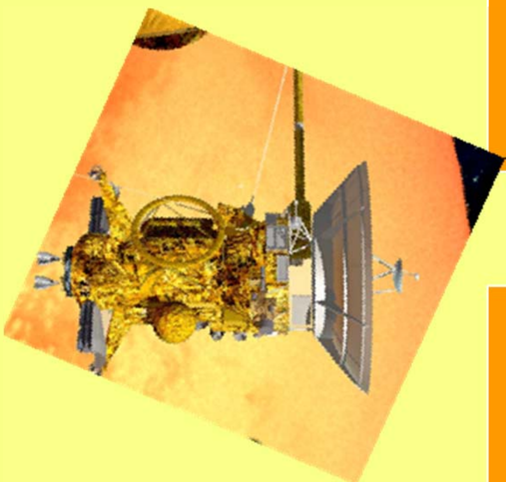
Huygens_Dinner_13Jan05@rssd.esa.int

Please confirm if you intend to use the bus service.

Timely reply would be most appreciated.

Jean-Pierre Lebreton
Huygens Mission Manager/Project Scientist

Huygens Radio Signal paths



TCXO

Channel B

TCXO

Huygens carrier + data

Channel A

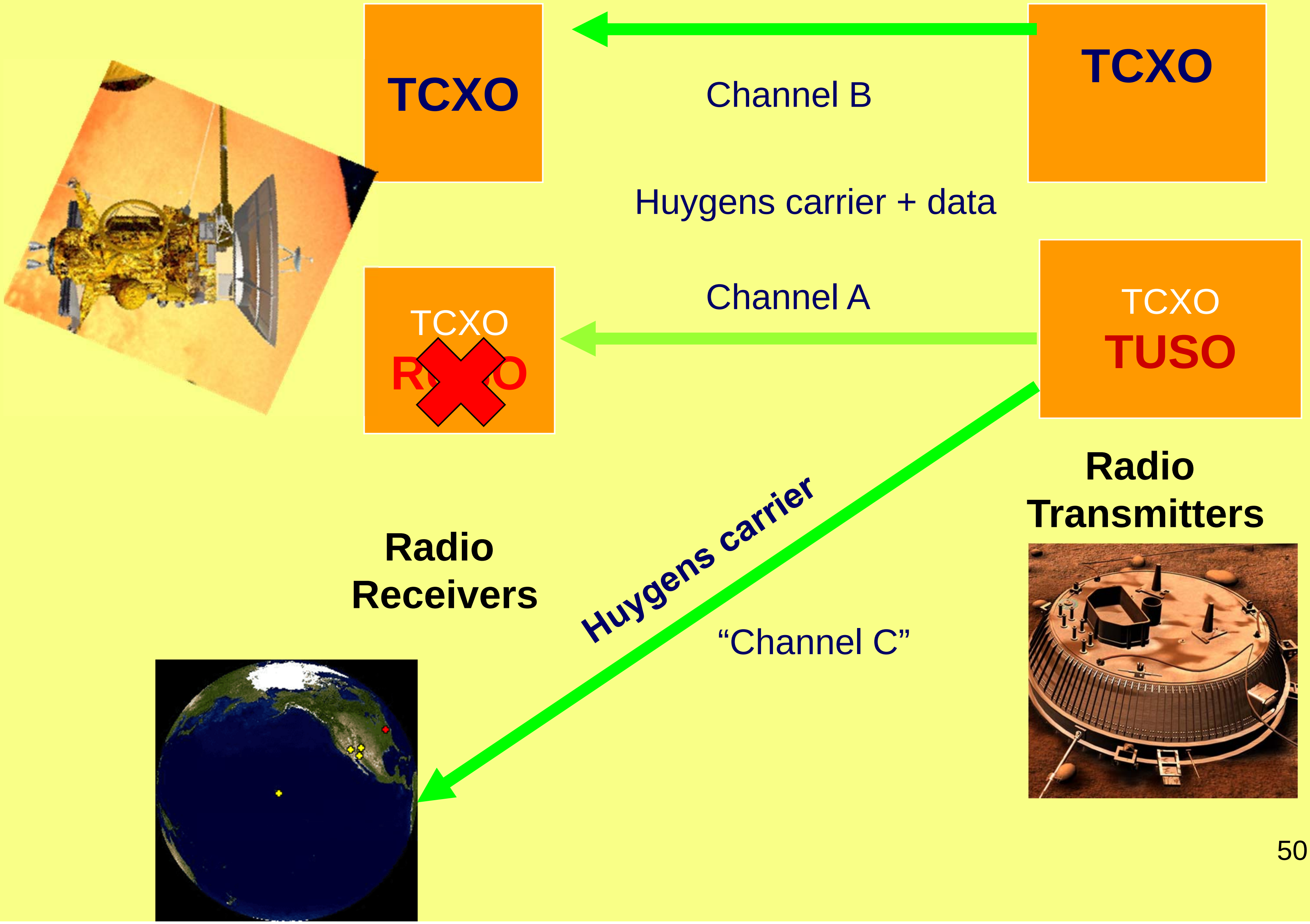
TCXO
RUSO

TCXO
TUSO

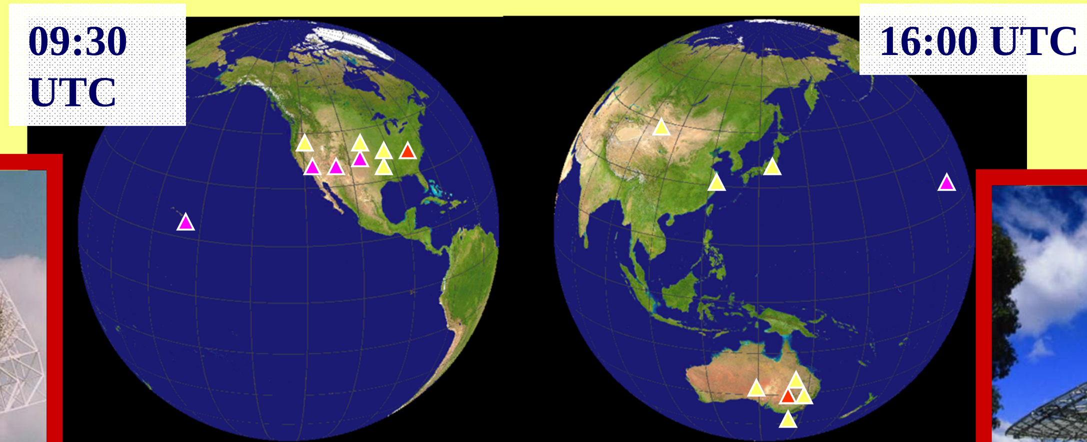
Radio Transmitters

Radio Receivers

Huygens Radio Signal paths



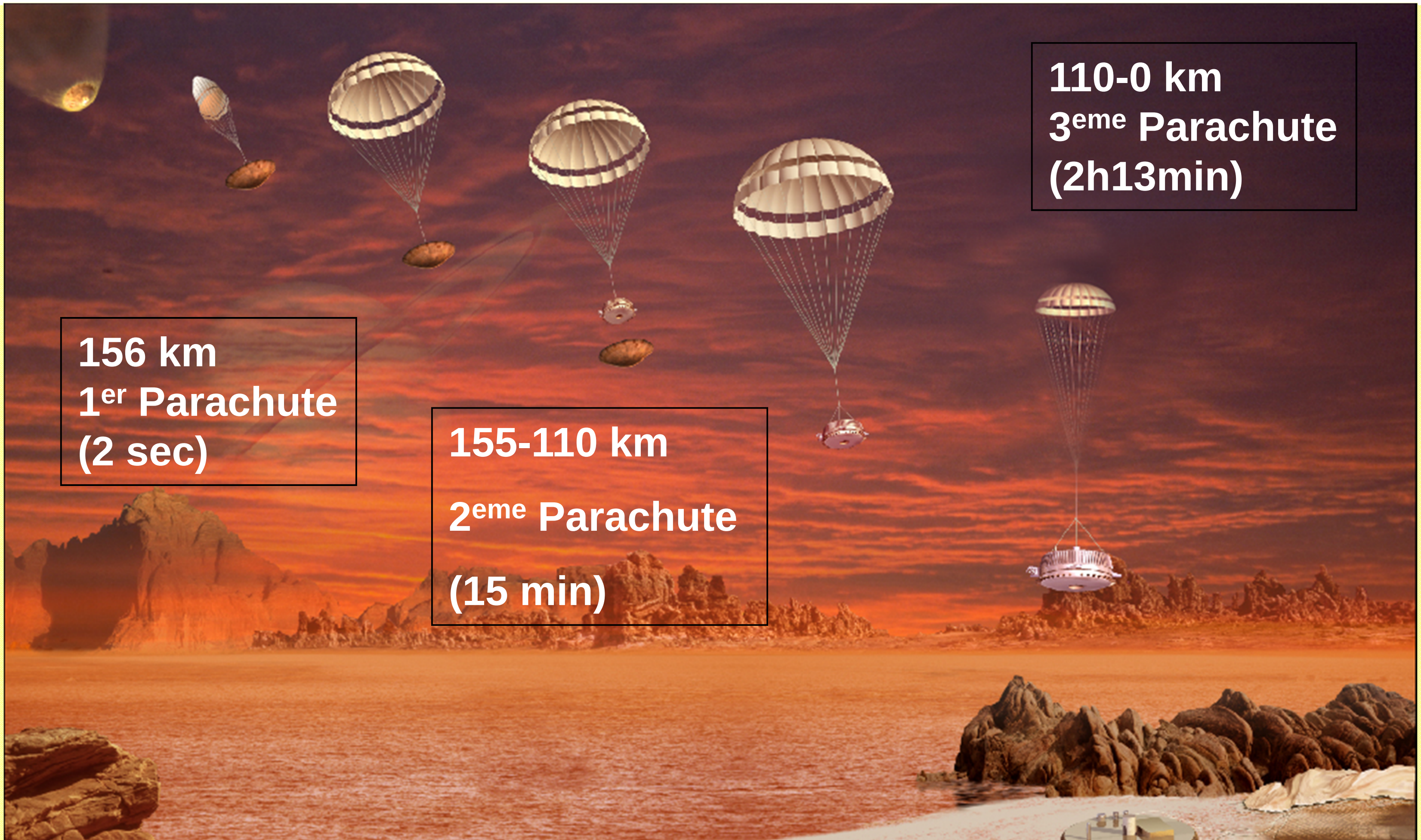
Earth-based Huygens signal (carrier) detection



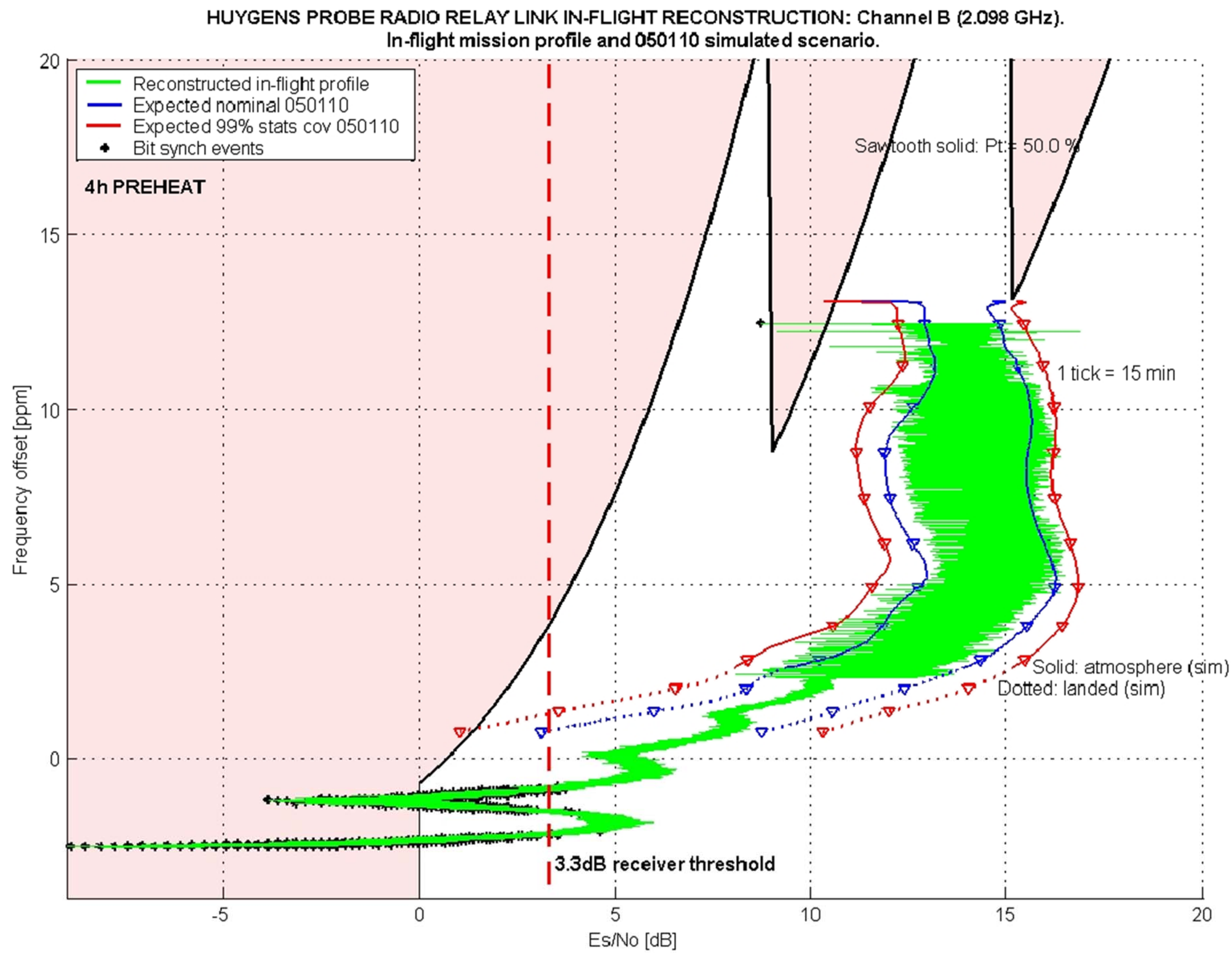
Real time Signal Detection
Radio Science Group/JPL

VLBI observation
JIVE, Netherlands

14 Janvier 2005: la descente



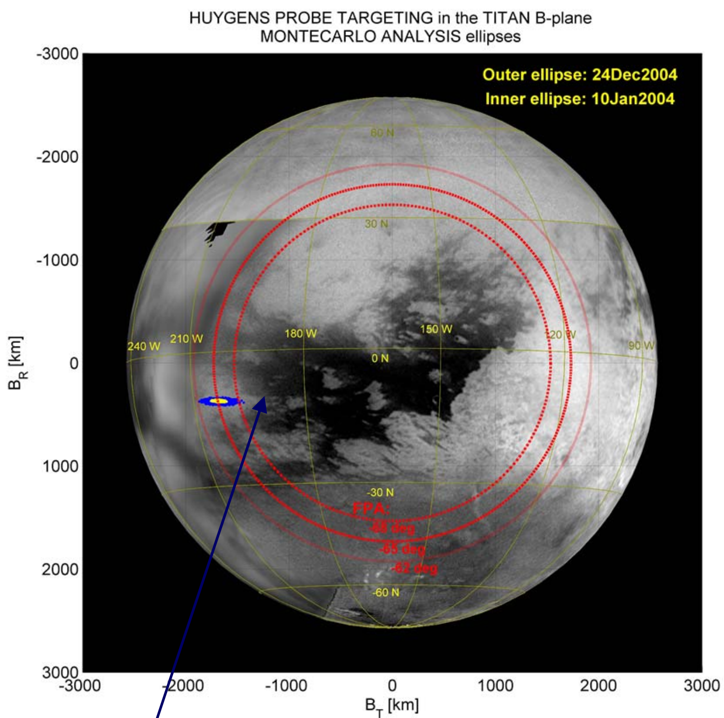
Données via Cassini: 2h28min de descente et 1h12min sur la surface
Signal via telescopes radio: 5h42min, y inclus 3h14min sur la surface



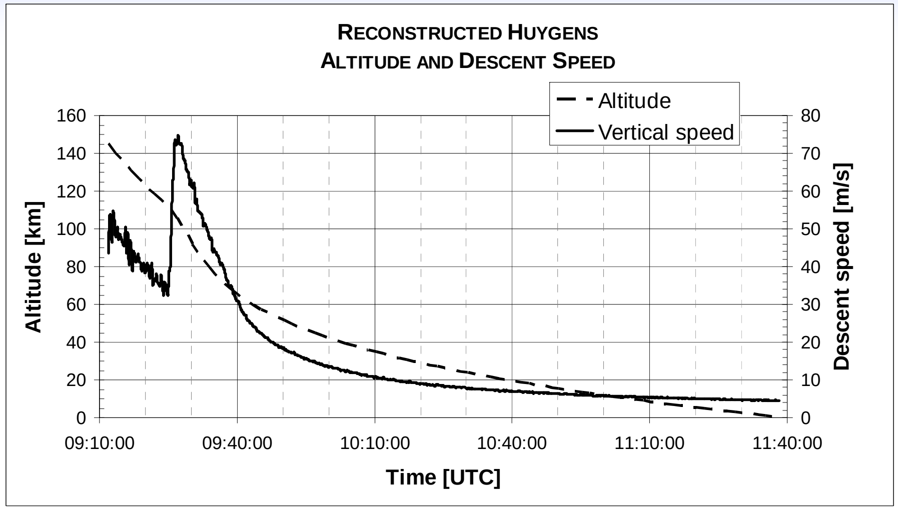
Lebreton et al, to be submitted to Nature

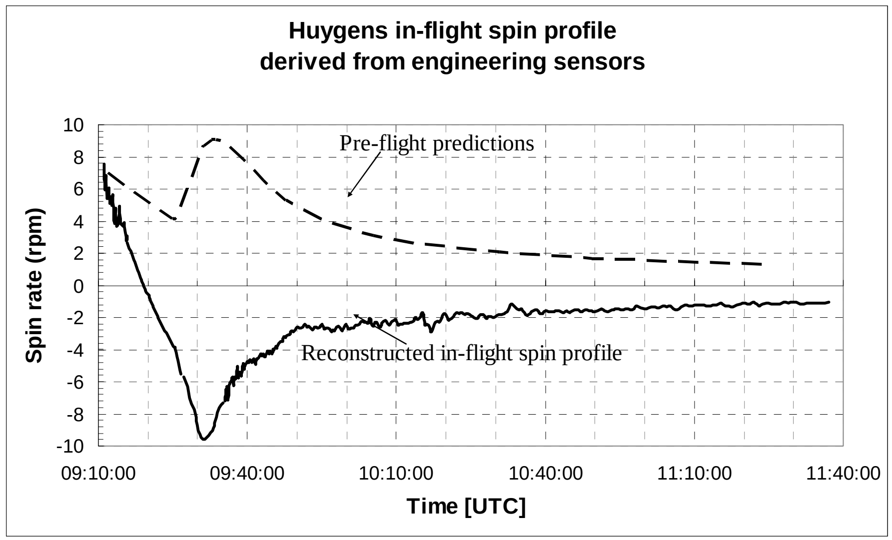
The Spin Story

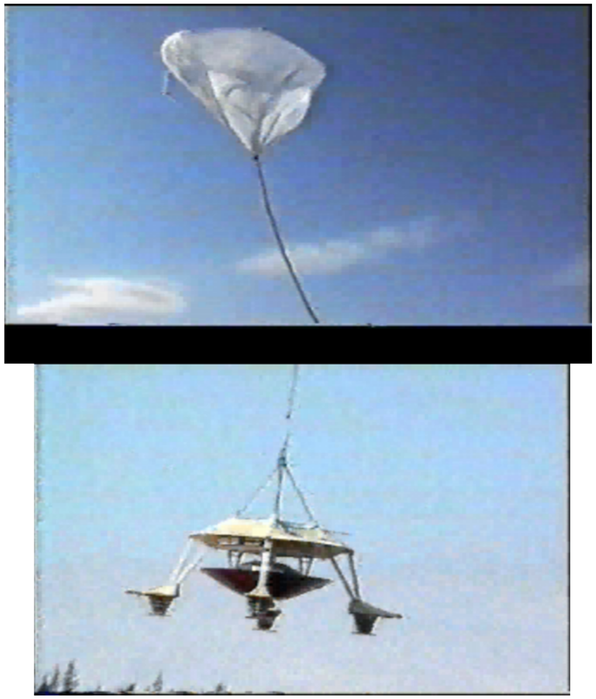
Huygens Descent and Landing.
Landing site location



Site atterrissage: 192.3º W; 10.3º S

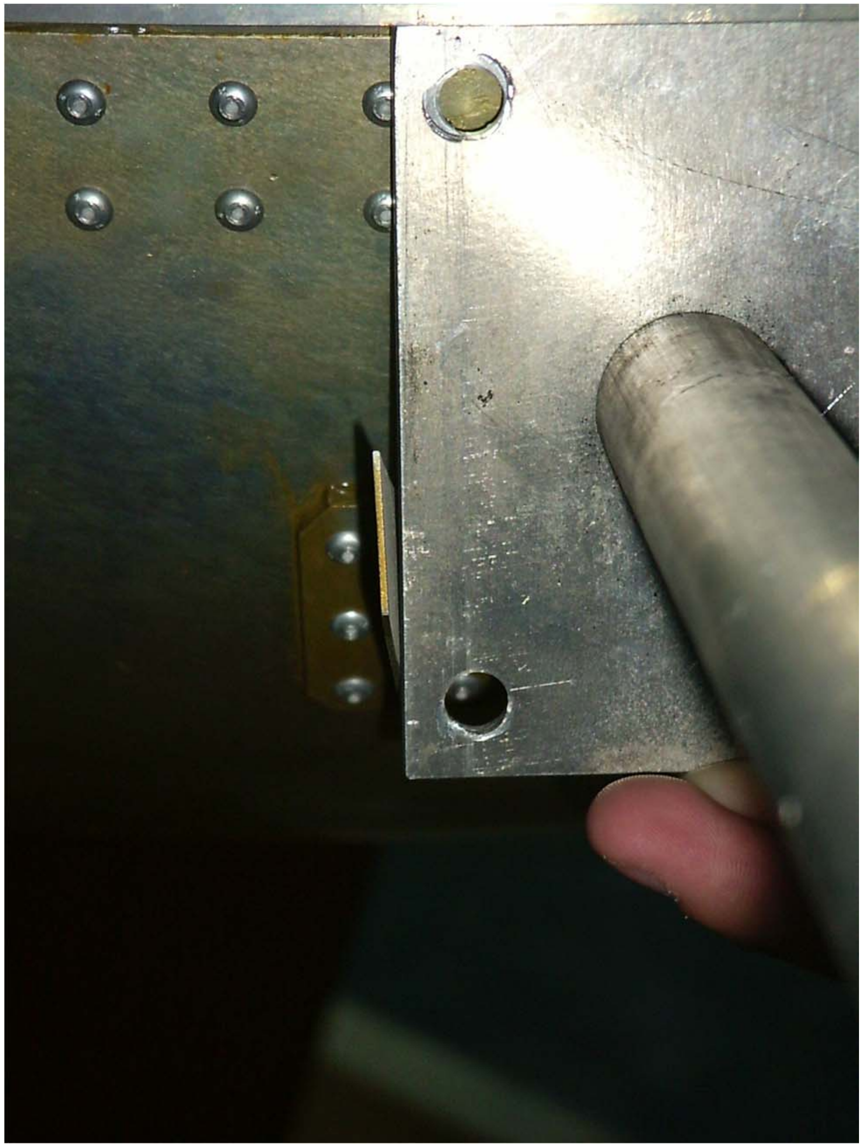


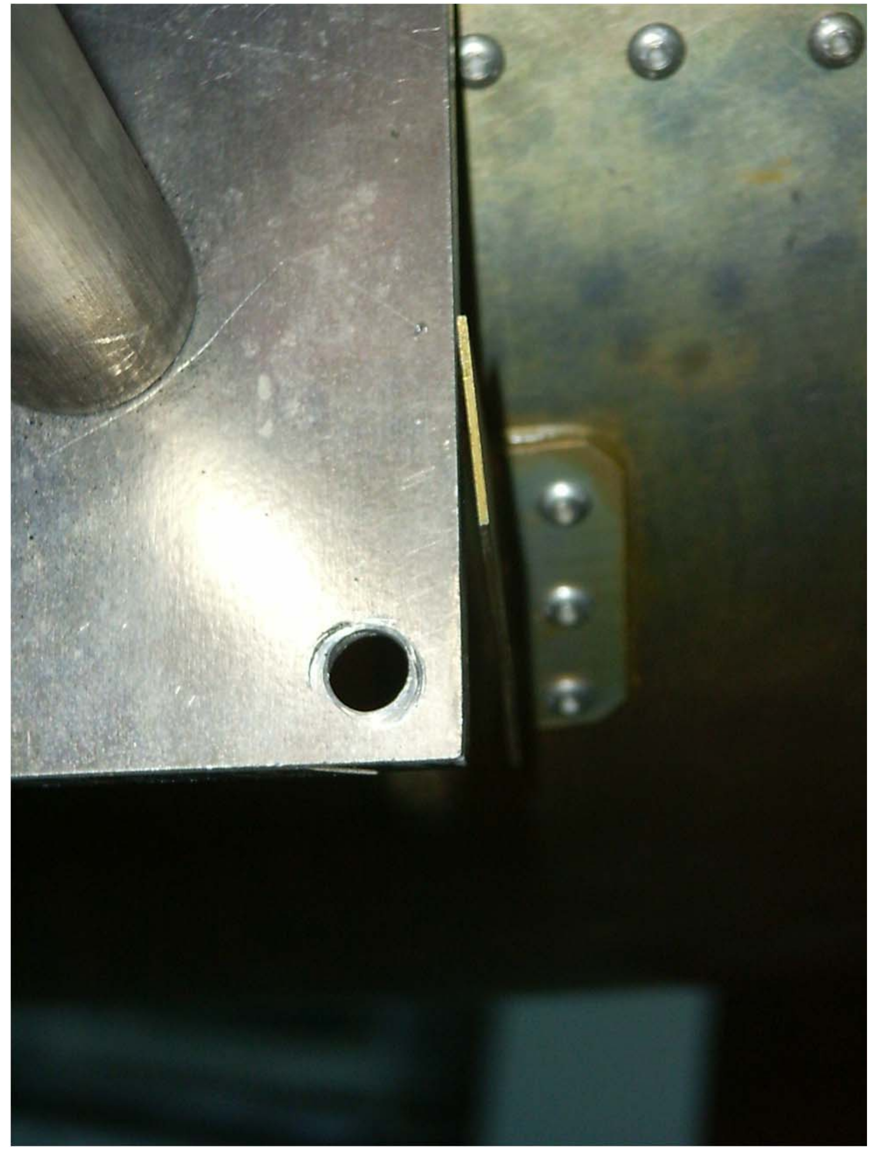




May 1995
Balloon drop test
In Kiruna

Spin Vanes: OK





Spin

Still being worked

Wind tunnel test required

Study Scientist Advice

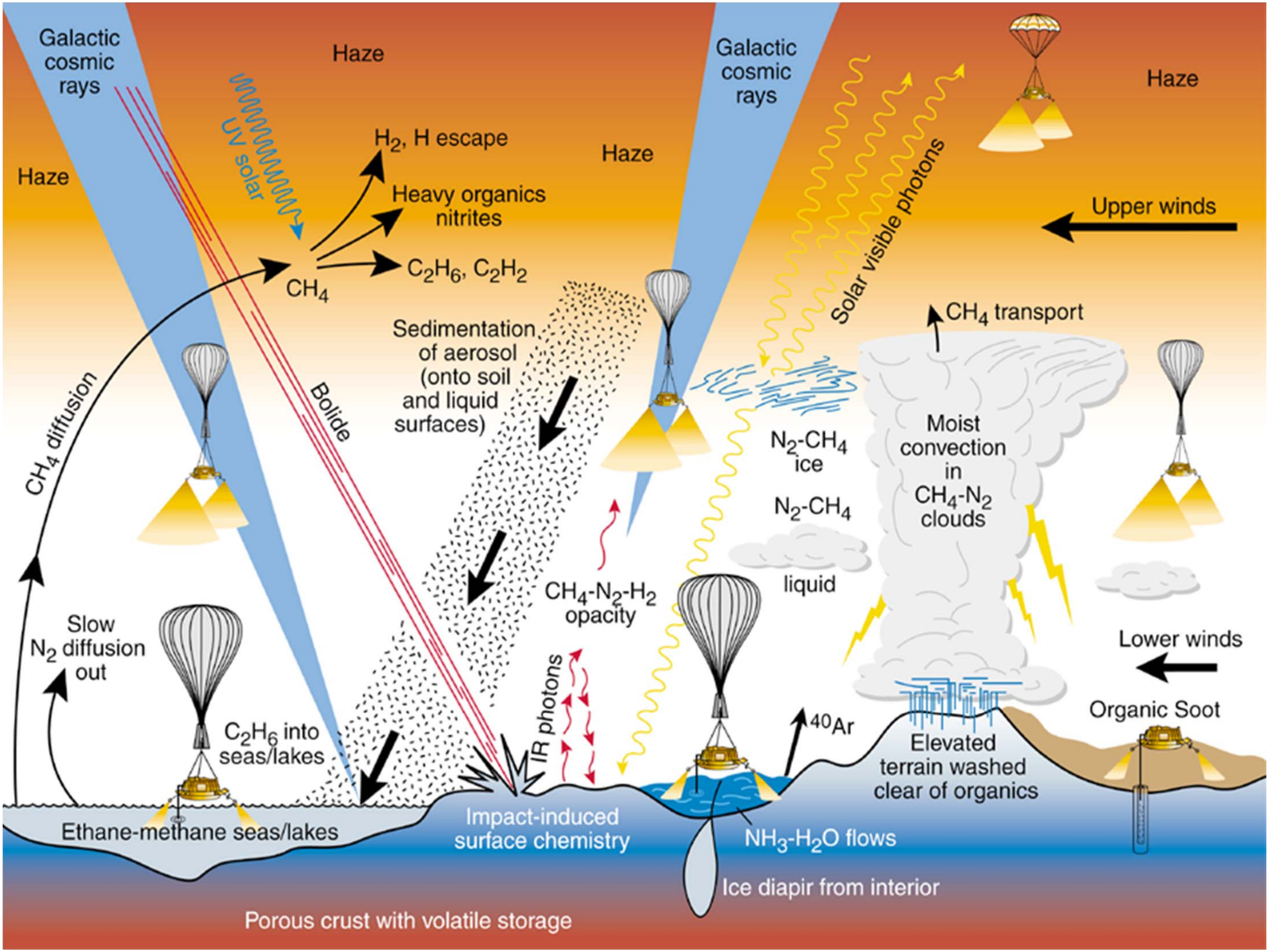
- Science Goals
- Science Objectives
- Science Investigations
- Model payload
- Establish mission/spacecraft environment from publications in the literature
- Understand environment parameters that may affect mission design (close interaction between science and engineering within your team => science engineering or engineering science ?

Characterize Ganymede as planetary object and possible habitat

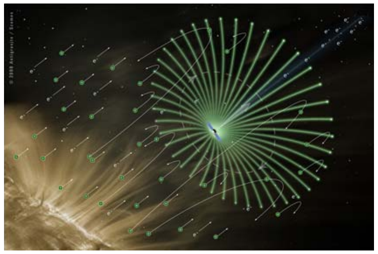
		Imaging	*Spectroscopy & spectro-imaging*			*Sounders and radio science*			*In situ fields and particles*		
Science Objectives	**Science Investigations**	**Imaging**	**UV**	**Vis & IR**	**Sub-mm**	**Laser altimetry**	**Sub-surface radar sounding**	**Radio science**	**Magnetic field**	**Radio & plasma waves**	**Neutrals & ions**
GA. Characterise the extent of the ocean and its relation to the deeper interior.	**GA.1** Determine the amplitude and phase of the gravitational tides										
	GA.2 Characterize the space plasma environment and determine magnetic induction response from the ocean										
	GA.3 Characterize surface motion over Ganymede's tidal cycle										
	GA.4 Determine satellite's dynamical rotation rate (forced libration, obliquity, nutation)										
	GA.5 Investigate the core and rocky mantle										
GB. Characterize the ice shell	**GB.1** Characterize the structure of the icy shell including its properties and distribution of any shallow subsurface water										
	GB.2 Correlate surface features and subsurface structure to investigate near surface and interior processes										

I.1. Characterise Ganymede as a planetary object and possible habitat

Science Objectives	Science Investigations		Reference Measurements
Characterise the extent of the ocean and its relation to the deeper interior.	GA.1	Determine the amplitude and phase of the gravitational tides.	GA.1a. Measure spacecraft acceleration to resolve 2^{nd} degree gravity field time dependence. Recover k_2 at the orbital frequency of Ganymede to 0.01 absolute accuracy and the phase to 10 degrees by performing range-rate measurements with an accuracy ~0.01 mm/s at 60 sec integration time to determine spacecraft orbit to better than 1-meter (rms) over several tidal cycles.
			GA.1b. Measure topographic differences from globally distributed repeat ranging measurements, to recover spacecraft altitude at crossover points to 1-meter vertical accuracy by contiguous global ranging to the surface with 10-cm accuracy.
			GA.1c. Determine the position of Ganymede's center of mass relative to Jupiter during the lifetime of the mission to better than 10 meters, by performing range measurements with an accuracy of 30 cm end-to -end and range-rate measurements with an accuracy ~0.01 mm/s at 60 sec integration time to determine spacecraft orbit to better than 1-meter (rms) throughout the lifetime of the orbiter.
	GA.2	Characterise the space plasma environment to determine the magnetic induction response from the ocean.	GA.2a. Measure three-axis magnetic field components at 8- to 32-Hz to determine the induction response at multiple frequencies to an accuracy of 0.1 nT. Measure three-axis magnetic field components at 32 Hz to 128 Hz. Measure the magnetic field at 8 vectors/s and a sensitivity of 0.1 nT .
			GA.2b. Determine three-dimensional distribution functions for electrons and ions (first order mass resolution) over 4p and an energy range of a few eV to a few hundred keV and cold plasma density and velocity to measure local plasma distribution function (ions, electrons) and its moments and to constrain contributions from currents not related to the surface and ocean. Identify open and closed field lines and magnetic field at the surface by measuring electrons over wide energy range.
			GA.2c. Determine electric field vectors (near DC to 3 MHz). Measure electron and ion density (0.001 to 10^4 /cm^3), and electron temperature (0.01 to 20 eV) for local conductivity and electrical currents determination.
	GA.3	Characterise surface motion over Ganymede's tidal cycle.	GA.3a. Measure topographic differences from globally distributed repeat measurements at varying orbital phase, with better than or equal to 1-meter vertical accuracy, to recover h_2 to 0.01 (at the orbital frequency) by contiguous global ranging to the surface with 10-cm accuracy.
			GA.3b. Measure spacecraft acceleration to resolve the position of the spacecraft to better than 1-meter (rms) by performing range-rate measurements with an accuracy ~0.01 mm/s at 60 sec integration time to determine spacecraft orbit to better than 1-meter (rms) over several tidal cycles.
	GA.4	Determine the satellite's dynamical rotation state (forced libration, obliquity and nutation).	GA.4a. Determine the mean spin pole direction (obliquity) to better than 10 meters by developing an altimetry-corrected geodetic control network (~100 points) at a resolution better than 100 meter/pixel.
			GA.4b. Determine forced nutation of the spin pole and amplitude of the forced libration at the orbital period to better than a few meters by developing an altimetry corrected geodetic control network at a resolution better than 10 meter/pixel at multiple tidal phases.
	GA.5	Investigate the core and rocky mantle.	GA.5a. Resolve the gravity field to degree and order 12 or better by performing range-rate measurements with an accuracy ~0.01 mm/s at 60 sec integration time to determine spacecraft orbit to better than 1-meter (rms).
			GA.5b. Perform topographic measurements to resolve coherence with gravity to degree and order 12 or better, with better than or equal to 1-meter vertical accuracy, by contiguous global ranging to the surface with 10-cm accuracy.
			GA.5c. Measure three-axis magnetic field components at 32 Hz to 128 Hz with a sensitivity of 0.1 nT.
			GA.5d. Perform astrometric determination of the rate of change of Ganymede's orbit by acquiring multiple images of the



Galactic cosmic rays
Haze
UV solar
H_2, H escape
Heavy organics nitrites
C_2H_6, C_2H_2
CH_4
Haze
Galactic cosmic rays
Haze
Haze
Solar visible photons
Upper winds
CH_4 transport
Sedimentation of aerosol (onto soil and liquid surfaces)
Bolide
CH_4 diffusion
N_2-CH_4 ice
N_2-CH_4
liquid
Moist convection in CH_4-N_2 clouds
CH_4-N_2-H_2 opacity
Slow N_2 diffusion out
IR photons
Lower winds
C_2H_6 into seas/lakes
^{40}Ar
Organic Soot
Elevated terrain washed clear of organics
Ethane-methane seas/lakes
Impact-induced surface chemistry
NH_3-H_2O flows
Ice diapir from interior
Porous crust with volatile storage



E-Sail: Artist's View

http://www.electric-sailing.fi