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Contents

Christiaan Huygens and his telescopes

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Louwman Collection of Historic Telescopes, Wassenaar, The Netherlands

As an amateur astronomer myself, I have personally always been very interested in the early development of the telescope in the 17th century. I regard it as a privilege to have been asked to tell you something about Christiaan Huygens and his telescopes.

To me, Christiaan Huygens is a very fascinating person. Christiaan not only designed his telescopes**,** he also built them himself and he also used them.

Christiaan's first involvement with telescopes was in the autumn of 1652, when he was 23 years of age. He started to become interested in the art of lens grinding and he decided to get more information from the well-known instrument maker, Johann Wiesel from Augsburg, southern Germany. The optical instruments Wiesel made, such as spectacles, telescopes and microscopes, were sold throughout many parts of Europe. Even in London his price lists were distributed among potential buyers.

Based on information he got from his correspondence with Wiesel, Christiaan instructed a certain 'Master Paul' in Arnhem to build a telescope for him. This seems not to have been a success, because in the next year Christiaan decided to grind lenses himself, assisted by his older brother Constantijn.

Figure 1: Johann Wiesel (Staats- und Stadts-Bibliothek, Augsburg)

At first the Huygens brothers had to rely on the experience of professional Dutch lens grinders, such as Jan van der Wyck from Delft and Caspar Calthoff from Dordrecht. Especially Calthoff had a fine reputation, but unfortunately for the Huygens brothers, he soon moved to England.

Lens grinding and polishing is very delicate and precise work. It is also very heavy manual work and very time-consuming. To lighten this hard labour for himself, Christiaan designed and built his own lens-grinding and -polishing machines (Figure 2).

One of the greatest problems with lens grinding is to make a suitable lap by utilising metal moulds with a perfect spherical shape. Another problem for the Huygens brothers was to find glass of high quality and homogeneous in structure. However, not only the quality was important: they also needed to acquire glass of suitable dimensions to be able to make a large objective lens for their telescopes.

According to research by Rob van Gent and Anne van Helden[2], the Huygens' brothers bought their glass from various sources, among others in Amsterdam and in London, but later also from the important glass works in the city of 's Hertogenbosch (Bois-le-Duc) in the centre of the Netherlands.

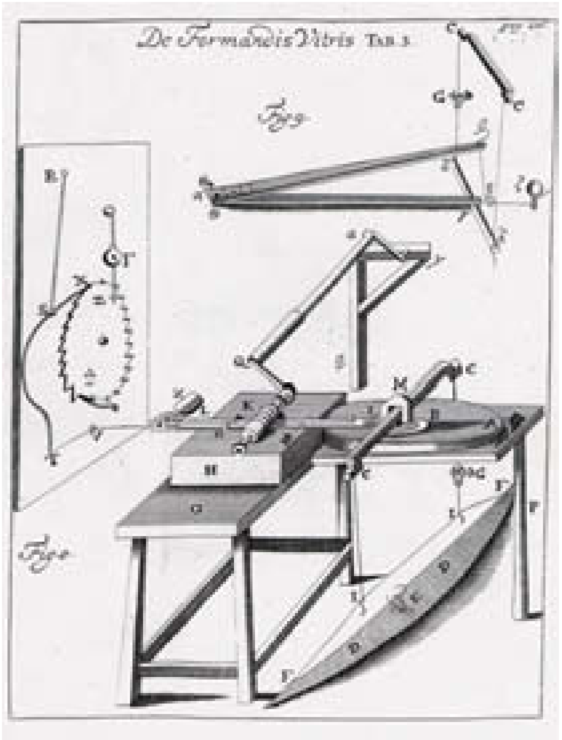

Figure 2: Lens-grinding machine of Christiaan Huygens (From his ‘Opuscula Posthuma’*, published posthumously by Janssonio Waesbergios, Amsterdam, 1728)*

What made it very difficult to produce usable lenses, as the Huygens brothers soon found, was that the whole art of lens grinding was surrounded by secrecy. They couldn’t benefit much from the experience of professional lens makers, because these lens makers weren’t very communicative and they vigorously protected their trade secrets from the competition.

One of the most surprising astronomical discoveries Christiaan Huygens made with one of his first self-made telescopes dates from March 25th, 1655, when he discovered that Saturn has a moon, revolving around the planet in about 16 days. The moon was later named ‘Titan’.

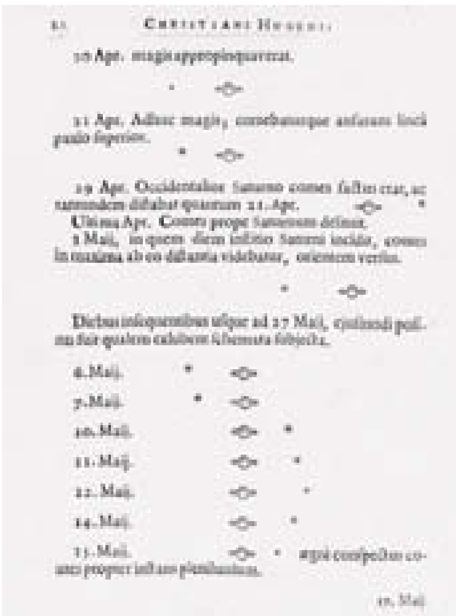

Figure 3: Sketches of the position of the newly-discovered moon relative to Saturn, in Christiaan’s book Systema Saturnium, *1659 (O.C. Vol 15)*

The telescope he used for his discovery was equipped with an objective lens (also known as an 'object glass') with a focal length of 10 Rhineland feet (about 337 cm). The eyepiece he used was a single-lens of 3 Rhineland inches (79 mm) focal length, resulting in a magnification of about 43x. Christiaan himself writes that he used a telescope of 12 Rhineland feet, but at that time this meant the total length of the telescope tube including the eyepiece, not the focal length of the objective lens.

The telescope itself doesn't exist anymore, but its objective lens, which is by far the most important part of a telescope, has been preserved. Researchers are fully convinced that Christiaan used this lens for discovering Titan, because he scratched with a diamond, in his own handwriting, not only his name and the date of manufacture of the lens (February 3, 1655) along the rim of the lens, but he also scratched on it in Latin "*Admovere oculis distantia sidera nostris*" ("they brought the distant stars closer to our eyes").

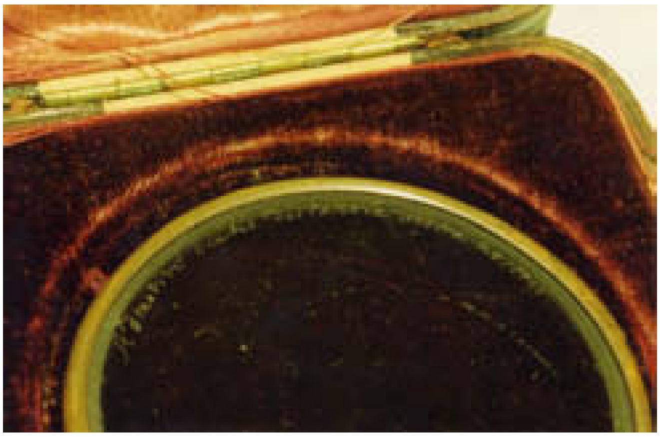

*Figure 4: The '*Admovere*' lens in a protective casing. Along the rim is visible "*Admovere oculis distantia sidera nostris*" that has been scratched on the glass with a diamond by Christiaan Huygens (Universiteits Museum Utrecht, photo by author)*

On June 13th 1655 Christiaan wrote a letter to Prof. J. Wallis in Oxford telling him that he had made 'a discovery' with his new 12-foot telescope. However, he didn't tell him exactly what his discovery was, but, as was the custom in those years, he re-wrote the sentence explaining his discovery into the following anagram:

> *Admovere oculis distantia sidera nostris*, v, v, v, v, v, v, v, c, c, c, r, r, h, n, b, q, x

On March 15, 1656 Christiaan disclosed the solution to the anagram by writing to Prof. J. Wallis that the letters of his anagram should be rearranged into the following sequence:

> *Saturno luna sua circunducitur diebus sexdecim horis quatuor*

It is therefore convincing that this lens (in literature it is often nicknamed the '*Admovere*') was used in Christiaan's 12-foot telescope when he discovered Titan. Normally the '*Admovere*' is safely kept in a well-protected vault at the University Museum of Utrecht, but for the occasion of the commemoration of Huygens' 375th birthday, it is now temporarily on display for the public in a showcase at Museum Boerhaave in Leiden.

It is very lucky that we can nowadays see and admire the '*Admovere*' lens, because it once was nearly lost! The lens is referred to in an auction catalogue dated 1722, and two years later it was mentioned by the Dutch physicist 's Gravenzande in his foreword to his publication about Christiaan Huygens' life and works '*Opera Varia*'. But after that, the lens was never again mentioned, nor seen. It seemed that nobody was really concerned. Then, in 1867 it was fortunately discovered by Professor Harting in a little old box, containing some old lenses, in the Physical Laboratory of Utrecht.

Figure 5: Here we see an objective lens made by Christiaan, similar to the one he used to discover Saturn's moon 'Titan'. Along the rim Christiaan signed: "Chr. Hugenius A° 1656". On the opposite side of the lens "PED II" tells us the focal length is 11 feet. (Lens from the Louwman Collection of Historic Telescopes; photo by author; also Figure 6)

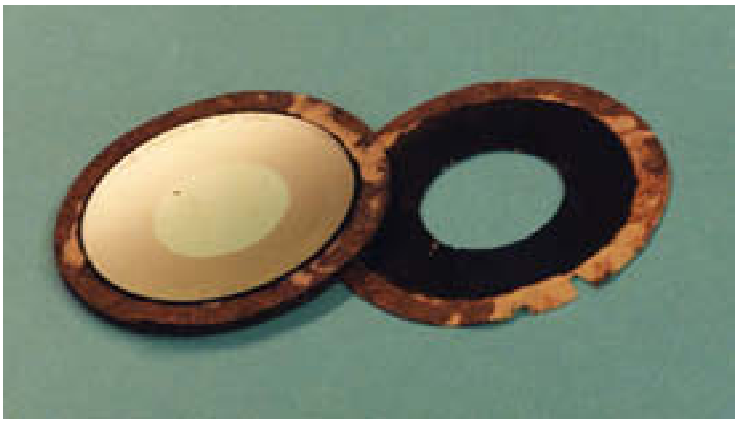

Figure 6: The same lens as left in its original protection fittings made of cardboard. The total diameter of this objective lens is 63 mm, but Christiaan stopped down the open aperture to 35 mm. He did this by covering the outer parts of the lens with a diaphragm (the black ring with the hole in the middle). As with most 17th century lenses, only the middle part of the lens has an optically perfect form. By installing the diaphragm only light rays passing through the middle of the lens are used to create an image. Light rays that would have passed through the outer parts of the lens are blocked by the diaphragm

Figure 7: Christiaan announced his discovery of the rings of Saturn in System Saturnium *in 1659*

At about the same time Christiaan made with this same telescope (though he may also have used his new 23-foot telescope) another most impressive discovery: he discovered the true nature of the puzzling appearance of the mysterious two 'attachments' (ears) of the planet Saturn. Actually, he didn't owe this discovery to his visual observations only: it was also the result of his deductive reasoning. Christiaan came to the right solution of the puzzle by examining old telescopic observations made by other astronomers during the first half of the 17th century. These astronomers didn't yet have telescopes with sufficient resolving power, as Christiaan had. They therefore never exactly understood what they were seeing through their telescopes. To make the mystery even more complex for these astronomers, the attachments (or 'appendages') regularly disappeared for a short time, then reappeared for several years.

Christiaan, with his genius and his remarkable sense of intuition, immediately grasped what he was seeing through his telescope. It was a three-dimensional view of a flat ring, floating in space around the planet.

With his discovery he was at the same time able to explain why the appendages regularly disappeared and reappeared. Really a marvellous, great discovery, which brought him much fame.

Another important astronomical discovery Christiaan Huygens made with his telescopes was determining the rotation period of the planet Mars. By observing spots on its surface for many weeks, Christiaan came to the correct conclusion that Mars rotates. He found that it takes Mars about 24½ hours to complete one rotation, so a little longer than the Earth.

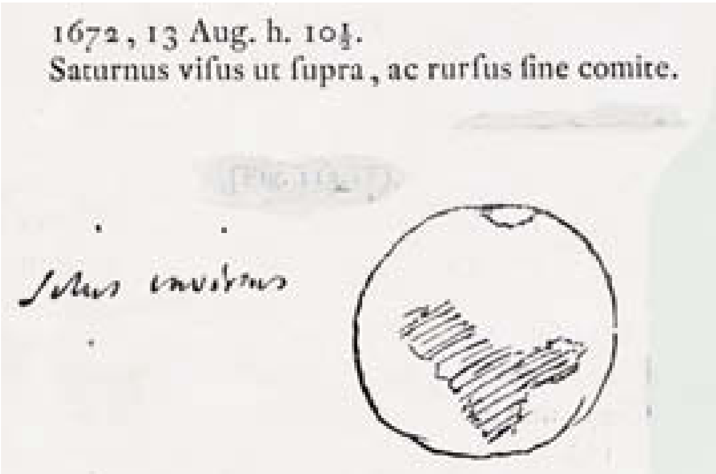

Figure 8: Sketch of Mars drawn by Christiaan on August 13th, 1672 (O.C. Vol 15 p113)

Figure 9: Modern photograph of the same part of Mars by the Dutch amateur astronomer John Sussenbach. Compare the white polar cap and the triangular shaped region called 'Syrtis Major' with those in Christiaan's drawing

At this time, in about 1659, both Christiaan and Constantijn Huygens temporarily stopped making lenses and telescopes, although they didn't lose their interest in them. Only after 1681, so more than 20 years later, did they resume making lenses and telescopes.

In 1666 Christiaan was invited by the wealthy and influential King Louis 14th to come to Paris and to become a prominent member of the French *Académie des Sciences*. He stayed here 15 years (1666 to 1681) and worked together with famous astronomers, such as Cassini (from Italy) and Römer (from Denmark).

During his stay in Paris, he several times visited the important telescope maker Philippe-Claude Lebas. Lebas seemed to have found a superior method of polishing. But despite all Christiaan's efforts, he was never able to discover exactly how this new method worked. When Lebas died, Christiaan tried to persuade Lebas' widow to kindly disclose the method, but in vain, because she, too, protected her husband's secret.

We now know that the Huygens brothers used paper as one of the main elements for polishing their lenses on a lap.

Also in Paris, in 1662 Christiaan Huygens greatly improved a special eyepiece for telescopes, which is now commonly known as the '*Huygens eyepiece*'. This eyepiece consists of two positive lenses with different focal lengths, separated from each other by a certain distance. It gives an improved and wider field of view and it fully removes lateral colour aberration.

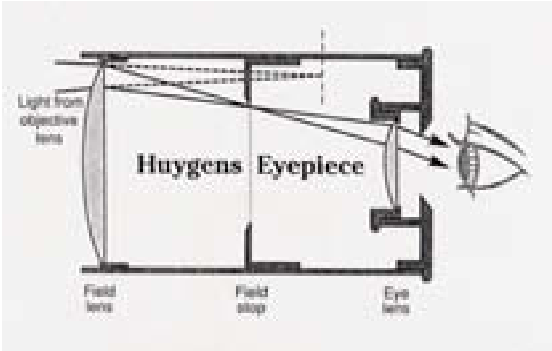

Figure 10: The Huygens eyepiece

Christian Huygens kept his fascination for telescopes all his life. This can be illustrated by a remarkable incident, when during one of his trips to England in 1661 he visited the shop of the telescope maker Richard Reeves at Longacre in London. On the day of his visit the coronation of King Charles II was taking place in London, but Christiaan preferred not to go and view all the festivities. No, he took his chance to observe with Reeves' telescopes the very rare 'transit of Mercury', which was on the very same day. Together with the astronomer Thomas Streete and Richard Reeves he observed to his delight the passage of the planet Mercury across the sun's disc[i].

When Christiaan returned home from Paris in 1681, he found that during his absence from Holland several lens makers had greatly improved the art of lens grinding, also in his hometown of The Hague. Telescopes and microscopes were in high demand by wealthy customers, who bought them to, more-or-less, play with them. However, despite the increased interest from the public, the Huygens brothers couldn't find lens makers who were able to deliver them lenses as good as they could make them themselves.

So, the Huygens brothers decided to continue making both their objective lenses and their eyepiece lenses themselves. As we know from correspondence, both brothers seemed to enjoy doing this highly specialised work together. To ease their share of the work, Christiaan and Constantijn limited themselves to polishing lenses. They were convinced nobody could

[i] Mercury revolves around the Sun in an orbit between the Earth's orbit and the Sun. When the Sun, Mercury and the Earth are exactly aligned in a straight line, a 'transit of Mercury' takes place. With a telescope we can then see Mercury as a tiny little black disc slowly crossing the solar disc. This, however, doesn't happen every time Mercury moves between the Sun and the Earth: because Mercury's orbit around the Sun is slightly inclined to the Earth's orbit, Mercury mostly 'misses' the disc of the Sun, as viewed from the Earth. A transit of Mercury occurs very rarely; only 9 were visible from the Netherlands in the last 100 years, and of these only 5 were visible from the beginning of the passage of Mercury across the solar disc till the end.

do this delicate work of polishing as well as they could. So, the Huygens brothers reserved for themselves the immensely important ‘finishing touch’.

However, the grinding of lenses they farmed out to craftsmen, who were better capable of doing this heavy and time-consuming task. It is interesting in this respect to note that the Huygens brothers often enlisted Master Dirck, nicknamed by them ‘the chimney sweep’. Dirck lived in ‘*het Achterom*’, just around the corner from their home (in Het Plein) in the centre of The Hague. Of course, it was the Huygens brothers who selected and supplied the necessary glass to Master Dirck.

With their renewed enthusiasm for telescope making, the Huygens brothers started, from 1681 onwards, making more powerful telescopes and especially much longer ones.

During his Paris period, Christiaan had seen and used the telescopes that the astronomer Cassini used at the Paris Royal Observatory. These had objective lenses with very long focal lengths, from 17 feet up to 100 and even 140 feet. They were made by the famous Italian lens maker Giuseppe Campani. The longest of the Cassini telescopes were tubeless and consisted only of two components: an objective lens fixed on top of the wooden Marly Tower and an eyepiece, which had to be held in the hand. The Marly Tower was originally built to lift water for the Versailles reservoirs and fountains.

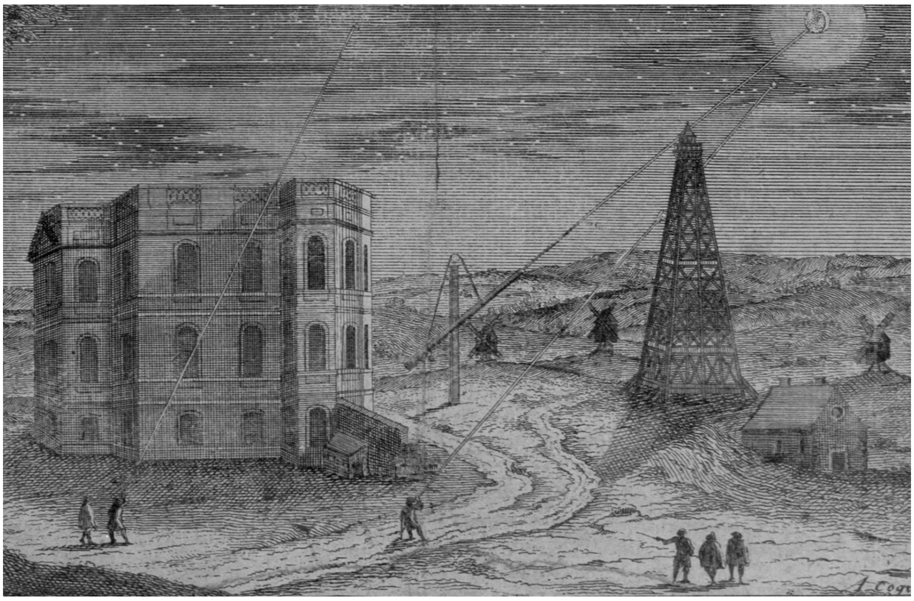

Figure 11: Ultra-long focus tubeless telescope used by Cassini at the Royal Observatory in Paris (©Bibliothèque Observatoire de Paris)

In The Hague, the Huygens brothers constructed similar long tubeless telescopes of which Christiaan made a technical drawing and published it in his booklet *Astroscopia Compendiaria* in 1684 (Figure 12).

At the top of the pole the objective lens is attached to a ball and socket mechanism and kept upright by a counterweight. The ball and socket is fixed to a platform, which is adjustable in height by a cable and which is also balanced by the counterweight hanging next to the pole. Christiaan used the lantern on the ground during his observations to locate the exact position of the objective lens (not so easy in the dark!). By picking up the lantern and holding it next to his ear and directing the light rays in the direction of the objective lens, Christiaan could see a reflection in the lens, and by doing so was able to do two things: he could find the objective lens through which he wanted to observe, *and* he could direct his telescope in the direction of the object in the sky to be observed.

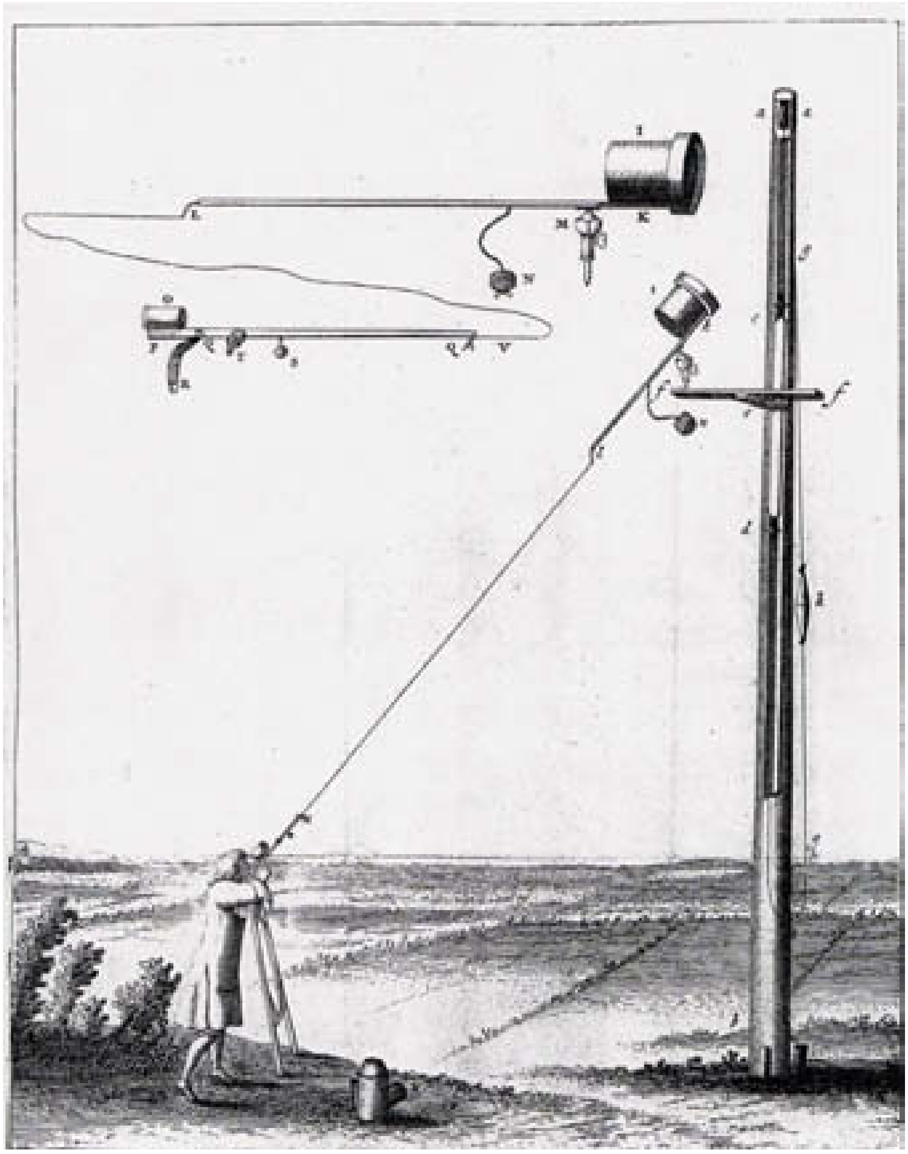

Figure 12: The tubeless telescope used by Christiaan in The Hague. From Astroscopia Compendiaria, *1684*

This very same illustration of Huygens' 'tubeless telescope' has become very well known and can be found reproduced in many popular astronomical books and magazines. It has even been used as a logo on the front cover of the "*Journal for the History of Astronomy*" ever since its first issues appeared in 1972.

Huygens' tubeless telescopes had some clever technical improvements compared with the telescopes used at the Royal Observatory in Paris. Christiaan erected his tubeless telescopes next to his home in the centre of The Hague, and possibly also one at his summer residence 'Hofwyck' in nearby Voorburg. In The Hague he had the problem that his tubeless telescope was so long that its upright supporting pole had to be placed in the garden of his neighbour. A notarial act has been found that tells us that Christiaan had negotiated with his neighbour for permission to set up the telescope-pole in his neighbour's garden. The act claims that Christiaan was legally permitted, when necessary, to enter his neighbour's garden through a specially-made gate in the stone wall separating the two gardens.

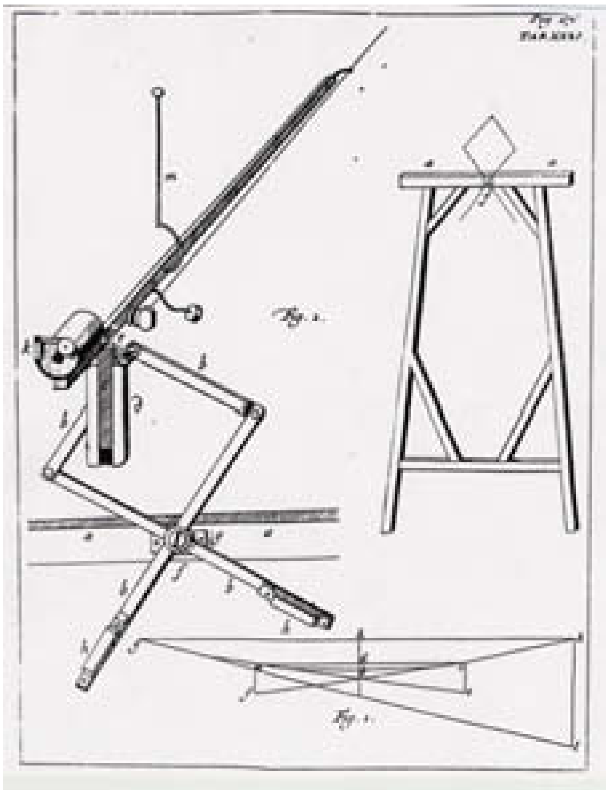

Figure 13: A close-up of the stand that Christiaan leaned against when using the eyepiece to observe through his tubeless telescope. The tube (k) at the left contains the eyepiece consisting of two lenses. Christiaan had to constantly keep the silk line, attached between the eyepiece and the ball and socket mechanism (on which the objective lens was mounted), straight and taut to ensure that the eyepiece remained perfectly aligned with the objective lens, AND to keep their mutual distance constant. Both conditions were necessary to obtain worthwhile and satisfactory images for his observations.
(From 'A Compleat System of Opticks', by Robert Smith, 1738)

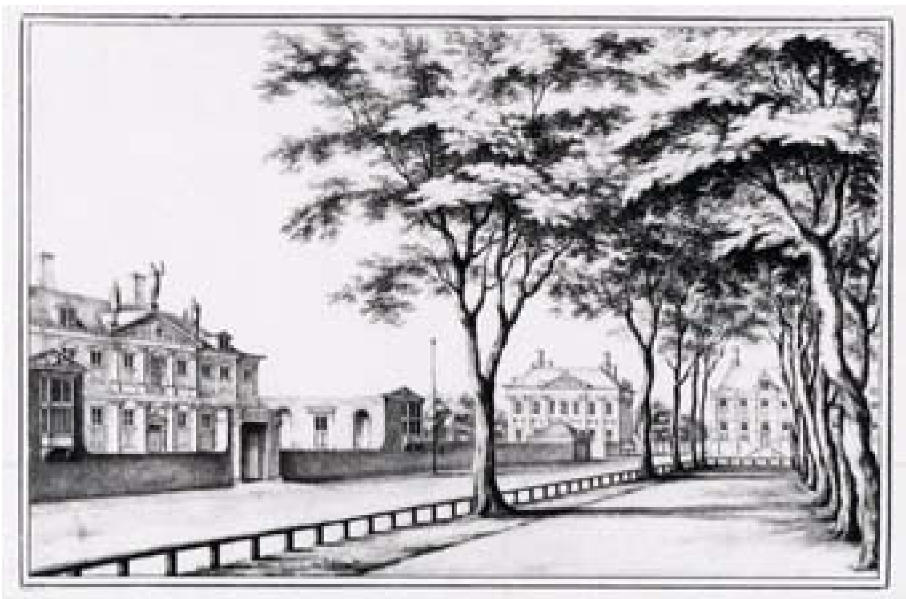

Figure 14: On the left the Huygens' home in the centre of The Hague, which was very unfortunately replaced by a modern building in 1876. In the distance, to the right of the tree in the middle, is 'Het Mauritshuis', now a museum. Christiaan's tubeless telescope was erected somewhere between these two buildings and behind the garden wall.
(Jan van Call, Collectie Haags Gemeentearchief)

Wielding his extremely long tubeless telescopes must have been very difficult. Of course, Christiaan had acquired much experience in the skill of doing this, but trying to share his astronomical observations with other people must have been nearly impossible. Using the tubeless telescope required a lot of patience too.

In a letter dated 1 September 1693, Christiaan proudly wrote to his brother Constantijn, who was on a military campaign in the south of the Netherlands, that a few days ago he had finished making a beautiful telescope with a square wooden tube for his 45-foot objective lens. He added that he had made it "especially for pleasing gentlemen of higher standing who ask me to show them the Moon and planets and who have too much trouble with the tubeless telescope, which I prefer". This last claim, that Christiaan preferred his tubeless telescope, is interesting. Because the Huygens brothers had a very close relationship, Christiaan's claim that he preferred using the tubeless telescope to a smaller, handier one, must be taken seriously.

Have any of Christiaan's telescopes survived?

Yes, but only one, as far as we know. It is on display at Museum Boerhaave (Figure 16) and it dates from 1683. This telescope was called by Christiaan Huygens the 'Campanine', because of the optical design of its eyepiece (Figure 15), which he had learned from Giuseppe Campani in Italy and whom I already mentioned before. This telescope has 5 metal drawtubes. Its total length, when focused, is about 5 metres and its magnification is 49x. It gives an upright image, so it was designed for terrestrial observations, not astronomical.

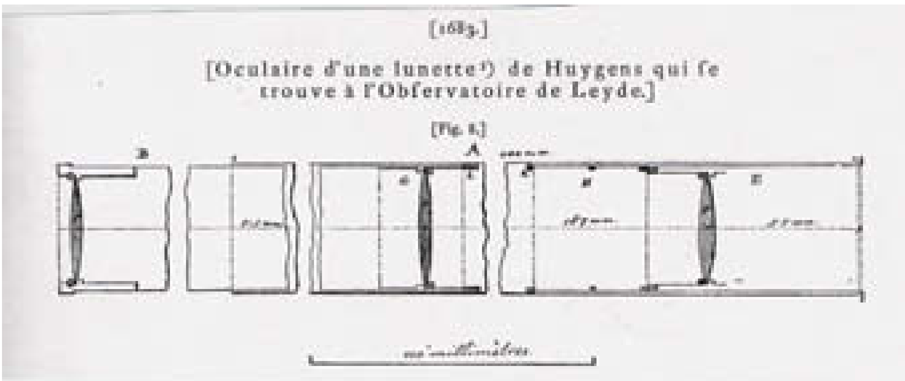

Figure 15: Here Christiaan sketched the eyepiece he constructed for his 'Campanine' telescope. It consists of three lenses. (O.C. Vol 13, p607)

Museum Boerhaave has in total 19 objective lenses made by the Huygens brothers, including the one mounted inside the Campanine telescope. In another showcase, Boerhaave exhibits five objective lenses all made by Constantijn.

Figure 16: The 'Campanine' telescope displayed standing vertically. The 5 metal drawtubes of the telescope are pushed in.

At the left we see six large objective lenses mounted vertically in the showcase. Three of the lenses are signed by Christiaan, and have focal lengths from 10 to 34 feet. The largest has a diameter of 13 cm. Two other lenses were made by Constantijn. One of them has a focal length of no less than 122 feet! The sixth lens is not a Huygens lens, but made by Nicolaas Hartsoeker. Finally, we also see, partly hidden behind the 'Campanine' telescope, two tubular metal housings. One contains an eyepiece, the other an objective lens. It is very plausible that they have always belonged together and that they were once part of a complete telescope.

(Museum Boerhaave, Leiden, photo by author)

In total, there are another nine lenses signed by the Huygens brothers preserved in other collections:

- Two at the University of Utrecht, of which one (the '*Admovere*') is now temporarily in Museum Boerhaave, Leiden
- Three at the Royal Observatory at Brussels (Figure 17)
- Three at the Royal Society in London
- One in a private Dutch collection

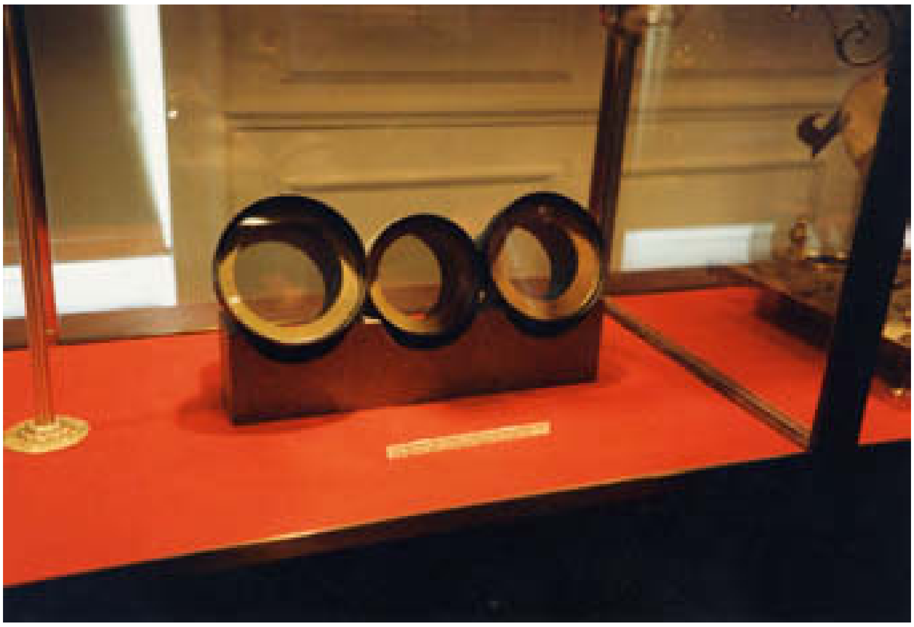

Figure 17: The three objective lenses in their original metal lens mounts at the Royal Observatory in Brussels, Belgium. One of them is made by Christiaan, the other two by Constantijn (photo by author)

More information about the objective lenses and eyepieces that Christiaan Huygens used for his telescopes can be found in “The Huygens Collection” by van Helden and van Gent[1].

References

[1] “The Huygens Collection”, by Anne C. van Helden and Rob H. van Gent, a Museum Boerhaave publication, 1995. ISBN 90-6292-107-8

[2] “The Lens Production by Christiaan and Constantijn Huygens”, Annals of Science, 56 (1999), pages 69-79.

The Huygens mission to Titan: an overview

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Abstract

The Huygens Probe is part of the NASA/ESA/ASI Cassini-Huygens mission to Saturn and Titan. Cassini-Huygens was launched on 15 October 1997 from Cape Canaveral Air Force Station, Florida, USA. It reached its target, Saturn, and went into orbit around it on 1 July 2004. Huygens will be released from the Saturn Orbiter on 25 December 2004 and will plunge into Titan's atmosphere 3 weeks later, on 14 January 2005. It will descend by parachute to the surface in about 2 to 2½ hours. During the whole descent, it will transmit data to the over-flying Orbiter. If it survives the landing, it will continue transmitting until it freezes. The orbiter will fly over the Probe's horizon 4½ hours after the start of the descent. In this paper we give a brief overview of the probe's mission.

1 Cassini-Huygens mission overview

The Cassini-Huygens mission[1] is designed to explore the Saturnian system and all its elements: the planet and its atmosphere, its rings, its magnetosphere and a large number of its moons, including Titan and the larger icy satellites. The mission will emphasise the exploration of Titan, Saturn's largest moon and the Solar System's second largest (after Jupiter's Ganymede), and the only satellite with a thick atmosphere.

The Cassini-Huygens spacecraft (Figure 1) was launched on 15 October 1997 by a Titan 4B/Centaur rocket from Cape Canaveral Air Station in Florida. With a launch mass of 5650 kg, it was too massive for a direct injection towards Saturn. Cassini-Huygens used a Venus-Venus-Earth-Jupiter gravity assist interplanetary trajectory, for a fixed arrival date at Saturn of 1 July 2004 (Figure 2).

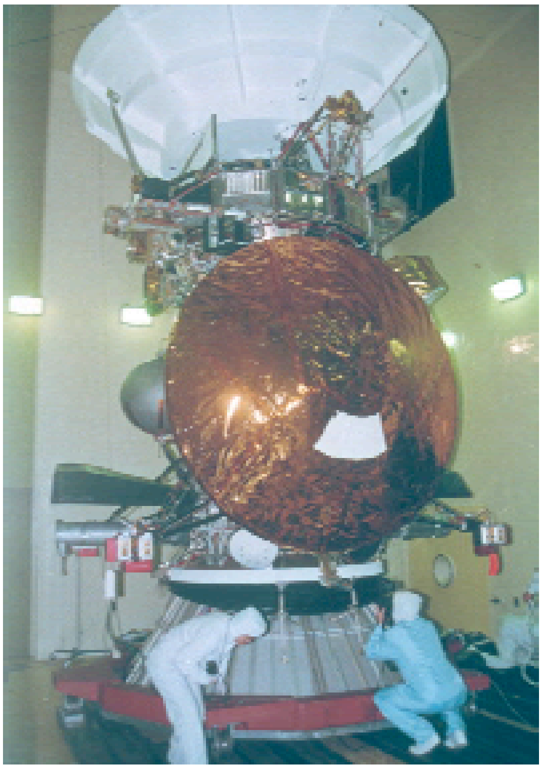

Figure 1: The Cassini-Huygens spacecraft during assembly. Huygens is attached on the side of the propulsion module.

Upon arrival at Saturn, the spacecraft will make a close swing-by of the planet at 1.3 Rs (Saturn radii) and execute the Saturn Orbit Insertion (SOI) propulsive manoeuvre. This puts Cassini-Huygens into a highly elliptical, 116-day orbit around the planet. Two days after SOI, on 2 July 2004, observations of Titan are planned during the distant flyby called T0, (339,000 km at closest approach). This first orbit sets the geometry for the first targeted encounter with Titan (Ta), on 26 October 2004, the second encounter with Titan (Tb) on 13 December 2004, and the third encounter (Tc) on 14 January 2005.

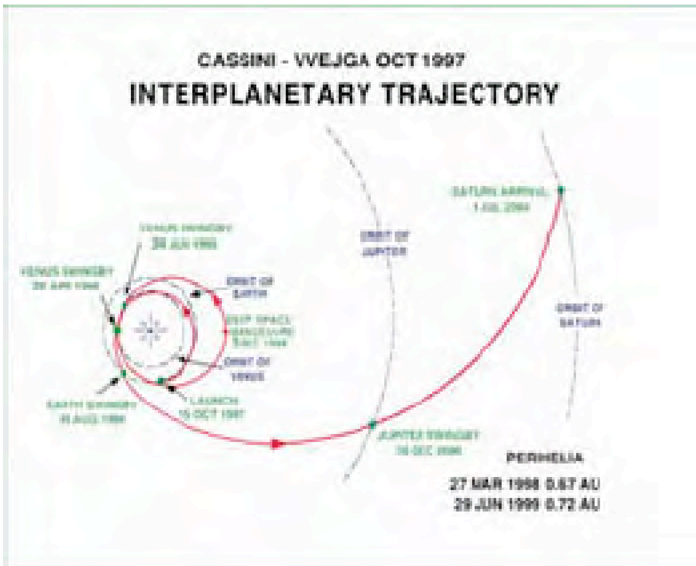

Figure 2: Cassini-Huygens interplanetary trajectory

The Tc encounter is for executing the Probe mission; it also sets up the subsequent satellite encounters during the four-year orbital tour. Figure 3 shows the spacecraft flight path for the approach to Saturn, the SOI manoeuvre, and the initial 3 orbits around Saturn. During the nominal four-year mission, the spacecraft will make 77 orbits around Saturn. 45 of the orbits include targeted flybys of Titan at altitudes as low as 950 km above the surface.

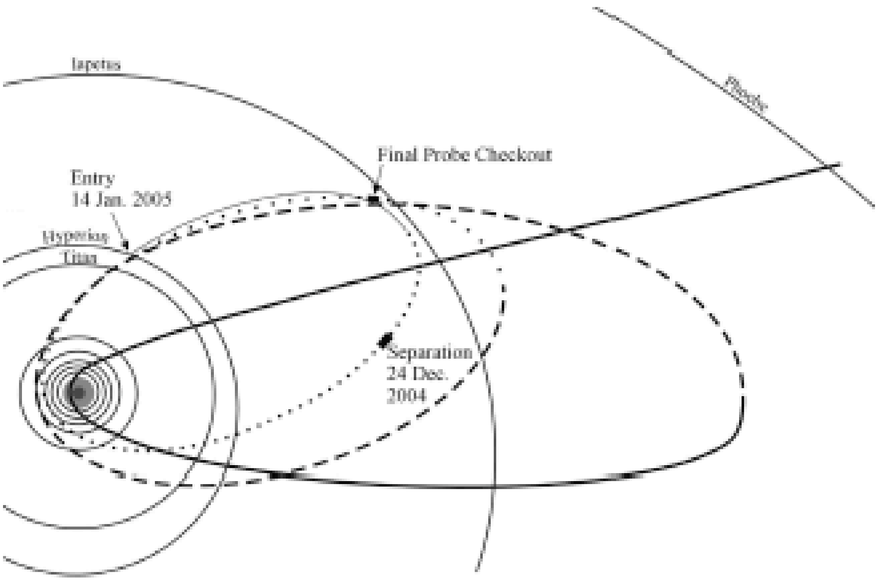

Figure 3: Cassini-Huygens flight path showing the Saturn approach trajectory and the first three orbits around Saturn

The Huygens Probe is carried to Titan attached to the Saturn Orbiter through its spin-and-eject mechanism. The probe will be released from the orbiter approximately 21 days before the third Titan flyby, Tc. Three days after probe release, the Orbiter will perform a deflection manoeuvre to place itself on the proper trajectory that will over-fly the probe landing site. When the Probe approaches Titan, the Orbiter points its High Gain Antenna (HGA) at the predicted Probe landing point on the surface to receive telemetry from the Probe during the whole descent and while it is on the surface, until the Orbiter goes below the Probe's horizon.

2 Huygens mission overview

2.1 Huygens Scientific Objectives

The scientific objectives of the Huygens mission[1][2] to Titan are to:

- Determine abundance of atmospheric constituents (including noble gases); establish isotope ratios for abundant elements; constrain scenarios of formation and evolution of Titan and its atmosphere;
- Observe vertical and horizontal distributions of trace gases; search for more complex organic molecules; investigate energy sources for atmospheric chemistry; model the photo-chemistry of the stratosphere; study formation and composition of aerosols;

- Measure winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere; search for lightning discharges;
- Determine the physical state, topography and the composition of the surface; infer the internal structure of the satellite;
- Investigate the upper atmosphere, its ionisation, and its role as a source of neutral and ionised material for the magnetosphere of Saturn.

Huygens will carry out a detailed study of Titan's atmosphere and characterise the surface of the satellite along the descent ground track and in the vicinity of the landing site. The objectives are to perform detailed *in-situ* measurements of atmospheric structure, composition and dynamics. Images and other remote sensing measurements of the surface will also be made during the descent through the atmosphere. A descent time of between 2 and 2½ hours is planned.

The Probe is expected to impact the surface at 5-6 m/s. Since Huygens may survive touchdown, the payload also includes an instrument for characterising the surface. The entry and descent scenario is illustrated in Figure 4.

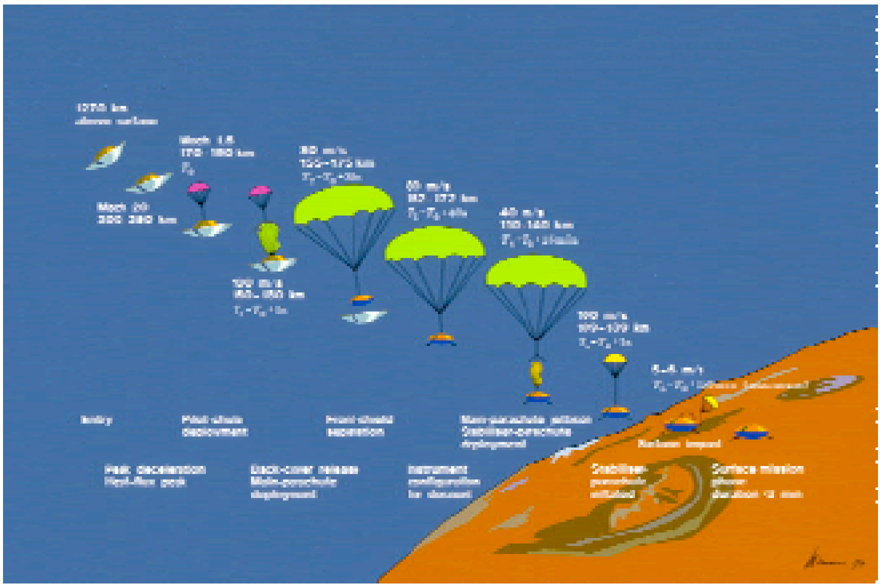

Figure 4: Huygens entry and descent scenario

The Probe will start transmitting data to the Orbiter after the main parachute deployment. The geometry of the Probe-Orbiter radio link is shown in Figure 5. The data link between the Probe and the Orbiter can last 4½ hours. It is terminated as the Orbiter flies over the horizon.

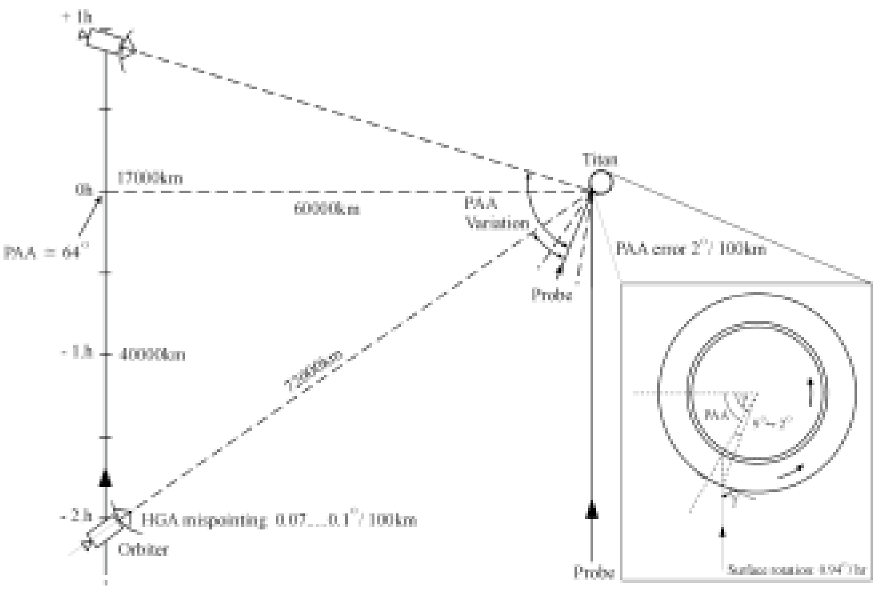

Figure 5: Orbiter Trajectory during the Probe mission

If everything proceeds nominally, the Probe batteries may function for half an hour, or possibly more. This would be a bonus for the mission. The current mission scenario allows for more than two hours of communication with the Probe on the surface. A surface lifetime of only a few minutes would permit a rapid characterisation of the state and composition of the landing site. A longer time would allow a detailed analysis of the physical and chemical composition of surface material.

2.2 Titan characteristics

Titan is the second largest moon of the solar system and it is the only one with a thick atmosphere. The main atmospheric constituent is N_2. The surface pressure is about 1.5 bar (i.e. 1.5 times the Earth's). The equatorial surface temperature is about 94K and the temperature of the tropopause, at an altitude around 45 km, is about 70K. Other major constituents are CH_4 (a few percent) and H_2 (0.2%). It is speculated that argon could also be present in quantities up to 6%. The physical properties of Titan are listed in Table 1.

Surface radius	2575 ± 0.5 km
Mass	1.346×10^{23} kg (2.2% of M_{earth})
GM	8978.1 km^3/s^2
Surface gravity	1.345 m/s^2
Mean density	1.881 g/cm^3
Distance from Saturn	1.226×10^6 km (20.3 Rs)
Orbital period	15.945 d
Rotation period	15.945 d
Surface temperature	~94 K (equator)
Surface pressure	1500 mbar

Table 1: Physical properties of Titan

2.3 Titan engineering models

The design of the Huygens Probe mission required the establishment of several 'engineering models' for Titan that provided a sound basis for various trade-offs and performance calculations during the Probe's development. These models were created thanks to the close working relationship between the Huygens scientists who provided the knowledge (and the speculations) and the Huygens engineers who provided the engineering wisdom and the necessary engineering conservatism that led to a robust Probe design. The engineering models are all documented in [3].

2.4 Huygens Payload

The Huygens payload consists of six instruments provided by Principal Investigators. The list of the payload is provided in Table 2. A brief description of each instrument is given below. Additional information is given in the article 'The Huygens instrument set – a summary' starting on page 267.

Instrument	PI	Function
Huygens Atmospheric Structure Instrument (HASI)	M. Fulchignoni, University Paris 7/ Obs. Paris-Meudon (France)	Atmospheric temperature and pressure profile, winds and turbulence Atmospheric conductivity Search for lightning Surface permittivity and radar reflectivity
Gas Chromatograph Mass Spectrometer (GCMS)	H.B. Niemann, NASA/GSFC, Greenbelt (USA)	Atmospheric composition profile Aerosol pyrolysis products analysis
Aerosol Collector and Pyrolyser (ACP)	G.M. Israel, SA/CNRS Verrières-le-Buisson (France)	Aerosol sampling in two layers – pyrolysis and injection to GCMS
Descent Imager/Spectral Radiometer (DISR)	M.G. Tomasko, University of Arizona, Tucson (USA)	Atmospheric composition and cloud structure Aerosol properties Atmospheric energy budget Surface imaging
Doppler Wind Experiment (DWE)	M.K. Bird, University of Bonn (Germany)	Probe Doppler tracking from the Orbiter for zonal wind profile measurement
Surface Science Package (SSP)	J.C. Zarnecki, University of Kent, Canterbury (UK)	Titan surface state and composition at landing site. Atmospheric measurements

Table 2: Summary of the Huygens instruments

3 Huygens probe design

3.1 Design Overview

The Huygens Probe System[6] consists of two principal elements:

i) The Huygens Probe itself, the element that will detach from the Saturn Orbiter and enter the atmosphere of Titan;

ii) The Probe Support Equipment (PSE), the Huygens element that will remain attached to the Orbiter after Probe separation, and will provide the radio relay link functions with the Probe.

The Probe (Figure 6) consists of two elements: the aeroshell (or 'entry assembly') and the Descent Module. The aeroshell is wrapped in a multi-layer thermal protection for the cruise phase. It is made of two parts: the front shield and the back cover. The Descent Module comprises two platforms, a fore-dome and an after-cone.

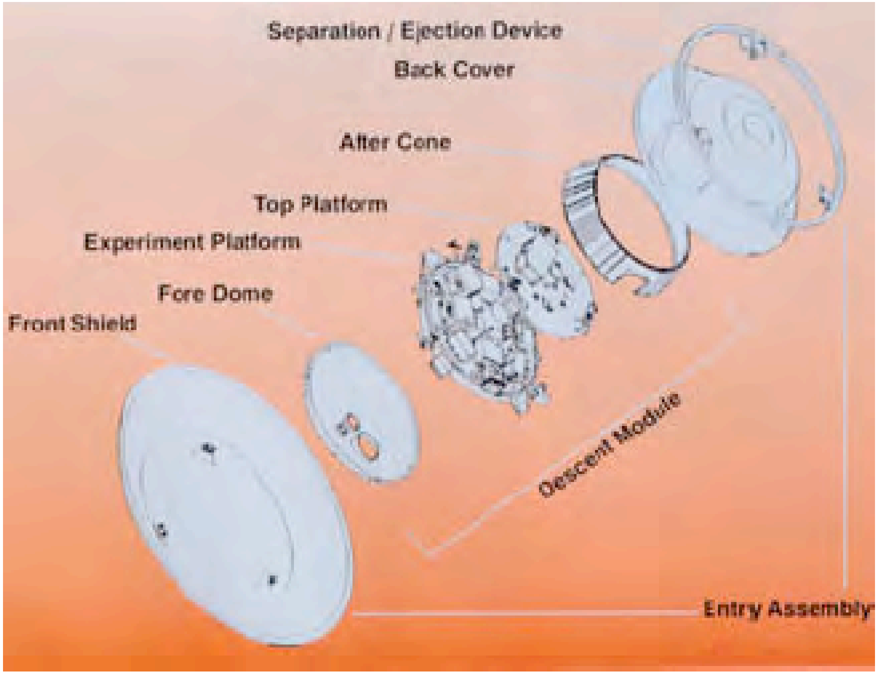

Figure 6: Exploded view of the Huygens Probe. It weighs 319 kg

The Descent Module is enclosed in the aeroshell like a cocoon. The aeroshell and the Descent Module are attached to each other by mechanisms at three points. The aeroshell is jettisoned after entry.

3.2 The entry aeroshell

The front shield

The 79 kg, 2.7 m diameter, 60-degree half-angle coni-spherical front shield is designed to decelerate the Probe in Titan's upper atmosphere from about 6 km/s at entry to a velocity equivalent to about Mach 1.5 (~ 400 m/s) by around 160 km altitude. Tiles of 'AQ60' ablative material – a felt of phenolic resin reinforced by silica fibres – provide protection against the entry convective and radiative heat flux up to 1.4 MW/m^2. The shield is then jettisoned and the descent control subsystem (DCSS) is activated to control (via parachutes) the descent of the Descent Module (DM) to the surface. The front-shield supporting structure is a carbon-fibre-reinforced plastic (CFRP) honeycomb shell. It is also designed to protect the DM from the heat generated during entry. The AQ60 tiles are attached to the CFRP structure by adhesive CAF/730. Prosial, a suspension of hollow silica spheres in silicon elastomer, is sprayed directly onto the aluminium structure of the FRSS rear surfaces, which are expected to experience heat fluxes ten times lower than those to be experienced by the front-shield.

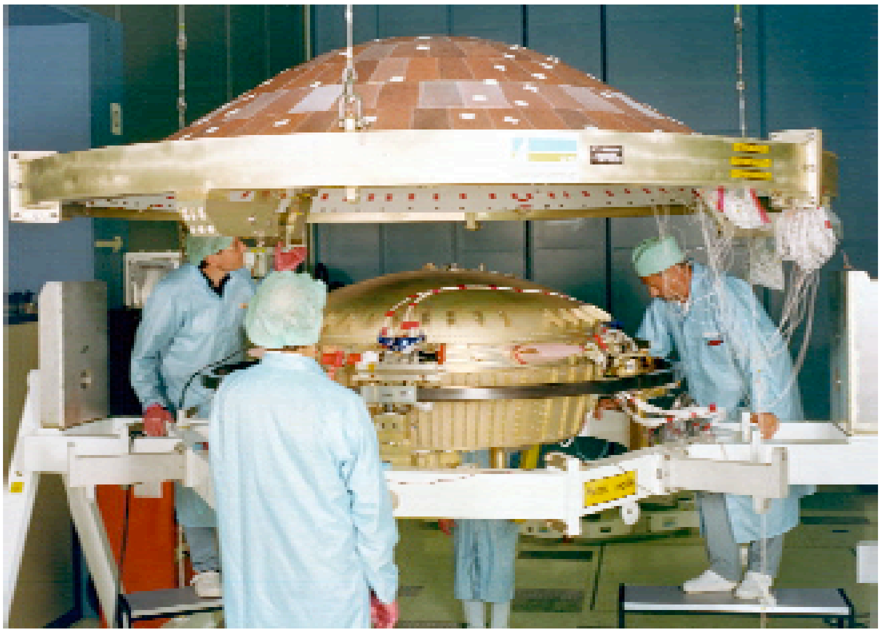

Figure 7: The Huygens probe during assembly

The back cover

The Back-cover (BC) protects the DM during entry, and carries multi-layer insulation for the cruise and coast. A hole in it ensures depressurisation during Launch and repressurisation during entry. As it does not have stringent aerothermodynamic requirements, it is a stiffened aluminium shell of minimal mass (11.4 kg) protected by Prosial (5 kg). It includes:

i) An access door for late integration and forced-air ground cooling of the Probe

ii) A breakout patch through which the first (drogue) parachute is fired

iii) A labyrinth sealing joint with the front-shield, which provides a non-structural thermal and particulate barrier

3.3 The Descent Control Subsystem (DCSS)

The DCSS controls the descent rate to satisfy the scientific payload's requirements, and to provide the attitude stability to meet the requirements of the Probe-to-Orbiter RF data link and the stability requirements of the descent imager (DISR). The DCSS is activated nominally at Mach 1.5, at about 160 km altitude.

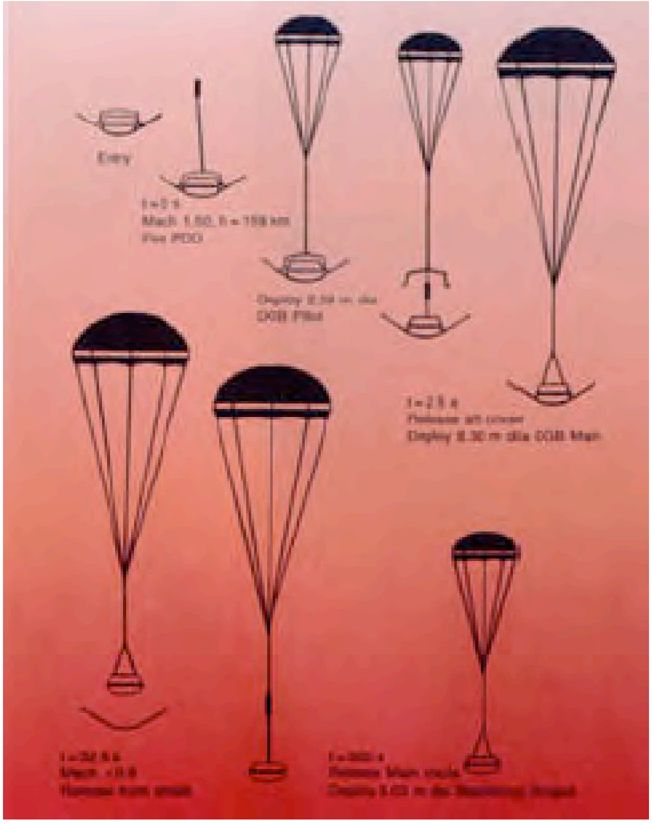

Figure 8: Huygens parachute deployment sequence

The sequence (Figure 8) begins by firing of the Parachute Deployment Device (PDD) to eject the pilot chute pack through the Back Cover's breakout patch, the attachment pins of which shear under the impact. The 2.59 m diameter Disk Gap Band (DGB) **pilot chute** inflates 27 m behind the DM and pulls the back-cover away from the assembly. As it goes, the back-cover pulls the 8.30 m diameter DGB **main parachute** from its container. This canopy inflates during the supersonic phase in order to decelerate and stabilise the Probe through the transonic regime. The front-shield is released at about Mach 0.6. In fact, the main parachute is sized by the requirement to provide sufficient deceleration to guarantee a positive separation of the front-shield from the Descent Module. The main parachute is too large for a nominal descent time shorter than 2.5 h, a constraint imposed by battery capacity, communication geometry between the Probe and the Orbiter, and thermal performances of the DM in Titan's atmosphere. It is therefore jettisoned after 15 min and a 3.03 m diameter DGB **stabilising parachute** is deployed. All parachutes are made of Kevlar lines and nylon fabric. The main and the stabiliser chutes are housed in a single canister on the DM's top platform. Compatibility with the Probe's spin is ensured by incorporating a swivel using redundant low-friction bearings in the connecting riser of both the main and stabiliser parachutes.

The main Huygens design parameters are summarised in Table 3.

Probe release:	25 December 2005 (12-day window)
Coast to Titan:	21 days
Probe wakeup:	4 h 23 min before expected arrival at Titan
Titan entry:	14 January at 9:00 UTC
Entry corridor:	-65° ± 3°
Entry velocity:	~6100 m/s
Peak deceleration:	100 – 190 m/s^2
Peak heat flux:	Up to 1400 kW/m^2
Heat load:	Up to 42 MJ/m^2
Parachute deployment altitude:	180 – 140 km (mach 1.5)
Descent time:	2h30 ± 15 min
Impact speed:	~5 m/s
Duration of radio link with Cassini:	4h35 min
$LiSO_2$ battery energy budget	4 – 7 hours after entry

Table 3: Summary of the Huygens mission parameters

4 Huygens probe trajectory

4.1 Entry Trajectory

The entry trajectory main characteristics are shown in Figure 9.

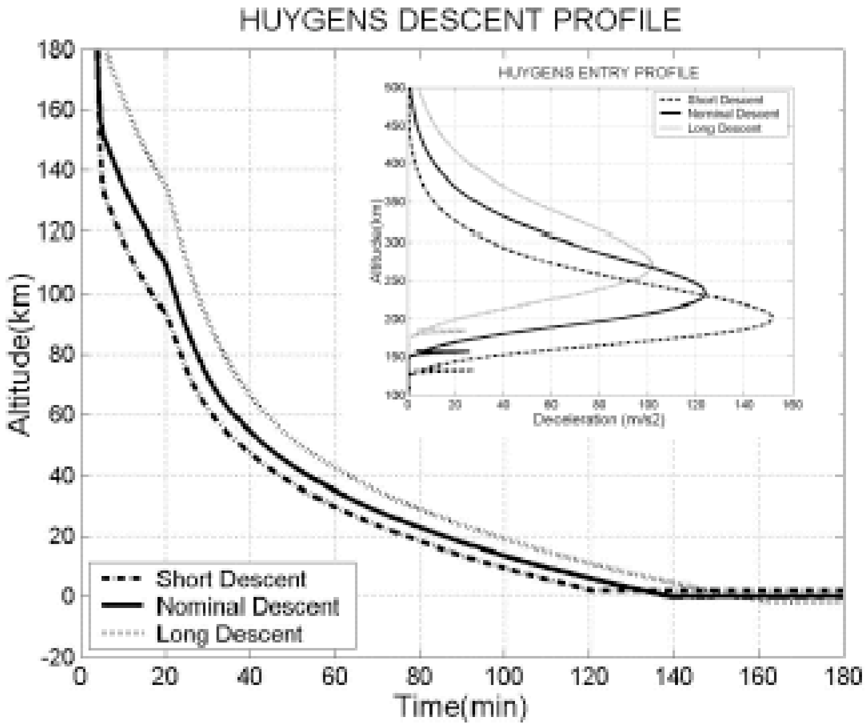

Figure 9: Huygens entry and descent trajectory

The deceleration is expected to occur in the altitude range below 350 km down to 220 km, where Huygens decelerates from about 6 km/s to 400 m/s

(Mach 1.5) in less than 2 min. The detection of the entry deceleration peak will be used to set the starting time of the parachute deployment sequence (see Figure 4).

The entry trajectory has been studied with various tools developed either by industry or by ESA. Currently all relevant aerodynamical parameters are compiled in the Huygens design aerodynamic database[7].

4.2 Descent Trajectory

At Mach 1.5, the parachute deployment sequence will be initiated. It starts with the firing of a pyrotechnic device that deploys the pilot chute, which, in turn, pulls away the aft cover and deploys the main chute. After inflation of the main parachute, the front heat shield is released so that it falls away from the Descent Module. Then, there is a 30 s delay to ensure that the shield is sufficiently far away to avoid instrument contamination. Now the GCMS and ACP inlet ports open and the HASI booms deploy. The DISR cover is ejected 2 min later. The main parachute is sized to pull the Descent Module safely out of the front-shield. After 15 min, it is jettisoned to avoid a protracted descent, and the stabilising parachute is deployed. The descent will last between 2 and 2½ hours (see Figure 9).

4.3 Probe Spin

Huygens is separated from the Orbiter by activation of its Spin-and-Eject device. It imparts a 7-RPM spin to the Probe that provides stability during the coast and the entry.

The main parachute and the stabiliser parachute are linked to the Probe descent module via a swivel mechanism that decouples the Probe spin from that of the parachute.

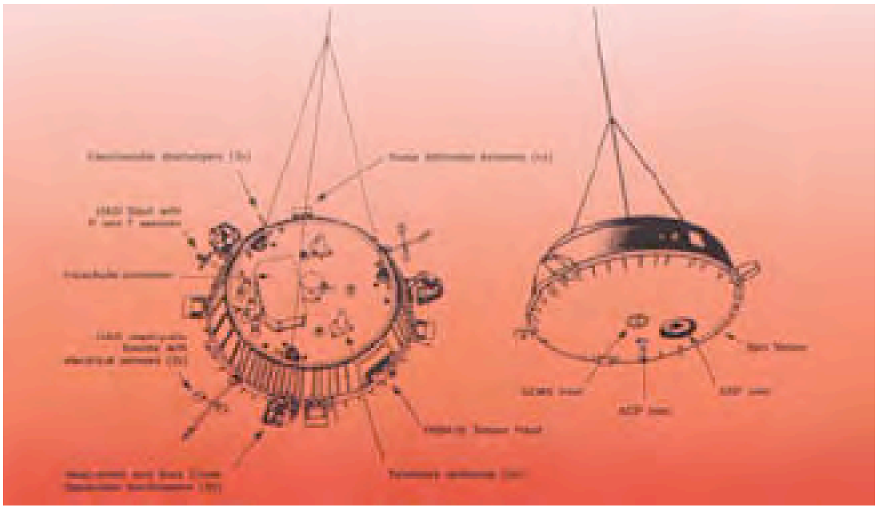

Figure 10: Perspective views of the Huygens Probe

During the descent, Huygens' spin is driven by a set of 36 spin vanes mounted on the bottom part of the fore dome (Figure 10). The main uncertainties in the predicted spin profile are due to: i) the atmosphere uncertainty and ii) the performance (torque) of the swivel during the descent to provide the azimuthal coverage needed by several sensors.

5 Post-flight data analysis

Preparations are underway for a coordinated analysis of the Huygens scientific data set, which requires a close collaboration between all investigators. There are large uncertainties in the predicted trajectory due to the uncertainties in the probe atmospheric environment during entry and descent. The proper reconstruction of the probe trajectory is one of the early priorities of the Huygens Science Working Team (HSWT) during the post-flight data analysis. The goal is to derive a reference trajectory as soon as possible in order to allow all instrument teams to process their data with respect to the same trajectory. The reconstruction of the trajectory is based on scientific measurements provided by both the payload and the probe sensors such as the system accelerometers and the radar altimeter. The reconstruction of the probe attitude is also an early priority of the post-flight data analysis phase, and a main objective of the DISR investigation[9].

A special effort is being made to test tools developed for the reconstruction of the trajectory. This is being undertaken by a subgroup of the HSWT[8]. One approach used for the tool validation is one based on using a simulated synthetic data set[11].

5.1 Coordinated Earth-based observations

Several unique observations that were not foreseen during the probe development are now being planned. Each observation will complement in its own way the Huygens data set. Ground-based radio and optical observations will be conducted from telescopes in the Pacific area, as only telescopes in that area will have visibility of Titan during the probe's descent.

Probe imaging after separation: It is planned to take images of the Huygens probe within 2-3 days after separation using the Orbiter camera. These images will allow determination of relative separation errors by using optical navigation techniques, thus helping to reconstruct the probe entry trajectory for the post-flight data analysis phase.

Huygens VLBI observation: A VLBI (very long baseline interferometry) network will be set up to record the Huygens signal (carrier only) using telescopes in the USA, Australia, Japan and China. It is expected that the VLBI network will include about 20 telescopes[13]. Within days/weeks of the observation, the data will be processed using the correlator facility in the JIVE institute in Dwingeloo, The Netherlands. Such data would provide sub-km localisation of the probe in the plane perpendicular to the line of sight between the Earth and Titan, and hence help to reconstruct the probe trajectory post-flight. The VLBI experiment is complementary to the single-dish Doppler tracking experiment described next.

Ground-based Doppler tracking of the Huygens Probe during descent: An attempt will also be made to receive the Huygens Probe signal through a large radio telescope (most likely Green Bank Telescope in West Virginia, USA). This single-dish recording will be used to determine the Doppler shift of the signal and hence the velocity of the Probe in the direction of Earth. These measurements will complement those of the Huygens Doppler Wind Experiment performed along the Probe-Orbiter direction. A similar experiment was performed with the Galileo Probe at Jupiter, the signal Doppler shift being recorded on the Galileo Orbiter and on the Earth[13].

Probe entry plume detection from Earth: The peculiar aerothermochemistry in the shock layer of a body entering Titan's methane-rich nitrogen atmosphere produces enough light as to make it possible to detect the 'meteor trail' created by the Huygens entry. Besides being of scientific value, such observations would also be of enormous public interest[14]. The observation will be attempted by using both ground-based telescopes and the Hubble Space Telescope.

Coordinated ground-based observations: Due to operational constraints, no Cassini Orbiter observation of Titan will be performed during and around the time of the Probe descent. However, a series of coordinated ground-based observations have been proposed, with the main purpose of observing Titan during and a few days before and after the Huygens descent in order to best place the Huygens data in their global context. Some of the telescopes involved are located at the following observatories: ESO/VLT (Chile), the Keck (Hawaii), CFHT (Hawaii), Subaru (Hawaii), CAHA/Calar Alto (Spain).

6 Huygens mission status

At the time of going to press, Cassini-Huygens had arrived safely at Saturn and gone into orbit. Cassini has returned astonishing images of the rings and some of the icy moons. Cassini has also discovered some new moonlets embedded within the rings of Saturn. An excellent data set was also obtained during the distant flyby of Titan that occurred on 2nd July 2004. Although new information has been obtained about Titan's surface, it largely remains a mystery that waits to be further explored by Huygens. New, exciting results are expected from the two low-altitude flybys of Titan before the probe mission, planned for 26th October and 13th December. The Titan data set obtained on 2nd July has, however, allowed confirmation that the structure of the upper atmosphere of Titan in the entry altitude range of Huygens is well within the design envelope (Yelle model). This data set, combined with the latest ground-based observation results, is being used to update the Titan atmosphere model as part of the process of revalidating the Huygens performance before separation.

New images are being received almost daily from Cassini and are posted on the web site. For the latest news and images, please visit the following web sites:

http://saturn.esa.int http://saturn.jpl.nasa.gov

References

[1] Matson, D.L., Spilker, L.J., and Lebreton, J-P, The Cassini/Huygens Mission to the Saturnian System, Space Science Reviews, 104:1-58,2002

[2] Lebreton J-P and Matson DL, The Huygens Probe: Science, payload and Mission Overview, Space Science Reviews, 104:59-100, 2002.

[3] ESA SP-1177 (ed. A. Wilson), Huygens: Science Payload; and Mission Overview, ESA Publication, (1997).

[4] Kazeminejad, B., Lebreton, J-P., Bird, M.K, and Atkinson D. H., Titan Wind Effects on the Descent Trajectory of the ESA Huygens Probe, Proc. ESLAB Symposium, 'Earth-Like planets and Moons', ESTEC, Noordwijk, 3-8 June 2002 (ESA SP-415, October 2002)

[5] Russell, C. (ed), The Cassini-Huygens Mission, Overview, Objectives and Huygens Instrumentarium, Vol. 104 Nos 1-4 (2002)

[6] Clausen, K. C., Hassan, H., Verdant, M., Couzin, P., Huttin, G., Brisson, M., Sollazzo, C., and Lebreton, J-P., The Huygens Probe System Design, Space Science Reviews, 104:155-189, 2002.

[7] Huygens design aerodynamic database, to be published.

[8] Kazeminejad, B., and Atkinson D. H., The ESA Huygens Probe Entry and Descent Trajectory Reconstruction, Proc. Intl. Workshop 'Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science', Lisbon, Portugal (ESA SP-544, October 2003)

[9] Rizk B., et al., Recovering the Attitude of the Huygens Descent Module using DISR Data (ESA SP-544, October 2003)

[10] Zarnecki J., Ferri F., Hathi, B., Leese, M.R., Ball, A.J., Colombatti G., and Fulchignoni, M., In-Flight Performance of the HASI Servo Accelerometer and Implications for Results at Titan (ESA SP-544, October 2003)

[11] Pérez Ayúcar, M., Witasse, O., Lebreton, J-P., Kazeminejad, B., and Atkinson, D.H, A Simulated Dataset of the Huygens Mission (ESA SP-544, October 2003)

[12] Folkner, W.M., et al., Ground-Based Tracking of the Huygens Probe During the Titan Descent (ESA SP-544, October 2003)

[13] Pogrebenko, S.V. et al., VLBI Tracking of the Huygens Probe in the Atmosphere of Titan (ESA SP-544, October 2003)

[14] Lorenz, R., An artificial meteor on Titan?, Astronomy and Geophysics, 2002

Flight through Titan's atmosphere

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Abstract

We assembled spectral image data cubes of Titan in H-band (1.413-1.808 μm), using adaptive optics on the 10-m W.M. Keck telescope, by stepping a spectrometer slit across Titan's disk. We constructed images of Titan at each wavelength by 'glueing' the spectra together, producing 1400ultra-narrowband (~0.1nm) views of the satellite. With this method one can characterise Titan's atmosphere over the entire disk, in more specific vertical detail than possible with either narrowband imaging or slit spectroscopy at one position. Data were obtained of Titan's leading hemisphere on UT 20 February 2001. At the shorter wavelengths we probe all the way down to the surface, revealing the familiar bright and dark terrain, while at longer wavelengths we probe various altitudes in the atmosphere. The data have been assembled into a movie, showing the surface and different haze layers while stepping up in altitude. The transitions from the surface to the tropospheric haze, and through the tropopause into the upper atmospheric haze, are clearly recognised.

1 Introduction

Titan, Saturn's largest satellite, was discovered in 1655 by Christiaan Huygens, using a telescope that he and his brother Constantijn had just completed building. During the time of discovery Saturn's rings were nearly edge-on, which most likely helped in the discovery since light from Saturn's rings was greatly reduced during this period. Except for its mere existence, we did not learn much more about this satellite until about 250 years later, when Jose Comas Sola claimed to see limb darkening on Titan, and suggested that the satellite might possess an atmosphere. A clear confirmation that Titan possesses an atmosphere came in the mid-1940s, when Gerard Kuiper reported the discovery of methane absorption bands in the satellite's spectrum. In these observations, as well as the ones we report on below (section 2), Titan is visible because sunlight is reflected back from it. At particular wavelengths, sunlight is absorbed by methane gas in Titan's atmosphere, so that at these wavelengths the satellite looks very dark.

In the 1970s, in anticipation of the Voyager encounters in 1980 and1981, Titan was observed at wavelengths across the electromagnetic spectrum from the UV well into the radio, and at the same time models of its atmosphere were developed. The fact that only methane gas had been detected on the satellite naturally led to a class of models in which methane gas was the main constituent of the atmosphere [7,3]. Lewis [16], however, suggested that Titan's atmosphere might be rich in nitrogen due to photolysis of ammonia gas, which he expected to be present in Titan's atmosphere, in (vapour-pressure) equilibrium with ammonia-ice (pure or as a hydrate - $NH_3.H_2O$) on Titan's surface. Donald Hunten [13] developed this idea into a model atmosphere dominated by nitrogen gas. Surface pressures on the satellite in these different classes of models ranged from ~20 mbar for methane-dominated atmospheres, up to 20 bar for a Titan dominated by nitrogen gas. The first Voyager spacecraft flew by Titan in 1980, when it was springtime on the satellite's northern hemisphere. Unfortunately, the surface was not revealed because Titan is enveloped by a thick, orange-brown, smog layer, composed of condensed photochemically produced hydrocarbons. It was confirmed, though, that Titan's atmosphere is dominated by nitrogen gas, and radio occultation experiments revealed a surface pressure of 1.5 bar. Titan thus appeared to be similar to early Earth, before our planet became rich in biogenically-produced oxygen.

Images of Titan recorded by the Voyager spacecraft revealed that the northern hemisphere was covered by more stratospheric haze than the south, and the N. polar hood was a prominent feature. In the 1990s, with the launch of the Hubble Space Telescope and the development of speckle imaging and adaptive optics techniques on ground-based telescopes, spatially resolved images of Titan were obtained from the ground and Earth-orbit. These images showed the excess haze over Titan's northern hemisphere had, somehow, moved to the south when it became winter in the southern hemisphere. This apparent seasonal migration from the spring/summer pole to the winter hemisphere has now been observed at many different wavelengths during the past decade. Most interesting, however, is that this so called reversal of the North-South asymmetry clearly lagged behind at certain wavelengths compared to others. Because atmospheric opacity varies with wavelength, one probes different altitudes at different wavelengths. The collection of data could therefore be used to derive the 3-dimensional response of Titan's atmosphere to the annual variations in insulation. The data reveal that the atmosphere responds more readily to seasonal changes at the highest altitudes, while the seasons lag behind more significantly at lower altitudes. Rannou and collaborators[21] developed an atmospheric model that couples haze formation to atmospheric transport. The circulation in this model is dominated by a summer-to-winter-pole cell, where air flows from the summer pole to the winter pole. Haze particles are photochemically produced at high altitudes (~400-600 km), and 'blown' to the winter pole, where they accumulate to form a polar hood. Here the particles slowly sediment out, while growing in size; a return flow takes place at lower altitudes. This model can indeed explain most of the observations.

Since the surface had not been observed by Voyager, speculations about what it might look like ranged from a regular surface composed of a mixture of rock and ice, up to a body completely covered by liquid hydrocarbons. Lunine and collaborators [19] showed that methane could persist in Titan's atmosphere for only ~10^7 years, i.e., much shorter than the age of our Solar System, unless it were recycled back into the atmosphere. Since the temperature and pressure on Titan's surface are such that many hydrocarbons, including methane, would probably be present in liquid form, they suggested the satellite might contain liquid hydrocarbons, which would supply methane gas to the atmosphere, in a sense analogous to the water cycle on Earth. Soon after the Voyager encounters, it was realised that the surface could actually be probed at infrared wavelengths, since the photochemical smog on Titan, while being opaque at visible wavelengths, is transparent at longer infrared wavelengths. As long as observations were conducted away from the methane absorption bands, the surface could be seen. Over the years quite detailed surface maps of the satellite were obtained. An example of one such map is given in Figure 1.

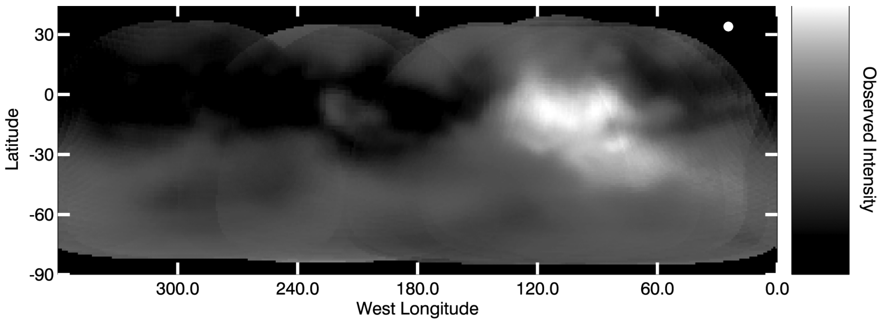

Figure 1: A surface map of Titan at 1.6 μm, constructed from Keck adaptive optics data (from: Roe et al. 2004)

On the leading hemisphere (that is, leading in Titan's orbit around Saturn) is a bright region, composed in part of exposed water-ice [6,8,12], which is suggestive of an elevated continent, perhaps washed clean of hydrocarbon residues by runoff [10,14]. The dark areas on Titan's surface maps have reflectivities close to zero, and hence may represent hydrocarbon oceans. This notion has been strengthened by recent Arecibo radar[4] observations of Titan's surface, which reveal specular reflections (a sharply-defined beam, as if incident radiation is reflected from a mirror) consistent with those expected from areas covered by liquid hydrocarbons.

Ever since the discovery of methane in Titan's atmosphere, the existence or absence of methane clouds has been debated. Some studies indicated a supersaturation of methane gas in Titan's troposphere, indicative of stagnant air without clouds [5,24], while others advocated a methane cycle analogous to Earth's hydrological cycle [26] that would form clouds. In the mid-1990s, Griffith and collaborators [10] presented the first evidence of clouds in Titan's troposphere through an analysis of disk-averaged spectra. In December 2001 we used the 10-m Keck telescope, equipped with adaptive optics, to image Titan and search for clouds at wavelengths which were sensitive only to Titan's troposphere, i.e., the lower atmosphere where clouds are expected to form. To our delight, clouds were seen, but to our surprise they were only present above Titan's south pole [2,22] (Figure 2).

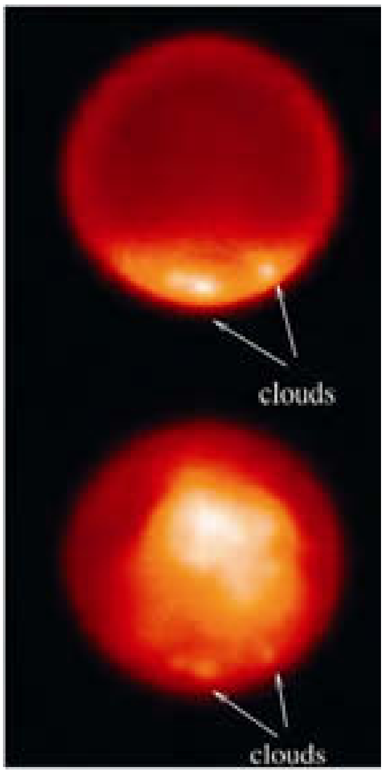

Figure 2: Clouds on Titan observed on 21 December 2001 (UT) with adaptive optics on the Keck telescope.

Top: Narrow-band filter centred at 2.108 μm, which probes just Titan's troposphere. At least 3 clouds and the tropopause haze near Titan's S. pole are visible.

Bottom: Broadband K' filter, centred near 2.2 μm, which probes both the surface and atmosphere. (Adapted from: Roe et al. 2002)

This suggests that perhaps the surface temperature at the pole is high enough during the summer for convection to be triggered, and/or that fall-out of condensates from Titan's stratosphere, properly coated by ethane, provides condensation nuclei for methane clouds to form.

2 Spatially-resolved image datacubes

From the introduction above, it may have become apparent that different layers of Titan's atmosphere, from a few hundred kilometres down to the surface, can be observed by choosing different wavelengths. With this in mind, we assembled spectral image data-cubes of Titan in H-band (1.413-1.808 μm) using adaptive optics with spectroscopy (NIRSPAO) on the 10-m Keck telescope, by stepping the spectrometer slit across Titan's disk. (For full details on the observations, please see [1].) A nice visual explanation of this technique can be found on the VIMS (Visual and Infrared Mapping Spectrometer on the Cassini spacecraft) website:

http://wwwvims.lpl.arizona.edu

The observations were carried out on the night of 20 February 2001 UT. The slit dimensions used were 3.96″ x 0.076″, with a spatial resolution along the slit of about 0.05″ (Titan is about 0.8″ across). Simultaneously with the slit spectroscopy, images of Titan were recorded with the infrared camera (SCAM on NIRSPEC). A series of Titan images with the spectrometer slit is shown in Figure 3.

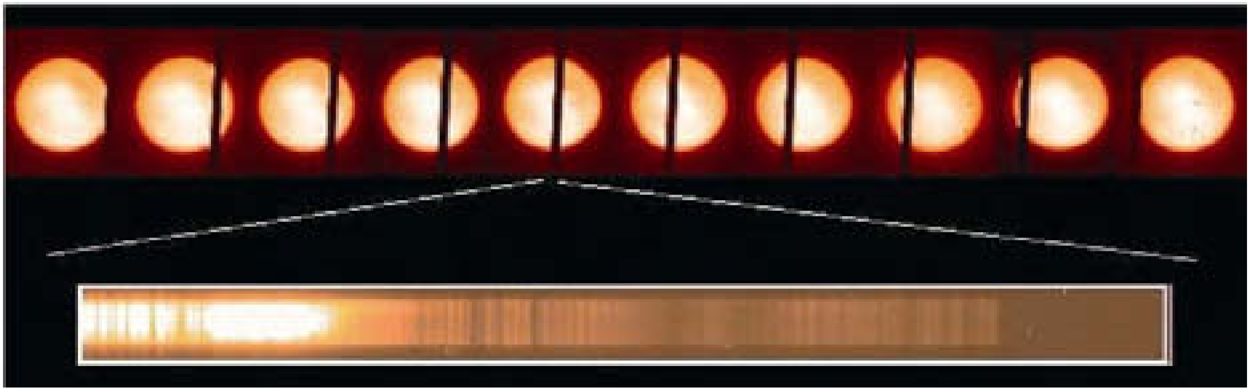

Figure 3: A series of infrared (SCAM) images of Titan taken on 20 Feb. 2001(UT) with adaptive optics on the Keck telescope, while data were obtained through the spectrometer slit (shown in each image) to construct the images shown in Figure 4 and Figure 5. One of the spectra obtained through the slit is shown as well

We then combined all spectra to construct images of Titan at each wavelength. This way we produced 1400 ultra-narrowband (~0.1 nm) views of the satellite, which were combined into a movie that can be viewed on:

http://astron.berkeley.edu/~imke/Infrared/Titan/Titanmovie.htm

Figure 4 shows the first frame of the movie on the website.

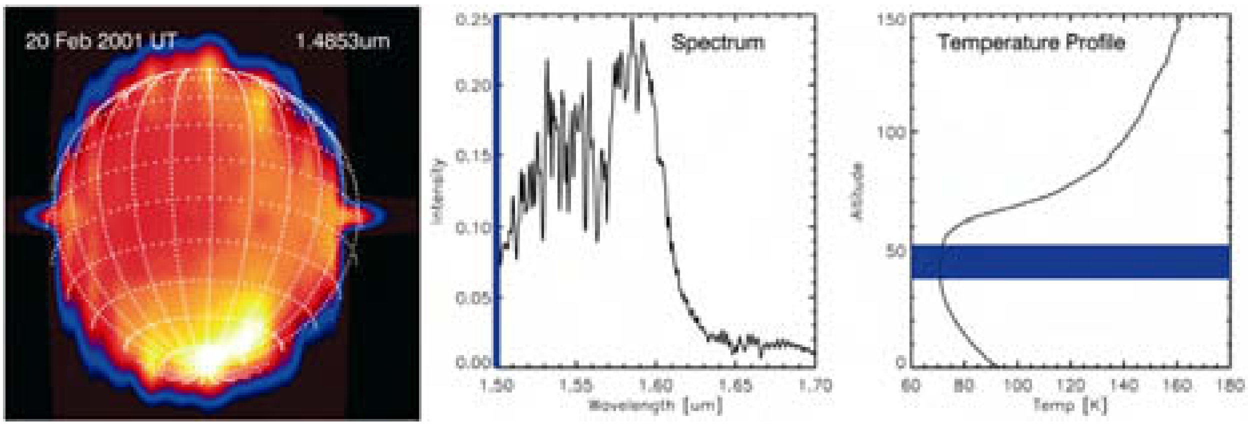

Figure 4: The first frame of the Titan movie.
The left frame shows an image of Titan's tropopause haze; the middle frame shows the spectrum (at the centre of the disk), and the right frame shows the temperature-pressure profile of Titan's atmosphere. The blue bars show, for the image on the left, at which wavelength the image was taken (centre frame; 1.42 µm) and where in the atmosphere it is probing (right frame; near tropopause).

We used a radiative transfer model to interpret Titan spectra at different positions on the disk. From these calculations we derive the altitudes in Titan's atmosphere that primarily contribute to the flux of each image. The blue bars in Figure 4 show at which wavelength (centre frame; 1.42 µm) the image on the left was taken and where in the atmosphere we probe (right frame; near tropopause). In the movie, one can see how Titan's image is changing while stepping though the spectrum/atmosphere. We note that each frame was scaled individually relative to its highest intensity, so that the large variation in intensity across the wavelength band (e.g. 0.25 → 0.01 on centre frame in Figure 4) is not noticeable in the movie.

In Figure 5 we show a subset of images from the movie.

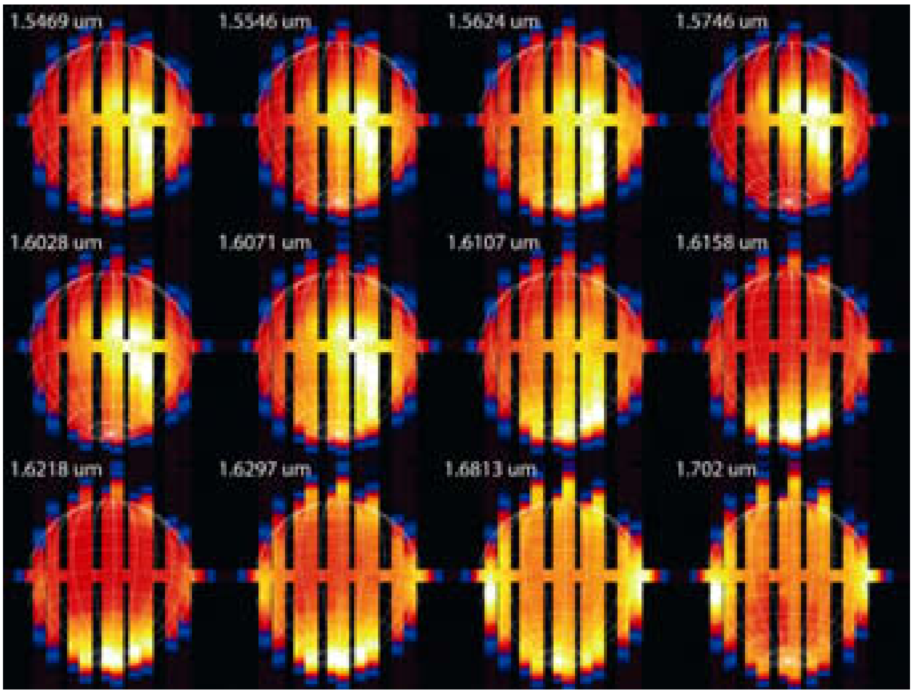

Figure 5: Spectral image maps of Titan, constructed from data obtained with adaptive optics on the Keck telescope on 20 Feb. 2001 (UT). These images were constructed from spectra through the slits indicated in Figure 3. The sub-observer point is 111° West longitude, and 23° South latitude. The wavelength is indicated in the upper left of each frame (from [1]).

The first row of images is from 1.55-1.57 µm, where methane absorption is weak, and we probe Titan's surface. However, even within this 20 nm wide window, there are wavelengths (e.g. 1.5546 and 1.5624 µm) where we see a contribution from haze particles in Titan's atmosphere near the southern pole. The dominant surface feature is the 'bright continent' located at ~100° W (see Figure 1). The middle row of images in Figure 5 show that as methane opacity increases with wavelength, flux from higher altitudes in the atmosphere is observed. At 1.6028 µm the surface dominates the signal, whereas at 1.6158 µm flux from a layer of haze near the tropopause, at altitudes between 30 and 50 km, is observed – the same haze as seen in Figure 2a. At intermediate wavelengths a combination of the surface and lower atmosphere contribute to the observed intensity. At wavelengths longer than 1.6158 µm the bright surface feature is no longer visible. Methane absorption here is strong enough to completely attenuate the light from the Sun before it reaches the surface. The observed signal is therefore from photons that are scattered from particulates in the atmosphere. At wavelengths longer than 1.6218 µm (bottom row of Figure 5), we see stratospheric haze, at altitudes between about 50 and 150 km. At these wavelengths the observed intensity is diminished, signal-to-noise decreases, and limb brightening becomes more pronounced. At the highest altitudes we see a N-S asymmetry, as discussed in the introduction, with more haze above the northern hemisphere.

3 Conclusion

With image datacubes as presented above, one can thus characterise Titan's atmosphere over the entire disk in more specific vertical detail than is possible with either narrowband imaging or slit spectroscopy at one position. At these particular wavelengths (1.4 - 1.8 μm), we probe all the way down to the surface at the short wavelengths, revealing the familiar bright and dark terrain, while at longer wavelengths we probe different atmospheric levels. At 1.62 μm we probe just the upper troposphere, while upwards of 1.64 μm we probe different levels in Titan's stratosphere. The transitions from the surface to the tropospheric haze, and through the tropopause into the upper atmospheric haze, are clearly recognised.

This work is a prelude to future observations with integral-field spectrographs, where image datacubes will be obtained directly at the telescope, so that it is no longer necessary to step a slit across the disk and painfully 'glue' the data together afterwards. These new detectors will come on-line on Keck and the VLT in 2005, which will make it possible to regularly produce image data-cubes to monitor seasonal variations in the 3-dimensional spatial distribution of hazes and clouds. Such information is necessary to test models that couple circulation and the photochemical formation of aerosols on Titan (as discussed in the introduction). Continued ground-based observation during and after the Cassini era is crucial to obtain a dynamical understanding of Titan's atmosphere, even with the detailed measurements expected from the Cassini spacecraft and Huygens probe. Since integral-field spectrographs are state-of-the-art instruments, the visual and near-infrared spectrographs on the Cassini spacecraft still consist of a slit, and hence spectral images with VIMS will be obtained by stepping their slit across Titan's disk, in the same way we constructed the Keck images shown in this paper.

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References

[1] Ádámkovics, M., I. de Pater, H. Roe, S. Gibbard, and C. Griffith, 2004. Spatially-resolved spectroscopy at 1.6μm of Titan's atmosphere and surface. Geophys. Res. Lett. **31**, L17S05, doi:10.1029/2004GL019929.

[2] Brown, M.J., A.H. Bouchez, and C.A. Griffith, 2002. Direct detection of variable tropospheric clouds near Titan's south pole. Nature **420**, 795-797.

[3] Caldwell, J., 1977. Thermal radiation from Titan's atmosphere. In Planetary Satellites. Ed. J.A. Burns (Tucson, Univ. of Arizona Press), pp. 438-450.

[4] Campbell, D.B., G.J. Black, L.M. Carter, and S. Ostro, 2003.Radar Evidence for Liquid Surfaces on Titan. Science **302**, 431-434.

[5] Courtin, R., D. Gautier, and C. McKay, 1995. Titan's thermal emission spectrum: reanalysis of the Voyager infrared measurements. Icarus **114**, 144-162.

[6] Coustenis, A., E. Lellouch,, J.P. Maillard, and C.P. McKay, 1995.Titan's surface: composition and variability from the near-infrared albedo. Icarus **118**, 87-104.

[7] Danielson, R.E., J.J. Caldwell, and D.R. Larach, 1973. An inversion in the atmosphere of Titan. Icarus **20**, 437-443.

[8] Gibbard, S.G., B. Macintosh, D. Gavel, C.E. Max, I. de Pater, A.M. Ghez, E.F. Young, and C.P. McKay, 1999, Titan: High resolution speckle images from the Keck telescope. Icarus **139**, 189-201.

[9] Gibbard, S. G., I. de Pater, B. A. Macintosh, H. G. Roe, C. E. Max, E. F. Young, and C. P. McKay, 2004, Titan's 2 micron surface albedo and haze optical depth in 1996-2004. Geophys. Res. Lett.31, L17S02, doi:10.1029/2004GL019803.

[10] Griffith, C.A., T. Owen, and R. Wagener. 1991. Titan's surface and troposphere, investigated with ground-based near-infrared observations. Icarus **93**, 362--378.

[11] Griffith, C.A., T. Owen, G.A. Miller, and T. Geballe, 1998. Transient clouds in Titan's lower atmosphere. Nature **395**, 575-578.

[12] Griffith, C. A., T. Owen, T.R. Geballe, J. Rayner, P. Rannou, 2003. Evidence for the Exposure of Water Ice on Titan's Surface. Science **300**, 628-630.

[13] Hunten, D.M., 1978. A Titan atmosphere with a surface temperature of 200K. In the Saturn System, Eds. D.M. Hunten and D. Morrison (Washington, NASA Conf. publ. **2068**). pp. 127-140.

[14] Kuiper, G.P., 1944. Titan: a Satellite with an Atmosphere. Astrophys. J. **100**, 378-383.

[15] Lemmon, M.T., E. Karkoschka, and M. Tomasko. 1993. Titan's rotation: surface feature observed. Icarus **113**, 27-38.

[16] Lewis, J.S., 1971. Satellites of the outer planets: Their physical and chemical nature. Icarus **15**, 174-185.

[17] Lorenz, R.D., 1993. The life, death and afterlife of a raindrop on Titan. Planetary and Space Science **41**, 647-655

[18] Lorenz, R. D., P. H. Smith, and M. T. Lemmon (2004), Seasonal change in Titan's haze 1992-2002 from Hubble Space Telescope observations. Geophys. Res. Lett. **31**, L10702, doi:10.1029/2004GL019864.

[19] Lunine, J.I. D.J. Stevenson and Y.L. Yung. 1983 Ethane ocean on Titan. Science **222**, 1229--1230.

[20] Meier, R. B.A. Smith, T.C. Owen, and R.J. Terrile, 2000. The surface of Titan from NICMOS observations with the Hubble Space telescope. Icarus **145**, 462-473.

[21] Rannou, P., F. Hourdin, and C.P. McKay, 2002. A wind origin for Titan's haze structure. Nature **418**, 853-856.

[22] Roe, H.G., I. de Pater, B.A. Macintosh, and C.P. McKay, 2002. Titan's clouds from Gemini and Keck adaptive optics imaging. Astrophys. J. **581**, 1399-1406.

[23] Roe, H. G., I. de Pater, S. G. Gibbard, B. A. Macintosh, C. E. Max, E. F. Young, M. E. Brown, and A. H. Bouchez 2004, A new 1.6-micron map of Titan's surface, Geophys. Res. Lett. 31,L17S03, doi:10.1029/2004GL019871.

[24] Samuelson, R.E., N.R. Nath, and A. Borysow, 1997. Gaseous abundances and methane super saturation in Titan's tropopause. Planet. Space Sci. **45**, 959-980.

[25] Smith, P.H., M.T. Lemmon, R.D. Lorenz, L.A. Sormovksy, J.J. Caldwell and M.D. Allison. 1996. Titan's surface, revealed by HST imaging. Icarus **119**, 336-349.

[26] Tyler, G.L., V.R. Eshleman, J.D. Anderson, G.S Levy, G.F. Lndal, G.E. Wood, and T.A. Crofty, 1981. Radio science investigations of the Saturn system with Voyager 1: preliminary results. Science **212**, 201-206.