
Distance from the Center of Saturn (km)
63500
63000
62500
62000
61500
61000
60500
60000
21 Apr 2017
12 May 2017
02 Jun 2017
23 Jun 2017
14 Jul 2017
04 Aug 2017
25 Aug 2017
Jet Propulsion Laboratory

1
00:00:00,934 --> 00:00:03,269
- NASA's Jet Propulsion
Laboratory presents

2
00:00:03,302 --> 00:00:04,837
the von Kármán Lecture,

3
00:00:04,870 --> 00:00:07,273
a series of talks by
scientists and engineers

4
00:00:07,306 --> 00:00:09,575
who are exploring
our planet,

5
00:00:26,492 --> 00:00:19,652
our solar system,
and all that lies beyond.

6
00:00:26,525 --> 00:00:28,027
- Good evening,
ladies and gentlemen.

7
00:00:28,060 --> 00:00:29,128
How's everyone tonight?

8
00:00:29,161 --> 00:00:30,563
- Good.
- Excellent.

9
00:00:30,596 --> 00:00:31,798
[applause]

10
00:00:31,831 --> 00:00:34,200
Really want to thank you guys
for coming out tonight,

11
00:00:34,233 --> 00:00:35,735
especially

in that weather.

12
00:00:35,768 --> 00:00:37,036
We didn't expect a house
anywhere near this full

13
00:00:37,069 --> 00:00:39,806
so thank you
very, very much.

14
00:00:39,839 --> 00:00:41,207
So, shall we?

15
00:00:41,240 --> 00:00:44,677
Mission planning is a core
strength of JPL engineering,

16
00:00:44,710 --> 00:00:45,845
along with deep space
communications,

17
00:00:45,878 --> 00:00:47,980
and navigation.

18
00:00:48,013 --> 00:00:49,449
Tonight, we're going to
take a look back

19
00:00:49,482 --> 00:00:52,552
at the various scenarios
and contingency plans

20
00:00:52,585 --> 00:00:55,188
that the Cassini team made as
they steered the spacecraft

21
00:00:55,221 --> 00:00:59,459
into unexplored space during
its 2017 grand finale.

22
00:00:59,492 --> 00:01:02,595
Our guest will discuss how
the possible scenarios,

23
00:01:02,628 --> 00:01:04,764
some of which could've
been mission ending,

24
00:01:04,797 --> 00:01:07,533
compared to the mission as
it was actually flown,

25
00:01:07,566 --> 00:01:09,402
along with sharing
some science highlights

26
00:01:09,435 --> 00:01:10,937
from the finale.

27
00:01:10,970 --> 00:01:14,107
Tonight's guest was the
mission planning lead

28
00:01:14,140 --> 00:01:15,308
for the Cassini mission.

29
00:01:15,341 --> 00:01:17,176
Prior to joining Cassini,
he served

30
00:01:17,209 --> 00:01:19,879
as a mission engineer
and mission architect

31
00:01:19,912 --> 00:01:21,747
for the Mars Advanced
Formulation Office

32
00:01:21,780 --> 00:01:25,318

and for other various
planetary mission concepts.

33
00:01:25,351 --> 00:01:27,019
He joined JPL in 2005,

34
00:01:27,052 --> 00:01:30,189
fresh out of Cal Poly,
San Luis Obispo,

35
00:01:30,222 --> 00:01:32,325
where he received his B.S.
in Aerospace Engineering,

36
00:01:32,358 --> 00:01:33,759
a B.A. in Physics,

37
00:01:33,792 --> 00:01:36,562
and a Masters degree in
Aerospace Engineering.

38
00:01:36,595 --> 00:01:37,997
Ladies and gentlemen,
please help me welcome

39
00:01:38,030 --> 00:01:40,333
tonight's guest,
Mr. Erick Sturm.

40
00:01:40,366 --> 00:01:47,707
[applause]

41
00:01:47,740 --> 00:01:50,176
- HI.

42
00:01:50,209 --> 00:01:52,245
Thank you very much and
let me second the thanks

43

00:01:52,278 --> 00:01:53,980
for coming out in the rain.

44
00:01:54,013 --> 00:01:55,348
That's very impressive.

45
00:01:55,381 --> 00:01:57,049
Thanks to the smarter ones
who are online,

46
00:01:57,082 --> 00:02:01,120
who are watching
from a nice warm, dry area.

47
00:02:01,153 --> 00:02:03,923
Okay, so yeah, as was said,
I'm Erick Sturm

48
00:02:03,956 --> 00:02:06,392
and I am Cassini's Lead
Mission Planner.

49
00:02:06,425 --> 00:02:08,794
And I say am, not was, because
while the Cassini mission

50
00:02:08,827 --> 00:02:11,631
ended six months ago the
project is still going.

51
00:02:11,664 --> 00:02:13,199
We're still archiving,
we're still closing out,

52
00:02:13,232 --> 00:02:14,534
we're still
writing reports.

53
00:02:14,567 --> 00:02:18,871
It's not as fun as it was,

but it's not past tense yet.

54
00:02:18,904 --> 00:02:22,041
So, I have the honor of
speaking to you guys tonight

55
00:02:22,074 --> 00:02:25,278
as Cassini's last Mission
Planner but I'm certainly not

56
00:02:25,311 --> 00:02:28,214
Cassini's only Lead
Mission Planner.

57
00:02:28,247 --> 00:02:31,517
In fact, I share that title
with five other people,

58
00:02:31,550 --> 00:02:33,786
and you can see
them all here.

59
00:02:33,819 --> 00:02:36,189
And so, without the hard
work of these people

60
00:02:36,222 --> 00:02:37,590
Cassini wouldn't have
gotten off the ground,

61
00:02:37,623 --> 00:02:39,125
it wouldn't have
gotten into space,

62
00:02:39,158 --> 00:02:40,693
wouldn't have made
it out to Saturn,

63
00:02:40,726 --> 00:02:43,262
and it certainly wouldn't have

made it through its tour

64
00:02:43,295 --> 00:02:45,097
and let me be here tonight
to talk to you

65
00:02:45,130 --> 00:02:48,334
about the end of that tour,
Cassini's grand finale.

66
00:02:48,367 --> 00:02:51,771
And as you can see, Cassini's
been around a long time.

67
00:02:51,804 --> 00:02:55,808
It first got a Lead Mission
Planner back in 1991,

68
00:02:55,841 --> 00:02:58,711
but the beginnings of Cassini
actually go back

69
00:02:58,744 --> 00:03:01,781
even before that,
back to 1982.

70
00:03:01,814 --> 00:03:04,116
That's when
Cassini was born.

71
00:03:04,149 --> 00:03:07,620
And at that time a working
group was formed between

72
00:03:07,653 --> 00:03:09,322
the European
Science Foundation

73
00:03:09,355 --> 00:03:11,257
and the National

Academy of Sciences

74
00:03:11,290 --> 00:03:13,125
and they were
supposed to come up

75
00:03:13,158 --> 00:03:17,330
with a joint concept for
exploring the planets.

76
00:03:17,363 --> 00:03:20,199
And eventually what came out
of that was a concept

77
00:03:20,232 --> 00:03:23,202
that involved
a U.S. Saturn orbiter

78
00:03:23,235 --> 00:03:24,971
and a European probe
that later

79
00:03:25,004 --> 00:03:27,006
became Cassini
and Huygens.

80
00:03:27,039 --> 00:03:29,308
And you can actually Cassini
and Huygens over there.

81
00:03:29,341 --> 00:03:32,144
That's our
half scale model.

82
00:03:32,177 --> 00:03:34,146
And just to give you
more of an appreciation

83
00:03:34,179 --> 00:03:38,484
of just how

long ago 1982 was...

84
00:03:38,517 --> 00:03:40,453
that's me back in 1982.

85
00:03:40,486 --> 00:03:42,455
[laughter]

86
00:03:42,488 --> 00:03:46,726
So, Cassini and I
were born in the same year.

87
00:03:46,759 --> 00:03:51,897
So yeah, it was
a long time ago.

88
00:03:51,930 --> 00:03:56,202
Okay, so jumping ahead a few
years, Cassini launched in 1997

89
00:03:56,235 --> 00:03:58,271
and it followed this nice
loopty-loop green path

90
00:03:58,304 --> 00:03:59,672
out to Saturn.

91
00:03:59,705 --> 00:04:02,408
That's actually two and a half
revolutions around the Sun.

92
00:04:02,441 --> 00:04:04,644
It flew by Venus twice,

93
00:04:04,677 --> 00:04:07,246
Earth and Jupiter all
on its way out there,

94
00:04:07,279 --> 00:04:10,149

and seven years later
it arrived at Saturn

95
00:04:10,182 --> 00:04:12,251
in July of 2004.

96
00:04:12,284 --> 00:04:13,653
And at that time,
it began its prime mission,

97
00:04:13,686 --> 00:04:15,354
which was a four year
mission to tour Saturn

98
00:04:15,387 --> 00:04:18,758
and explore it and
its moons and the rings.

99
00:04:18,791 --> 00:04:21,494
It got a mission
extension in 2008

100
00:04:21,527 --> 00:04:23,663
to go an additional
two years out to 2010,

101
00:04:23,696 --> 00:04:25,498
that was the Cassini
Equinox mission.

102
00:04:25,531 --> 00:04:27,233
And then, it did such
a good job there

103
00:04:27,266 --> 00:04:28,968
it got a seven year
mission extension,

104
00:04:29,001 --> 00:04:31,504
the Cassini Solstice mission,

which was so named

105
00:04:31,537 --> 00:04:33,072
because it extended the
mission all the way out

106
00:04:33,105 --> 00:04:35,474
to the northern
summer solstice,

107
00:04:35,507 --> 00:04:40,746
and that ended
six months ago.

108
00:04:40,779 --> 00:04:44,116
So here you can see the entire
Solstice mission trajectory.

109
00:04:44,149 --> 00:04:46,919
This is from when it started
in October of 2010

110
00:04:46,952 --> 00:04:50,623
up until the end
of November of 2016.

111
00:04:50,656 --> 00:04:53,993
And at that time, Cassini
began it's penultimate phase,

112
00:04:54,026 --> 00:04:55,461
which were the
ring-grazing orbits.

113
00:04:55,494 --> 00:04:58,664
These lighter gray
orbits that you see here.

114
00:04:58,697 --> 00:05:01,033
And so, this was a

series of 20 orbits.

115
00:05:01,066 --> 00:05:04,603
The farthest they get from
Saturn is out near Titan's orbit

116
00:05:04,636 --> 00:05:07,640
and the closest they get is
just outside the ring system,

117
00:05:07,673 --> 00:05:11,243
Saturn's F Ring, thus their name
the ring-grazing orbits.

118
00:05:11,276 --> 00:05:15,614
So these 20 orbits took a little
over a week to complete.

119
00:05:15,647 --> 00:05:17,917
They started at the beginning
of December of 2016

120
00:05:17,950 --> 00:05:22,822
all the way through
the middle of April, 2017.

121
00:05:22,855 --> 00:05:26,359
And here is the last of
those ring-grazing orbits.

122
00:05:26,392 --> 00:05:28,928
So, it's the last time that
it's going to pass outside

123
00:05:28,961 --> 00:05:30,463
Saturn's ring system.

124
00:05:30,496 --> 00:05:32,665
And this time, as it comes
back out towards Titan's orbit,

125
00:05:32,698 --> 00:05:34,667
Titan's actually
going to be there

126
00:05:34,700 --> 00:05:36,469
and what we're going to do
is we're going to form

127
00:05:36,502 --> 00:05:40,005
our last targeted
Titan flyby.

128
00:05:40,038 --> 00:05:42,908
This is 127th close
flyby of Titan.

129
00:05:42,941 --> 00:05:45,177
We came within 600 miles
of the moon

130
00:05:45,210 --> 00:05:47,913
and that changed
our orbit just enough

131
00:05:47,946 --> 00:05:50,182
that now as it comes back
through towards Saturn,

132
00:05:50,215 --> 00:05:52,718
instead of being outside
the ring system, it's inside,

133
00:05:52,751 --> 00:05:58,124
and it'll be between
the planet and the rings.

134
00:05:58,157 --> 00:06:01,660
And so, that dive happened
on April 26th, 2017,

135
00:06:01,693 --> 00:06:08,300
so just about
a year ago now.

136
00:06:08,333 --> 00:06:10,870
Okay, so that's what started
Cassini's grand finale.

137
00:06:10,903 --> 00:06:13,038
It's a series of 22
and a half orbits

138
00:06:13,071 --> 00:06:14,840
that dove between
Saturn and the rings

139
00:06:14,873 --> 00:06:16,942
in a gap of about
1,200 miles wide,

140
00:06:16,975 --> 00:06:19,211
and it did it at
76,000 miles per hour,

141
00:06:19,244 --> 00:06:22,815
which would get you to D.C.
in about three minutes,

142
00:06:22,848 --> 00:06:24,116
or to the moon
in a couple days.

143
00:06:24,149 --> 00:06:25,985
So, it was
going pretty fast.

144
00:06:26,018 --> 00:06:29,422
Also, periodically, as it came
back out to Titan's orbit,

145
00:06:29,455 --> 00:06:32,124
Titan would be there far away,
not as close at the 600 miles

146
00:06:32,157 --> 00:06:33,526
but it would
give it a little tug

147
00:06:33,559 --> 00:06:36,429
and change exactly where
we flew through the gap.

148
00:06:36,462 --> 00:06:37,963
The last of those
distant flybys,

149
00:06:37,996 --> 00:06:40,733
which is happening right there,
was on September 11th,

150
00:06:40,766 --> 00:06:43,068
and that's where Titan
gave us a goodbye kiss,

151
00:06:43,101 --> 00:06:45,604
some may call it a shove,
and it actually made it,

152
00:06:45,637 --> 00:06:48,674
so instead of passing safely
through the gap four days later,

153
00:06:48,707 --> 00:06:50,976
on September 15th, 2017,

154
00:06:51,009 --> 00:06:54,747
we are permanently
captured by Saturn.

155
00:06:54,780 --> 00:06:57,183
Okay, so one of the first
questions I get

156
00:06:57,216 --> 00:06:58,918
when I tell people
that we did this,

157
00:06:58,951 --> 00:07:01,086
they're like,
"Well, why did you do that?

158
00:07:01,119 --> 00:07:03,522
"Cassini was a
cool spacecraft."

159
00:07:03,555 --> 00:07:05,291
So, first, why we had
to do it at all

160
00:07:05,324 --> 00:07:07,293
was for
planetary protection.

161
00:07:07,326 --> 00:07:09,895
The Saturn system has
two protected moons

162
00:07:09,928 --> 00:07:12,665
and protected just means that
they have environments

163
00:07:12,698 --> 00:07:15,668
that could possibly be
habitable for life.

164
00:07:15,701 --> 00:07:18,003
So, one of those
is Enceladus.

165
00:07:18,036 --> 00:07:19,271
Enceladus is pretty cool.

166
00:07:19,304 --> 00:07:22,341
It has a global subsurface
ocean under a thick ice shell

167
00:07:22,374 --> 00:07:25,077
and it's in direct contact
with an active rocky core,

168
00:07:25,110 --> 00:07:27,713
very much like
environments found in our--

169
00:07:27,746 --> 00:07:30,783
near our deep
ocean events.

170
00:07:30,816 --> 00:07:33,419
And then, there's Titan
with its thick atmosphere.

171
00:07:33,452 --> 00:07:36,055
It has rivers and lakes of
liquid methane and ethane.

172
00:07:36,088 --> 00:07:38,624
And both of these are
thought to be environments

173
00:07:38,657 --> 00:07:40,426
where we could find life,
and because of that

174
00:07:40,459 --> 00:07:42,194
it means we have to
absolutely ensure

175

00:07:42,227 --> 00:07:44,196
that Cassini would
never impact these

176
00:07:44,229 --> 00:07:46,699
and possibly contaminate
those environments

177
00:07:46,732 --> 00:07:47,733
with our own life.

178
00:07:47,766 --> 00:07:48,801
Because the last thing
we'd want to do

179
00:07:48,834 --> 00:07:51,003
is send a future mission
there and discover life,

180
00:07:51,036 --> 00:07:53,305
only to find out, no,
that's life that we just

181
00:07:53,338 --> 00:07:55,441
brought when we crashed
Cassini into one of them.

182
00:07:55,474 --> 00:07:57,943
So, that meant Cassini
needed to be removed

183
00:07:57,976 --> 00:08:01,080
from the Saturn system
one way or the other,

184
00:08:01,113 --> 00:08:05,417
either through leaving it or
through crashing into Saturn.

185
00:08:05,450 --> 00:08:07,720

The reason it needed
to happen now

186
00:08:07,753 --> 00:08:11,891
is actually because of
Cassini's gas tank.

187
00:08:11,924 --> 00:08:13,526
We were running
low on fuel.

188
00:08:13,559 --> 00:08:15,995
So, here's our spacecraft

189
00:08:16,028 --> 00:08:18,030
and this is not
an engineering representation,

190
00:08:18,063 --> 00:08:20,266
but a good representation
of our gas tank

191
00:08:20,299 --> 00:08:23,269
and we're going to fill
this up with gas right now.

192
00:08:23,302 --> 00:08:25,170
I should say, when I asked
my wife what color

193
00:08:25,203 --> 00:08:27,339
is Cassini's
gas she said,

194
00:08:27,372 --> 00:08:29,408
"It's orange.
It's definitely orange."

195
00:08:29,441 --> 00:08:32,678
So, we're going to fill it up

now with definitely orange.

196
00:08:32,711 --> 00:08:35,681
It's a little like cerulean
blue, but definitely orange.

197
00:08:35,714 --> 00:08:36,949
So there it is.

198
00:08:36,982 --> 00:08:39,051
And another nice thing about
it actually being orange,

199
00:08:39,084 --> 00:08:42,354
well, think of this
as 100 oranges, okay?

200
00:08:42,387 --> 00:08:45,758
So, this is 100 oranges worth
of fuel, okay, at launch.

201
00:08:45,791 --> 00:08:49,295
Okay, now, just
getting out to Saturn

202
00:08:49,328 --> 00:08:53,732
we used 24 oranges,
so we're down to 76.

203
00:08:53,765 --> 00:08:55,668
Okay, now we want to go into
orbit around Saturn,

204
00:08:55,701 --> 00:08:58,704
all right, well that's
another 45 oranges.

205
00:08:58,737 --> 00:09:00,506
Now, we're down to 31.

206
00:09:00,539 --> 00:09:03,442
Four years after the start
of our prime mission,

207
00:09:03,475 --> 00:09:06,211
used another 17,
only 14 left.

208
00:09:06,244 --> 00:09:07,279
Okay, two year
mission extension,

209
00:09:07,312 --> 00:09:10,583
we can do this,
8.5 oranges.

210
00:09:10,616 --> 00:09:12,818
Okay, seven year
mission extension,

211
00:09:12,851 --> 00:09:15,321
we've got 5.5
oranges left.

212
00:09:15,354 --> 00:09:18,057
All right, well, we can use
them all, and okay,

213
00:09:18,090 --> 00:09:19,658
now we have the ring-grazing
orbits and the grand finale

214
00:09:19,691 --> 00:09:22,628
for the last year and
I think you can see

215
00:09:22,661 --> 00:09:24,129
some propellant
still in there.

216
00:09:24,162 --> 00:09:27,399
That's-- Oranges have
about 10 to 11 wedges,

217
00:09:27,432 --> 00:09:29,535
that's a common
knowledge, right?

218
00:09:29,568 --> 00:09:33,906
Okay, that's one
orange worth of fuel--

219
00:09:33,939 --> 00:09:36,008
Or, one orange wedge
worth of fuel,

220
00:09:36,041 --> 00:09:37,109
that's how much
we had left.

221
00:09:37,142 --> 00:09:41,413
We started with 100 oranges,
we ate 99,

222
00:09:41,446 --> 00:09:43,682
opened that 100th
and ate 10 of the 11 wedges.

223
00:09:43,715 --> 00:09:45,751
That's what
we were left with.

224
00:09:45,784 --> 00:09:51,824
Okay, so that's what we flew
the last year of the mission on.

225
00:09:51,857 --> 00:09:54,026
Okay, and so why did we
do it by going in to Saturn?

226
00:09:54,059 --> 00:09:55,527
Like I said, we
could've tried to

227
00:09:55,560 --> 00:09:57,496
get out of
the Saturn system,

228
00:09:57,529 --> 00:10:00,766
but by going into Saturn
it gave us the opportunity

229
00:10:00,799 --> 00:10:02,901
to collect a bunch
of unique science.

230
00:10:02,934 --> 00:10:04,536
So, we were going closer to
Saturn than ever before

231
00:10:04,569 --> 00:10:07,339
so we could get
lots of information

232
00:10:07,372 --> 00:10:09,041
about Saturn's
internal structure,

233
00:10:09,074 --> 00:10:11,343
like gravity,
magnetic field.

234
00:10:11,376 --> 00:10:13,178
We were also going inside
the rings for the first time,

235
00:10:13,211 --> 00:10:14,913
which would let us
see their structure

236
00:10:14,946 --> 00:10:15,814
and possibly
estimate their mass

237
00:10:15,847 --> 00:10:18,884
and get an idea of
how old they are.

238
00:10:18,917 --> 00:10:20,152
Also, because of
how close we were,

239
00:10:20,185 --> 00:10:22,087
we were flying
through the auroras,

240
00:10:22,120 --> 00:10:24,556
through radiation belts,
through ring dust,

241
00:10:24,589 --> 00:10:26,592
so we were going to
get direct measurements

242
00:10:26,625 --> 00:10:28,627
of all of those things.

243
00:10:28,660 --> 00:10:30,596
And then, simply because
we were so close,

244
00:10:30,629 --> 00:10:32,231
we'd get really
high resolution images,

245
00:10:32,264 --> 00:10:33,966
and these images
are amazing

246

00:10:33,999 --> 00:10:36,268
and these aren't even the ones
from the grand finale.

247
00:10:36,301 --> 00:10:42,474
We got better, higher
resolution images than these.

248
00:10:42,507 --> 00:10:45,444
Okay, so that's a long windup
of the grand finale

249
00:10:45,477 --> 00:10:46,779
and why we did it.

250
00:10:46,812 --> 00:10:49,815
As Cassini's Mission Planner
for the four years

251
00:10:49,848 --> 00:10:51,550
before the end
of mission

252
00:10:51,583 --> 00:10:54,720
I spent all my time
worrying about this gap.

253
00:10:54,753 --> 00:10:58,257
Minding the gap-- So the
region between the rings

254
00:10:58,290 --> 00:11:01,527
and the planet, and here you can
see where the 22 orbits passed

255
00:11:01,560 --> 00:11:03,062
and you can see the final
orbit in orange

256
00:11:03,095 --> 00:11:06,065

that actually
impacts Saturn.

257
00:11:06,098 --> 00:11:08,867
And you can compare that
to an actual image

258
00:11:08,900 --> 00:11:15,407
that was taken
by Cassini.

259
00:11:15,440 --> 00:11:17,676
And so, you can see
we're flying

260
00:11:17,709 --> 00:11:20,879
right where
that D Ring dust

261
00:11:20,912 --> 00:11:23,115
and the atmospheric haze
just sort of fade into

262
00:11:23,148 --> 00:11:24,650
the background
of the image.

263
00:11:24,683 --> 00:11:30,155
So, like really going right
where we think it's safest.

264
00:11:30,188 --> 00:11:31,423
And so, those really
were our two concerns

265
00:11:31,456 --> 00:11:32,991
for these orbits--

266
00:11:33,024 --> 00:11:35,794
how much dust was the spacecraft

going to encounter

267
00:11:35,827 --> 00:11:37,763
and how thick of an atmosphere
was it going to fly through.

268
00:11:37,796 --> 00:11:39,398
And that meant that
each of the 22 orbits

269
00:11:39,431 --> 00:11:41,600
could be characterized
by two points.

270
00:11:41,633 --> 00:11:43,902
The first was
the ring-plane crossings,

271
00:11:43,935 --> 00:11:45,337
so this is how high
into the ring-plane

272
00:11:45,370 --> 00:11:48,140
did they go and how much
dust was potentially

273
00:11:48,173 --> 00:11:50,976
going to impact
the spacecraft.

274
00:11:51,009 --> 00:11:54,313
Now, the second point was how
close did they get to Saturn.

275
00:11:54,346 --> 00:11:56,215
They're at minimum altitude,
how much atmosphere

276
00:11:56,248 --> 00:11:59,184
were they going to fly through

and how much drag and torque

277
00:11:59,217 --> 00:12:04,089
was going to be imparted
on the spacecraft.

278
00:12:04,122 --> 00:12:05,290
And you can get a little
better idea

279
00:12:05,323 --> 00:12:08,360
of how these are distributed
through the gap

280
00:12:08,393 --> 00:12:10,295
by looking at them
down from above.

281
00:12:10,328 --> 00:12:12,564
So now you can see
Saturn down below,

282
00:12:12,597 --> 00:12:13,866
we got
the rings up above,

283
00:12:13,899 --> 00:12:16,368
and you can see
the orbits going through.

284
00:12:16,401 --> 00:12:18,237
And what's neat about
looking at it in this--

285
00:12:18,270 --> 00:12:19,705
from this perspective,

286
00:12:19,738 --> 00:12:21,640
these are actually
in chronological order,

287
00:12:21,673 --> 00:12:24,676
so the first one's on the left
and the last one's on the right.

288
00:12:24,709 --> 00:12:27,179
And so, you can see each of
the ring-plane crossings

289
00:12:27,212 --> 00:12:29,414
and the minimum
altitude points.

290
00:12:29,447 --> 00:12:31,450
You can also see how
there's the variations

291
00:12:31,483 --> 00:12:32,885
and those are caused,
like I said,

292
00:12:32,918 --> 00:12:36,288
by the distant Titan flybys
that we're having periodically

293
00:12:36,321 --> 00:12:37,923
as we flew
the grand finale.

294
00:12:37,956 --> 00:12:40,526
And to get a better idea
of those variations,

295
00:12:40,559 --> 00:12:42,795
we can take all those points
and plot them up.

296
00:12:42,828 --> 00:12:44,797
I'm an engineer, I've got
to put things into Excel,

297
00:12:44,830 --> 00:12:47,399
I can't just
look at pictures.

298
00:12:47,432 --> 00:12:49,802
And so, now we have time
on the horizontal axis,

299
00:12:49,835 --> 00:12:51,036
starting at
the end of April

300
00:12:51,069 --> 00:12:52,938
going to the middle
of September.

301
00:12:52,971 --> 00:12:56,074
Again, D Ring dust up above,
atmosphere down below,

302
00:12:56,107 --> 00:12:58,644
and we have distance from
the center of Saturn

303
00:12:58,677 --> 00:13:00,779
and kilometers
on the horizontal axis.

304
00:13:00,812 --> 00:13:02,447
And I know everybody is
familiar with kilometers

305
00:13:02,480 --> 00:13:05,417
and 63,000 kilometers
makes perfect sense

306
00:13:05,450 --> 00:13:06,552
to everybody
in the room.

307
00:13:06,585 --> 00:13:08,620
But just in case is doesn't,
we're also familiar

308
00:13:08,653 --> 00:13:10,355
with how wide
the Earth is, right?

309
00:13:10,388 --> 00:13:11,757
So that's about
five Earth diameters

310
00:13:11,790 --> 00:13:13,458
from the center
of Saturn.

311
00:13:13,491 --> 00:13:15,294
Another very
common measurement.

312
00:13:15,327 --> 00:13:17,963
Okay, so these are
our ring-plane crossings

313
00:13:17,996 --> 00:13:19,798
at minimum altitudes.

314
00:13:19,831 --> 00:13:21,900
You can see at the end we get
low in the atmosphere,

315
00:13:21,933 --> 00:13:23,635
but for the 17 orbits
before that

316
00:13:23,668 --> 00:13:25,737
we're actually
much higher up

317
00:13:25,770 --> 00:13:28,574
and we're more concerned
about the dust environment

318
00:13:28,607 --> 00:13:29,842
than the atmosphere.

319
00:13:29,875 --> 00:13:32,110
And so, we're going to
start by looking at that.

320
00:13:32,143 --> 00:13:33,946
So what do we know about
the dust environment?

321
00:13:33,979 --> 00:13:35,647
This is literally
everything we knew about

322
00:13:35,680 --> 00:13:36,682
the dust environment.

323
00:13:36,715 --> 00:13:39,785
This is our best picture
of the D Ring dust.

324
00:13:39,818 --> 00:13:41,553
And so, what we did
is we took this picture

325
00:13:41,586 --> 00:13:44,723
and we overexposed it and
you can draw a line and say,

326
00:13:44,756 --> 00:13:47,993
"Hey, outside that
line there's dust.

327
00:13:48,026 --> 00:13:50,829

"Inside that line,
we're not really sure,

328
00:13:50,862 --> 00:13:52,364
"but we think
there's not dust."

329
00:13:52,397 --> 00:13:55,367
And if we go back to--
Oh, and compare that

330
00:13:55,400 --> 00:13:59,071
to the range through
which we flew the orbits,

331
00:13:59,104 --> 00:14:00,205
you can see that
our highest orbit's

332
00:14:00,238 --> 00:14:01,440
actually one above it.

333
00:14:01,473 --> 00:14:04,309
They went into a region that
we knew there'd be dust.

334
00:14:04,342 --> 00:14:08,013
And so, going back to
our corridor chart

335
00:14:08,046 --> 00:14:09,948
and adding that line,
we can see it was

336
00:14:09,981 --> 00:14:11,316
actually our
four highest crossings.

337
00:14:11,349 --> 00:14:13,785
So, those four crossings

flew through a region

338
00:14:13,818 --> 00:14:15,721
that we knew there
would be dust.

339
00:14:15,754 --> 00:14:16,788
And so,
what does that mean?

340
00:14:16,821 --> 00:14:18,290
Well, it doesn't particularly
mean a whole lot

341
00:14:18,323 --> 00:14:20,993
because Saturn
is a dusty place.

342
00:14:21,026 --> 00:14:24,663
We've flown through dust a lot
before, and so whenever the dust

343
00:14:24,696 --> 00:14:27,165
was such that it could've
posed a risk to the spacecraft

344
00:14:27,198 --> 00:14:29,067
what we would do is we'd
take the entire thing--

345
00:14:29,100 --> 00:14:30,435
again, you can
look at it over there.

346
00:14:30,468 --> 00:14:32,638
We'd take that huge antenna
and we'd turn it into

347
00:14:32,671 --> 00:14:35,207
the direction that the dust was

coming from and you can see

348
00:14:35,240 --> 00:14:38,677
that that shields all of
the spacecraft behind it

349
00:14:38,710 --> 00:14:40,545
so all of our sensitive
electronics and instruments

350
00:14:40,578 --> 00:14:45,083
were protected behind
the high gain antenna.

351
00:14:45,116 --> 00:14:49,521
So, good, we have a shield,
we will use it.

352
00:14:49,554 --> 00:14:51,423
So, there we go.

353
00:14:51,456 --> 00:14:55,227
Our four highest
crossings were shielded.

354
00:14:55,260 --> 00:14:58,030
But then the question is,
well, what about

355
00:14:58,063 --> 00:15:00,565
those other 13 crossings?

356
00:15:00,598 --> 00:15:03,402
Like I said, if we go
back to this picture,

357
00:15:03,435 --> 00:15:04,603
we don't necessarily
know what's happening

358
00:15:04,636 --> 00:15:07,506
inside that purple line.

359
00:15:07,539 --> 00:15:09,207
It could be that
there's no dust there,

360
00:15:09,240 --> 00:15:11,376
but it could be the nature
of the dust is changing

361
00:15:11,409 --> 00:15:12,611
and reflecting less light.

362
00:15:12,644 --> 00:15:15,981
As an example, think about
if it's nighttime

363
00:15:16,014 --> 00:15:17,716
and it's foggy
and you're driving,

364
00:15:17,749 --> 00:15:19,084
you have
your headlights on.

365
00:15:19,117 --> 00:15:21,320
The fog is just reflecting
everything back at you,

366
00:15:21,353 --> 00:15:22,454
all you can see is fog.

367
00:15:22,487 --> 00:15:23,956
You can see the
fog very easily.

368
00:15:23,989 --> 00:15:26,525
But then, if it's

raining instead of foggy,

369
00:15:26,558 --> 00:15:28,794
you have still lots of
droplets in the air

370
00:15:28,827 --> 00:15:29,928
but they're much bigger

371
00:15:29,961 --> 00:15:31,697
and they don't reflect
as much light back to you.

372
00:15:31,730 --> 00:15:35,734
So, we couldn't know for sure
if it was foggy outside

373
00:15:35,767 --> 00:15:38,203
and not foggy inside,
or if instead of foggy

374
00:15:38,236 --> 00:15:40,639
it just started raining and
if it just started raining

375
00:15:40,672 --> 00:15:43,108
that meant there were large
dust particles there

376
00:15:43,141 --> 00:15:46,645
that could pose
a risk to the spacecraft.

377
00:15:46,678 --> 00:15:50,449
So given that information, I
know what you're all thinking.

378
00:15:50,482 --> 00:15:53,385
Okay, well, we have a shield,
let's just use this.

379
00:15:53,418 --> 00:15:55,387
We're going to
Captain America this sucker

380
00:15:55,420 --> 00:15:57,522
and we're good,
we're done.

381
00:15:57,555 --> 00:15:59,791
And if you thought
that, "Great."

382
00:15:59,824 --> 00:16:01,960
You'd probably make a very
good spacecraft engineer,

383
00:16:01,993 --> 00:16:03,962
but you'd probably upset
a lot of scientists.

384
00:16:03,995 --> 00:16:07,933
The reason being, everything
on Cassini is body fixed,

385
00:16:07,966 --> 00:16:09,901
it can't point in two
directions at once.

386
00:16:09,934 --> 00:16:12,037
So, if we're using our antenna
as a shield it means

387
00:16:12,070 --> 00:16:13,405
the cameras can't
look over here

388
00:16:13,438 --> 00:16:14,840
at this very
interesting thing.

389
00:16:14,873 --> 00:16:17,909
And so, while that may not
seem like a big problem,

390
00:16:17,942 --> 00:16:20,545
because hey this is only
for ring-plane crossing,

391
00:16:20,578 --> 00:16:23,482
that's just this small
little piece of the orbit.

392
00:16:23,515 --> 00:16:27,386
Cassini is the size of a
school bus and it's not

393
00:16:27,419 --> 00:16:30,655
very nimble and it doesn't
have very large thrusters.

394
00:16:30,688 --> 00:16:31,823
And so, what that means is it
takes a lot of time

395
00:16:31,856 --> 00:16:33,025
to turn the spacecraft,

396
00:16:33,058 --> 00:16:35,027
and when you
factor that in the time to

397
00:16:35,060 --> 00:16:38,296
turn to that shielded
direction and then the time

398
00:16:38,329 --> 00:16:40,732
to turn back to our nice
science friendly attitude,

399
00:16:40,765 --> 00:16:41,733
suddenly we wipe out

400
00:16:41,766 --> 00:16:44,436
all of our high
priority science areas.

401
00:16:44,469 --> 00:16:48,407
So, okay, we know
this is a bad idea,

402
00:16:48,440 --> 00:16:50,208
but it's possible
this is a bad idea too

403
00:16:50,241 --> 00:16:51,576
because we don't
actually know what's there.

404
00:16:51,609 --> 00:16:54,146
So what we did was we came up
with a contingency plan

405
00:16:54,179 --> 00:16:56,915
that said, hey,
we're going to shield

406
00:16:56,948 --> 00:16:59,017
that very first crossing
and when we do that

407
00:16:59,050 --> 00:17:00,018
we're going to
use an instrument,

408
00:17:00,051 --> 00:17:01,953
the radio and plasma wave
science instrument

409

00:17:01,986 --> 00:17:04,122
to detect the dust particles
that are there.

410
00:17:04,155 --> 00:17:05,857
When the dust hits the
spacecraft it creates

411
00:17:05,890 --> 00:17:08,026
plasma waves and that instrument
can detect those waves

412
00:17:08,059 --> 00:17:13,098
and from that we can see if
the environment is safe or not.

413
00:17:13,131 --> 00:17:17,369
But, the catch here is that
those-- that first orbit

414
00:17:17,402 --> 00:17:20,906
and that second orbit are only
six and a half days apart,

415
00:17:20,939 --> 00:17:22,674
so we had to get the data back,
analyze it, and decide

416
00:17:22,707 --> 00:17:24,709
what to do with the spacecraft
in six and a half days

417
00:17:24,742 --> 00:17:27,646
if we were going to keep
everything else unprotected.

418
00:17:27,679 --> 00:17:28,914
And so, this is what
this looked like.

419

00:17:28,947 --> 00:17:31,917
So here we have our first
ring-plane crossing in green,

420
00:17:31,950 --> 00:17:34,886
coming around to the second
one in red, and then we have

421
00:17:34,919 --> 00:17:37,089
all of our communications
passes in blue

422
00:17:37,122 --> 00:17:39,291
out on the far side.

423
00:17:39,324 --> 00:17:42,294
And so, after we came through
that first crossing it took

424
00:17:42,327 --> 00:17:44,196
a whole day before we even
got to talk to the spacecraft,

425
00:17:44,229 --> 00:17:45,630
so that wiped a day out.

426
00:17:45,663 --> 00:17:46,665
We only have
five days left.

427
00:17:46,698 --> 00:17:50,435
The spacecraft gave us back
all of the radio

428
00:17:50,468 --> 00:17:53,338
and plasma wave science
instrument data.

429
00:17:53,371 --> 00:17:56,641
And then, we wanted two

opportunities to tell

430
00:17:56,674 --> 00:18:00,078
the spacecraft if it needed
to go to the safe attitude,

431
00:18:00,111 --> 00:18:01,480
and so that's
what you see there,

432
00:18:01,513 --> 00:18:03,048
those next
two opportunities.

433
00:18:03,081 --> 00:18:06,518
And had it seen hazardous
dust, it could've turned

434
00:18:06,551 --> 00:18:11,423
the spacecraft and gone in
the next one shielded.

435
00:18:11,456 --> 00:18:12,524
Okay, so that
was the plan.

436
00:18:12,557 --> 00:18:13,558
That was
our contingency plan.

437
00:18:13,591 --> 00:18:15,193
And what
actually happened?

438
00:18:15,226 --> 00:18:17,963
Well, in order to
understand what happened

439
00:18:17,996 --> 00:18:20,198
let's take a step back to

our ring-grazing orbit.

440
00:18:20,231 --> 00:18:22,801
Okay, these are the 20 orbits
before the grand finale.

441
00:18:22,834 --> 00:18:26,071
During the third
ring-grazing orbit

442
00:18:26,104 --> 00:18:27,305
the radio and plasma wave
science instrument

443
00:18:27,338 --> 00:18:29,674
was on and it
took data for us.

444
00:18:29,707 --> 00:18:32,944
And the data it gives us is
this and what this is

445
00:18:32,977 --> 00:18:36,248
is time on
the horizontal axis,

446
00:18:36,281 --> 00:18:39,351
it is dust particle size
on the vertical axis,

447
00:18:39,384 --> 00:18:42,654
and it is the density
we see at that time

448
00:18:42,687 --> 00:18:45,457
at that size of that
dust particle.

449
00:18:45,490 --> 00:18:48,326
So, this is how thick of a

dust cloud do we fly through?

450
00:18:48,359 --> 00:18:50,662
And so, you can see on this
third ring-grazing orbit,

451
00:18:50,695 --> 00:18:52,264
the ring crossing
should probably

452
00:18:52,297 --> 00:18:53,265
jump right
out at it you.

453
00:18:53,298 --> 00:18:55,534
What happened,
happened right there.

454
00:18:55,567 --> 00:18:59,237
And on this scale of less
dense to more dense,

455
00:18:59,270 --> 00:19:00,939
the red that
we're seeing here

456
00:19:00,972 --> 00:19:03,208
actually isn't even
dangerous to the spacecraft.

457
00:19:03,241 --> 00:19:06,211
So this is what we saw when we
went through the first time.

458
00:19:06,244 --> 00:19:07,379
We wouldn't even
have to shield it.

459
00:19:07,412 --> 00:19:09,948
It'd have to go into a nice

deep, dark maroon for us

460
00:19:09,981 --> 00:19:11,516
to be worried about it.

461
00:19:11,549 --> 00:19:13,885
So, what did we see?

462
00:19:13,918 --> 00:19:16,454
We saw this.

463
00:19:16,487 --> 00:19:17,956
We almost literally
saw nothing.

464
00:19:17,989 --> 00:19:19,691
You can't even tell a
ring-plane crossing happened.

465
00:19:19,724 --> 00:19:23,962
It happened there, but
there was just no dust.

466
00:19:23,995 --> 00:19:26,631
And so, we didn't have to
invoke the contingency.

467
00:19:26,664 --> 00:19:29,401
The scientists-- there
was much rejoicing.

468
00:19:29,434 --> 00:19:31,469
And so, this is
what it looked like.

469
00:19:31,502 --> 00:19:34,673
And in fact, we didn't see
a noticeable amount of dust

470

00:19:34,706 --> 00:19:38,143
until that first
orbit above the line,

471
00:19:38,176 --> 00:19:41,479
and there the dust
wasn't hazardous.

472
00:19:41,512 --> 00:19:43,682
And so, it turns out we did
use our contingency,

473
00:19:43,715 --> 00:19:46,284
but we used it
in reverse.

474
00:19:46,317 --> 00:19:48,653
We took-- we were able to
take that third orbit

475
00:19:48,686 --> 00:19:52,657
and unshield it,
and what that meant was--

476
00:19:52,690 --> 00:19:54,125
on the left we have
the original design,

477
00:19:54,158 --> 00:19:56,261
on the right we have
what we did.

478
00:19:56,294 --> 00:19:58,663
And so, instead of turning
and pointing straight down

479
00:19:58,696 --> 00:20:01,099
to look at the dust
and shield us as we came in,

480

00:20:01,132 --> 00:20:02,834
we kept rotating past.

481
00:20:02,867 --> 00:20:05,837
And this let our cosmic
dust analyzer peek out

482
00:20:05,870 --> 00:20:09,708
from beside the antenna
and directly sample

483
00:20:09,741 --> 00:20:11,042
the D Ring
dust particles.

484
00:20:11,075 --> 00:20:13,345
So, we were actually able
to get more science

485
00:20:13,378 --> 00:20:17,916
than we thought
we were going to.

486
00:20:17,949 --> 00:20:20,285
Okay.

487
00:20:20,318 --> 00:20:24,823
So, that brings us
back to our corridor.

488
00:20:24,856 --> 00:20:25,991
And now, now we're
done with dust.

489
00:20:26,024 --> 00:20:27,025
We're done with
those first 17.

490
00:20:27,058 --> 00:20:29,661
Nobody's worried about

dust anymore, right?

491
00:20:29,694 --> 00:20:31,029
Okay, good, good.

492
00:20:31,062 --> 00:20:33,365
No one's
worried about dust.

493
00:20:33,398 --> 00:20:35,767
Now we're worried about the
atmosphere for those last five

494
00:20:35,800 --> 00:20:37,202
and this is not
the first time Cassini

495
00:20:37,235 --> 00:20:38,603
flew through atmosphere.

496
00:20:38,636 --> 00:20:39,771
Titan has a very
thick atmosphere

497
00:20:39,804 --> 00:20:44,242
and we flew by Cassini
I would say lots of times.

498
00:20:44,275 --> 00:20:47,112
So again, 127 times
we flew by Cassini

499
00:20:47,145 --> 00:20:52,183
and during those
low Titan flybys

500
00:20:52,216 --> 00:20:55,720
we switched from
reaction remote control

501
00:20:55,753 --> 00:20:57,355
to thruster control.

502
00:20:57,388 --> 00:20:59,858
And the reason we do that
is the thrusters can provide

503
00:20:59,891 --> 00:21:02,260
about ten times
the control authority

504
00:21:02,293 --> 00:21:03,762
that the reaction
wheels do.

505
00:21:03,795 --> 00:21:05,330
And that means that
we can fly through

506
00:21:05,363 --> 00:21:06,798
a ten times
thicker atmosphere

507
00:21:06,831 --> 00:21:08,700
and still point the spacecraft
in the direction

508
00:21:08,733 --> 00:21:11,036
we wanted to point it.

509
00:21:11,069 --> 00:21:12,804
Now, if the atmosphere
was so thick

510
00:21:12,837 --> 00:21:14,706
that it would
overwhelm our thrusters,

511
00:21:14,739 --> 00:21:17,609

what we could actually do
is perform a maneuver,

512
00:21:17,642 --> 00:21:18,877
change the trajectory,
and fly through

513
00:21:18,910 --> 00:21:20,478
a less dense part
of the atmosphere.

514
00:21:20,511 --> 00:21:22,681
So, these are our two
options when it comes to

515
00:21:22,714 --> 00:21:26,251
dealing with
Saturn's atmosphere.

516
00:21:26,284 --> 00:21:27,619
So what did
we have to do?

517
00:21:27,652 --> 00:21:29,654
Well, first, we needed
to know what do we know

518
00:21:29,687 --> 00:21:31,790
about Saturn's
atmosphere at the time.

519
00:21:31,823 --> 00:21:33,425
Well, everything
we knew came from

520
00:21:33,458 --> 00:21:34,859
solar and
stellar occultations,

521
00:21:34,892 --> 00:21:38,430

which is having Cassini
watch the Sun and stars

522
00:21:38,463 --> 00:21:39,864
set into
Saturn's atmosphere

523
00:21:39,897 --> 00:21:43,168
and see how their light
gets filtered through it.

524
00:21:43,201 --> 00:21:47,672
And from that, the scientists
derived a density model.

525
00:21:47,705 --> 00:21:50,342
So this is-- this gives us
density as a function

526
00:21:50,375 --> 00:21:53,178
of radius
and latitude on Saturn.

527
00:21:53,211 --> 00:21:56,881
And so, we can use that
model and go back to

528
00:21:56,914 --> 00:22:00,485
the proximal corridor and start
adding some boundaries.

529
00:22:00,518 --> 00:22:04,422
So, the first is our
spacecraft capture boundary,

530
00:22:04,455 --> 00:22:06,791
so this is the region that
we had to get to in order to

531
00:22:06,824 --> 00:22:10,128

ensure that Cassini would not
come back out of Saturn again.

532
00:22:10,161 --> 00:22:13,698
And you can see the very last
plus on September 15th

533
00:22:13,731 --> 00:22:16,868
is well below
that region.

534
00:22:16,901 --> 00:22:20,238
Above that, we have the tumble
boundary for thrusters,

535
00:22:20,271 --> 00:22:22,741
so this is the point where
the density of the atmosphere

536
00:22:22,774 --> 00:22:25,377
is such that if we were
on thruster control

537
00:22:25,410 --> 00:22:26,411
we couldn't point
in the direction

538
00:22:26,444 --> 00:22:29,447
we wanted to point and
we'd start to drift.

539
00:22:29,480 --> 00:22:30,815
And then, above that,
we have that same boundary

540
00:22:30,848 --> 00:22:32,083
but for
the reaction wheels,

541
00:22:32,116 --> 00:22:34,519

so this is where the atmosphere
is ten times less dense

542
00:22:34,552 --> 00:22:36,020
than the boundary
for the thrusters.

543
00:22:36,053 --> 00:22:39,357
And you can see
that our final five

544
00:22:39,390 --> 00:22:41,726
are right between
those two.

545
00:22:41,759 --> 00:22:45,363
So what that meant was
we flew those last five

546
00:22:45,396 --> 00:22:49,200
on thruster control, and
you also see that two others

547
00:22:49,233 --> 00:22:51,102
were on thruster control
earlier than that.

548
00:22:51,135 --> 00:22:52,837
That wasn't because of
atmosphere, it was actually

549
00:22:52,870 --> 00:22:55,373
because of science
observations that wanted

550
00:22:55,406 --> 00:22:58,543
to take advantage of the higher
turn rates that were allowed

551
00:22:58,576 --> 00:23:03,515

thanks to the thrusters
higher torque.

552
00:23:03,548 --> 00:23:07,185
Okay, so to get an idea of
just how close we're coming

553
00:23:07,218 --> 00:23:09,254
to not just having to use
thrusters but potentially

554
00:23:09,287 --> 00:23:12,791
having to use a maneuver
and get out of this region.

555
00:23:12,824 --> 00:23:16,161
We can zoom up on
the final five.

556
00:23:16,194 --> 00:23:19,030
And so, here you can see
about how close we're getting

557
00:23:19,063 --> 00:23:20,398
to the tumble point.

558
00:23:20,431 --> 00:23:26,871
And so, we thought we had
about 120 miles of margin

559
00:23:26,904 --> 00:23:30,008
between where we were going to
fly and where we would tumble.

560
00:23:30,041 --> 00:23:31,543
And to get a better idea of
just what this meant

561
00:23:31,576 --> 00:23:33,845
for the spacecraft in

terms of the thrusters,

562
00:23:33,878 --> 00:23:35,380
we can convert that
altitude margin

563
00:23:35,413 --> 00:23:38,349
into a thruster
duty cycle margin.

564
00:23:38,382 --> 00:23:42,654
And so, here thruster duty
cycle is the percentage of time

565
00:23:42,687 --> 00:23:45,723
that the thrusters are on
while they're in the atmosphere.

566
00:23:45,756 --> 00:23:47,692
So if they're on 0% it means
they didn't really

567
00:23:47,725 --> 00:23:49,093
encounter atmosphere.

568
00:23:49,126 --> 00:23:51,262
If they're on 100% it means
they're flying through

569
00:23:51,295 --> 00:23:53,064
more atmosphere
than they can handle

570
00:23:53,097 --> 00:23:55,300
and we're about
to lose pointing control.

571
00:23:55,333 --> 00:23:59,437
And you can see that
our worst case scenario

572
00:23:59,470 --> 00:24:01,639
had us at
just over 30%.

573
00:24:01,672 --> 00:24:05,143
And as a point of reference,
Titan flybys-- low Titan flybys

574
00:24:05,176 --> 00:24:08,680
in the past were designed
to have a 70% worst case,

575
00:24:08,713 --> 00:24:11,282
so we were even less
than half of that.

576
00:24:11,315 --> 00:24:13,985
So, we felt pretty comfortable
going in, but again,

577
00:24:14,018 --> 00:24:15,286
we were prepared
to be surprised.

578
00:24:15,319 --> 00:24:17,755
So, just like with dust
we had a contingency plan,

579
00:24:17,788 --> 00:24:20,725
for the atmosphere we had
a contingency plan.

580
00:24:20,758 --> 00:24:25,897
So, the plan was to fly that
very first one just as planned.

581
00:24:25,930 --> 00:24:27,765
It has the lowest duty
cycle of all of them.

582
00:24:27,798 --> 00:24:29,267
It was the highest
in the atmosphere,

583
00:24:29,300 --> 00:24:31,302
it was the least
likely to lose control,

584
00:24:31,335 --> 00:24:33,905
but if what we saw there
was more atmosphere

585
00:24:33,938 --> 00:24:38,209
than we thought we could
perform a maneuver in between

586
00:24:38,242 --> 00:24:41,646
the two passages and
pop up into a safer part

587
00:24:41,679 --> 00:24:42,814
of the atmosphere.

588
00:24:42,847 --> 00:24:44,782
We could then fly this blue
trajectory to the end

589
00:24:44,815 --> 00:24:48,520
all by performing
one maneuver.

590
00:24:48,553 --> 00:24:51,589
Okay, so again, all of
you wanted to shield

591
00:24:51,622 --> 00:24:54,459
absolutely every crossing,
so now you're all just ecstatic,

592
00:24:54,492 --> 00:24:57,862
hey, we have lots of margin here
and we have a contingency plan,

593
00:24:57,895 --> 00:24:59,030
so we're good.

594
00:24:59,063 --> 00:24:59,898
We're going to
sit back, relax,

595
00:24:59,931 --> 00:25:02,667
and enjoy these
last five orbits.

596
00:25:02,700 --> 00:25:05,069
Again, you're going to
upset a lot of scientists.

597
00:25:05,102 --> 00:25:06,237
The scientists came back
and they said,

598
00:25:06,270 --> 00:25:08,573
"Well, you know,
that's only 25%.

599
00:25:08,606 --> 00:25:10,942
"You can go to 70, so
you can go lower, right?"

600
00:25:10,975 --> 00:25:15,647
Well, that really depends on
how much fuel we have

601
00:25:15,680 --> 00:25:18,349
and what actually we saw
in the atmosphere.

602

00:25:18,382 --> 00:25:21,185
But, let's just go ahead
and take a look at it.

603
00:25:21,218 --> 00:25:23,621
We can go lower and
specifically they want to

604
00:25:23,654 --> 00:25:26,190
go lower for those last two
because those are the ones

605
00:25:26,223 --> 00:25:29,894
where we're doing a direct
sampling of the atmosphere.

606
00:25:29,927 --> 00:25:35,567
And so, looking at the higher
of those two, the rev 291,

607
00:25:35,600 --> 00:25:38,102
now we're changing
the horizontal axis.

608
00:25:38,135 --> 00:25:40,438
Now the horizontal axis is the
size of the burn we'd need

609
00:25:40,471 --> 00:25:43,374
to perform to get lower
into the atmosphere

610
00:25:43,407 --> 00:25:45,143
and to hit different
duty cycles.

611
00:25:45,176 --> 00:25:47,812
It's in meters per second,
which is speed.

612

00:25:47,845 --> 00:25:49,847
It's how much do we have
to change the speed

613
00:25:49,880 --> 00:25:52,517
of the spacecraft to get
lower in the atmosphere?

614
00:25:52,550 --> 00:25:53,418
Four and a half meters
per second

615
00:25:53,451 --> 00:25:55,987
is about
10 miles per hour.

616
00:25:56,020 --> 00:25:58,990
And so, as we start to change
the speed of the spacecraft

617
00:25:59,023 --> 00:26:02,560
out near Titan's orbit we get
lower in the atmosphere

618
00:26:02,593 --> 00:26:05,863
and we find that it would take
about 2.25 meters per second,

619
00:26:05,896 --> 00:26:08,833
about 5 miles
per hour of speed change

620
00:26:08,866 --> 00:26:10,735
in order to get low enough
in the atmosphere

621
00:26:10,768 --> 00:26:12,637
that we'd hit that 70%,

622
00:26:12,670 --> 00:26:14,606

which also corresponds
to a best guess,

623
00:26:14,639 --> 00:26:18,409
best estimate
of a 40% duty cycle.

624
00:26:18,442 --> 00:26:21,846
To give you some idea of
the size of that burn,

625
00:26:21,879 --> 00:26:26,250
we're going 3,700 miles
per hour out at Titan

626
00:26:26,283 --> 00:26:29,754
and we need to change the speed
by 5 miles per hour,

627
00:26:29,787 --> 00:26:30,955
so it's kind
of like sticking your head

628
00:26:30,988 --> 00:26:32,657
out of the car window
and blowing backwards

629
00:26:32,690 --> 00:26:34,292
to see how much speed
that adds to you.

630
00:26:34,325 --> 00:26:36,628
[laughter]

631
00:26:36,661 --> 00:26:37,829
So, not a lot.

632
00:26:37,862 --> 00:26:40,331
We are one wedge-- or one
orange wedge of propellant.

633
00:26:40,364 --> 00:26:41,699
It was going to be
enough to do this.

634
00:26:41,732 --> 00:26:45,370
So, this in fact became a viable
option and what it meant

635
00:26:45,403 --> 00:26:47,538
for the scientists was
now if we're looking at

636
00:26:47,571 --> 00:26:49,240
change in altitude
on the left

637
00:26:49,273 --> 00:26:51,142
and change in orbit
period on the right,

638
00:26:51,175 --> 00:26:52,644
or the amount of time
it takes to get back around

639
00:26:52,677 --> 00:26:57,582
to the same point in the orbit
as we do different burn sizes,

640
00:26:57,615 --> 00:27:00,184
what it meant was they got a
little over 100 miles deeper

641
00:27:00,217 --> 00:27:02,787
into the atmosphere,
176 kilometers,

642
00:27:02,820 --> 00:27:04,589
and it only changed their orbit
period by 2 minutes.

643
00:27:04,622 --> 00:27:06,824
So all the other science
observations we were doing

644
00:27:06,857 --> 00:27:08,893
during the orbit other than
right there where we're at

645
00:27:08,926 --> 00:27:11,095
the lowest point
really weren't affected

646
00:27:11,128 --> 00:27:14,399
because 2 minutes over
6.5 days, not too bad.

647
00:27:14,432 --> 00:27:17,368
And so, this became
our third viable path

648
00:27:17,401 --> 00:27:21,839
through these final five.

649
00:27:21,872 --> 00:27:23,107
All right.

650
00:27:23,140 --> 00:27:26,744
So now the question is,
well, what really happened?

651
00:27:26,777 --> 00:27:29,714
So, we flew through
that first time

652
00:27:29,747 --> 00:27:32,183
and it came in
right there, 30%.

653

00:27:32,216 --> 00:27:35,520
And doing some quick math, that
is two to three times thicker

654
00:27:35,553 --> 00:27:37,455
than we thought
the atmosphere should be.

655
00:27:37,488 --> 00:27:40,058
And if you use that data point
to update our model

656
00:27:40,091 --> 00:27:43,728
the other
predicts do this.

657
00:27:43,761 --> 00:27:45,697
So, wow, that's 70% line,

658
00:27:45,730 --> 00:27:46,898
we didn't fudge
the numbers for that.

659
00:27:46,931 --> 00:27:50,034
That second one
is actually 69.7%,

660
00:27:50,067 --> 00:27:51,736
so it came in
just under it.

661
00:27:51,769 --> 00:27:53,438
But needless to say,
the scientists were like,

662
00:27:53,471 --> 00:27:54,939
"Okay, we don't
need to go deeper."

663
00:27:54,972 --> 00:27:58,543

[laughter]

664
00:27:58,576 --> 00:27:59,444
And then the Project
Manager said,

665
00:27:59,477 --> 00:28:01,312
"Hey, you know what?

666
00:28:01,345 --> 00:28:05,249
"We're still below the line
and that's our worst case,

667
00:28:05,282 --> 00:28:07,385
"so we're going to
stay the course

668
00:28:07,418 --> 00:28:10,121
"and we're just going to
not perform any maneuver."

669
00:28:10,154 --> 00:28:13,791
So turns out that
was the right call.

670
00:28:13,824 --> 00:28:15,393
The next four
came in here.

671
00:28:15,426 --> 00:28:17,395
So, you can see they were
actually below

672
00:28:17,428 --> 00:28:18,963
what the updated
model would've said.

673
00:28:18,996 --> 00:28:21,365
So, we flew through some
thick clouds that first time

674
00:28:21,398 --> 00:28:23,134
and scared ourselves.

675
00:28:23,167 --> 00:28:26,504
But they were still above
the original estimate, so--

676
00:28:26,537 --> 00:28:28,106
and this is
still a mystery.

677
00:28:28,139 --> 00:28:29,107
We're still trying
to figure out

678
00:28:29,140 --> 00:28:31,442
exactly why our
stellar occultations

679
00:28:31,475 --> 00:28:33,811
and the direct
measurement of the atmosphere

680
00:28:33,844 --> 00:28:37,248
didn't quite line up.

681
00:28:37,281 --> 00:28:39,884
So, going back to our final
five chart, we can update this

682
00:28:39,917 --> 00:28:41,786
for where the
atmosphere actually was

683
00:28:41,819 --> 00:28:43,421
and we think
it was about there.

684

00:28:43,454 --> 00:28:48,025
And so, that was our
as-flown final five.

685
00:28:48,058 --> 00:28:50,361
And then we come back out
again, now we've done dust,

686
00:28:50,394 --> 00:28:51,763
we've done atmosphere,

687
00:28:51,796 --> 00:28:54,298
and here's the as-flown
grand finale.

688
00:28:54,331 --> 00:28:57,201
So, four shielded crossings
instead of five,

689
00:28:57,234 --> 00:29:02,273
and no maneuvers
in those final five.

690
00:29:02,306 --> 00:29:06,344
Okay, so that's the end of
my talk as a Mission Planner.

691
00:29:06,377 --> 00:29:08,980
Now, I'm going to try
and play scientist,

692
00:29:09,013 --> 00:29:10,348
which can be interesting.

693
00:29:10,381 --> 00:29:12,450
Or, maybe just
space enthusiast,

694
00:29:12,483 --> 00:29:15,052
that's probably

a better way to put it.

695
00:29:15,085 --> 00:29:16,621
Okay, so some fun
science stuff.

696
00:29:16,654 --> 00:29:18,823
So what was the
result of all this?

697
00:29:18,856 --> 00:29:21,225
Well first, before we even
got to the grand finale

698
00:29:21,258 --> 00:29:24,428
one of my favorite images
was taken during

699
00:29:24,461 --> 00:29:26,531
the seventh
ring-grazing orbit.

700
00:29:26,564 --> 00:29:29,901
And here it's Daphnis
orbiting in the Keeler gap.

701
00:29:29,934 --> 00:29:32,837
Yeah, you're having some
trouble seeing it, huh?

702
00:29:32,870 --> 00:29:36,340
Here.

703
00:29:36,373 --> 00:29:38,743
Here's the actual
image that was taken.

704
00:29:38,776 --> 00:29:41,512
And so, here you can see
Daphnis, one of Saturn's moons,

705
00:29:41,545 --> 00:29:44,048
orbiting in the Keeler
gap between the rings

706
00:29:44,081 --> 00:29:45,416
and the main ring system.

707
00:29:45,449 --> 00:29:48,753
And you can see as the ring
particles go by Daphnis

708
00:29:48,786 --> 00:29:52,390
it actually creates a wake,
and you can get an even better

709
00:29:52,423 --> 00:29:55,626
view of this by applying
some false motion.

710
00:29:55,659 --> 00:30:00,498
And so you can see that as
Daphnis orbits to the right,

711
00:30:00,531 --> 00:30:01,899
the rings below
are orbiting slower

712
00:30:01,932 --> 00:30:03,734
and appear to move
to the left.

713
00:30:03,767 --> 00:30:06,804
The rings above are orbiting
faster and go to the right.

714
00:30:06,837 --> 00:30:10,007
And so you have a wake
on the outside ring

715
00:30:10,040 --> 00:30:12,343
going out to the left,
and on the inside ring

716
00:30:12,376 --> 00:30:15,746
you may just be able to make
out the start of a wake

717
00:30:15,779 --> 00:30:22,286
going in the other direction
because of the relative motions.

718
00:30:22,319 --> 00:30:28,025
So very analogous to that
is this other fun image

719
00:30:28,058 --> 00:30:30,228
of a ring propeller.

720
00:30:30,261 --> 00:30:31,762
So a ring propeller is
very much like Daphnis

721
00:30:31,795 --> 00:30:33,698
only on a very,
very small scale.

722
00:30:33,731 --> 00:30:35,499
It's orbiting in the
main ring system.

723
00:30:35,532 --> 00:30:39,670
It's a very small moonlet, and
it creates that similar wake

724
00:30:39,703 --> 00:30:42,406
where you have these wakes
coming off the opposite edges.

725

00:30:42,439 --> 00:30:45,343
What's really neat about this
particular set of images

726
00:30:45,376 --> 00:30:47,211
is because of the way the ring
grazing orbits came in

727
00:30:47,244 --> 00:30:49,413
over the top and then
exited down below,

728
00:30:49,446 --> 00:30:51,582
we're able to photograph
the same propeller

729
00:30:51,615 --> 00:30:52,817
in a relatively
short amount of time

730
00:30:52,850 --> 00:30:55,786
from both the lit side and
the unlit side of the rings.

731
00:30:55,819 --> 00:30:59,657
And so that's what
you're seeing there.

732
00:30:59,690 --> 00:31:01,859
And scientists are interested
in these because they think

733
00:31:01,892 --> 00:31:06,163
that they are analogous
to a baby planet

734
00:31:06,196 --> 00:31:08,532
in a protoplanetary disk
and how it can start

735

00:31:08,565 --> 00:31:15,907
to accrete mass in
an early solar system.

736
00:31:15,940 --> 00:31:17,875
Okay, so now we're actually
at the grand finale.

737
00:31:17,908 --> 00:31:20,378
This is grand finale
orbit number one.

738
00:31:20,411 --> 00:31:23,681
We're a day out from the first
dive through the rings,

739
00:31:23,714 --> 00:31:26,050
and we're over
Saturn's north pole.

740
00:31:26,083 --> 00:31:29,520
And so we've got this
series of images of Saturn's

741
00:31:29,553 --> 00:31:32,757
hexagonal jet stream and
hurricane at its north pole.

742
00:31:32,790 --> 00:31:34,325
And you can see
it's really neat.

743
00:31:34,358 --> 00:31:36,260
What's even more interesting
is we have a similar

744
00:31:36,293 --> 00:31:39,196
set of images from
four years earlier.

745

00:31:39,229 --> 00:31:40,932
And these are
true color images.

746
00:31:40,965 --> 00:31:44,235
And you can see that the hexagon
has very clearly changed

747
00:31:44,268 --> 00:31:47,004
from blue to this
nice yellowish orange.

748
00:31:47,037 --> 00:31:49,507
And the reason
for that is in 2013,

749
00:31:49,540 --> 00:31:52,176
the hexagon had only just
become exposed to light.

750
00:31:52,209 --> 00:31:56,347
And 2017 now we're at the
northern summer solstice,

751
00:31:56,380 --> 00:31:58,349
so sunlight's been hitting
this region for a long time.

752
00:31:58,382 --> 00:32:01,419
And this region is full of
photochemical aerosols,

753
00:32:01,452 --> 00:32:04,088
and so when the ultraviolet
light from the sun hits them,

754
00:32:04,121 --> 00:32:07,992
they form a smoggy haze
that turns the hexagon

755

00:32:08,025 --> 00:32:11,796
from blue to
yellowish orange.

756
00:32:11,829 --> 00:32:13,531
As for why that hurricane
in the center stays blue,

757
00:32:13,564 --> 00:32:15,032
there's a couple thoughts.

758
00:32:15,065 --> 00:32:16,667
One is that that hurricane
is actually at

759
00:32:16,700 --> 00:32:18,736
a lower altitude than
the surrounding clouds,

760
00:32:18,769 --> 00:32:21,205
and so they're
shading it from the sun.

761
00:32:21,238 --> 00:32:24,742
So given enough time, they
could eventually form a haze.

762
00:32:24,775 --> 00:32:28,546
However, if it acts at all
like Earth hurricanes,

763
00:32:28,579 --> 00:32:30,514
it actually creates a
downwelling that's right there.

764
00:32:30,547 --> 00:32:32,416
And so it's sucking any haze
particles that are formed

765
00:32:32,449 --> 00:32:34,652

back down into
the deep atmosphere.

766
00:32:34,685 --> 00:32:39,790
And so that keeps it that
nice pristine blue color.

767
00:32:39,823 --> 00:32:42,426
Okay, so day after this,

768
00:32:42,459 --> 00:32:44,929
we did our first
dive through the gap.

769
00:32:44,962 --> 00:32:46,297
And while we were doing it,

770
00:32:46,330 --> 00:32:48,933
we were taking images with
our camera from the north pole

771
00:32:48,966 --> 00:32:50,634
all the way down
to the equator.

772
00:32:50,667 --> 00:32:54,238
And you can see the images
in the lower right there.

773
00:32:54,271 --> 00:32:56,540
At the end of this animation,
the spacecraft will actually

774
00:32:56,573 --> 00:32:59,510
turn, because we had to go
to our shielded attitude.

775
00:32:59,543 --> 00:33:02,113
And so you can see it turning
in order to protect itself

776
00:33:02,146 --> 00:33:03,180
during that first crossing.

777
00:33:03,213 --> 00:33:04,415
We still didn't
know that there was

778
00:33:04,448 --> 00:33:07,118
absolutely no dust there.

779
00:33:07,151 --> 00:33:08,119
But you can take
all those images,

780
00:33:08,152 --> 00:33:09,553
and you can stitch
them together,

781
00:33:09,586 --> 00:33:11,122
and you get
a Saturn noodle.

782
00:33:11,155 --> 00:33:14,025
So this is a thin little
strip all the way from

783
00:33:14,058 --> 00:33:18,596
Saturn's north pole
down to its equator.

784
00:33:18,629 --> 00:33:22,266
On our second dive, we were
in a high rate spin

785
00:33:22,299 --> 00:33:25,336
to get high resolution
magnetic field data.

786

00:33:25,369 --> 00:33:26,537
And here you can
see the spacecraft

787
00:33:26,570 --> 00:33:27,805
diving through the graph,

788
00:33:27,838 --> 00:33:30,641
and that colored line is
Saturn's magnetic field line

789
00:33:30,674 --> 00:33:32,843
that passes
through the spacecraft.

790
00:33:32,876 --> 00:33:34,979
And so you can see where that
field line both hits Saturn

791
00:33:35,012 --> 00:33:36,580
and intersects
the ring plane.

792
00:33:36,613 --> 00:33:41,085
And that can give a lot of
interesting results as far--

793
00:33:41,118 --> 00:33:43,287
there are particles that
travel along that field line,

794
00:33:43,320 --> 00:33:46,057
and this kind of shows you
what the source of those

795
00:33:46,090 --> 00:33:49,326
particles may be as far as
the latitudes on Saturn,

796
00:33:49,359 --> 00:33:56,867

or the exact distance into
the ring plane that they are.

797
00:33:56,900 --> 00:33:58,269
On our third dive-- I'm not
going to go through these

798
00:33:58,302 --> 00:34:00,838
one by one, but the first
three were pretty cool.

799
00:34:00,871 --> 00:34:02,973
On the third dive,
we were on Earth point,

800
00:34:03,006 --> 00:34:06,343
and communicating with Earth
as we dove through.

801
00:34:06,376 --> 00:34:11,449
And Earth is above the ring
plane relative to Saturn.

802
00:34:11,482 --> 00:34:12,750
And so you can see here,

803
00:34:12,783 --> 00:34:14,085
we're pointing up
above the ring plane,

804
00:34:14,118 --> 00:34:16,287
but as we dive through it, what
that means is the signal's

805
00:34:16,320 --> 00:34:18,989
actually going to
pass through those rings.

806
00:34:19,022 --> 00:34:21,659
And from that, we can look at

what that does to the signal

807
00:34:21,692 --> 00:34:23,094
and get some information
about the rings.

808
00:34:23,127 --> 00:34:25,096
It looks a little like this,
which is a messy plot,

809
00:34:25,129 --> 00:34:28,332
but it's basically the
transmission strength

810
00:34:28,365 --> 00:34:30,267
of the signal
as it goes through.

811
00:34:30,300 --> 00:34:31,635
And it lets us see
how thick the rings are,

812
00:34:31,668 --> 00:34:38,142
how sharp those edges
are between the ringlets.

813
00:34:38,175 --> 00:34:41,112
Okay, so jumping ahead
now to the 12th orbit.

814
00:34:41,145 --> 00:34:43,747
Here we got a really good
look, a really high resolution

815
00:34:43,780 --> 00:34:46,717
picture of Saturn's B Ring,
which the rings are made up

816
00:34:46,750 --> 00:34:47,852
of mostly water ice.

817
00:34:47,885 --> 00:34:48,953
And if they were
pure water ice,

818
00:34:48,986 --> 00:34:50,154
they'd probably
look like this,

819
00:34:50,187 --> 00:34:52,523
but in this particular
opportunity, we were actually

820
00:34:52,556 --> 00:34:54,725
able to get this
image in color.

821
00:34:54,758 --> 00:34:59,130
And here, the color comes from
impurities in the water ice.

822
00:34:59,163 --> 00:35:01,098
And the source of those
impurities is actually

823
00:35:01,131 --> 00:35:02,733
still debated
by the scientists.

824
00:35:02,766 --> 00:35:05,269
It could have been rocks and
minerals that were part of

825
00:35:05,302 --> 00:35:06,737
the accretion disk of Saturn
as it was forming,

826
00:35:06,770 --> 00:35:09,240
or it could have also
been meteorites that are

827
00:35:09,273 --> 00:35:10,841
coming in and impacting
the ring system

828
00:35:10,874 --> 00:35:17,448
and getting obliterated
and orbiting with it.

829
00:35:17,481 --> 00:35:21,118
Okay, on the 14th orbit, a day
or two after we passed through

830
00:35:21,151 --> 00:35:25,556
the gap for the 14th time,
we look back at Saturn,

831
00:35:25,589 --> 00:35:27,224
and specifically
at the south pole

832
00:35:27,257 --> 00:35:29,326
and we got to
watch the aurora.

833
00:35:29,359 --> 00:35:32,329
This is a false color image,
but it's reproduced with what

834
00:35:32,362 --> 00:35:34,965
should be a somewhat natural
color for the aurora.

835
00:35:34,998 --> 00:35:38,302
And so here you have Saturn
as the big black body up top.

836
00:35:38,335 --> 00:35:41,572
You can see the starry sky
sweeping by in the background

837
00:35:41,605 --> 00:35:44,542
and the aurora orbiting
the south pole.

838
00:35:44,575 --> 00:35:46,610
If you look close, you can
also see that the stars

839
00:35:46,643 --> 00:35:48,145
sort of take
a sharp right turn

840
00:35:48,178 --> 00:35:50,314
just before
they set behind Saturn.

841
00:35:50,347 --> 00:35:51,916
That's because their light
actually is refracted

842
00:35:51,949 --> 00:35:58,122
by Saturn's atmosphere as
it travels back to Cassini.

843
00:35:58,155 --> 00:36:00,057
Okay, so next is one of
my favorite observations

844
00:36:00,090 --> 00:36:03,160
because I actually had
a hand in helping plan it,

845
00:36:03,193 --> 00:36:05,362
which as a Mission Planner
I don't normally do.

846
00:36:05,395 --> 00:36:06,597
That's science
planning's job.

847
00:36:06,630 --> 00:36:09,333
And what we did is
we actually were able

848
00:36:09,366 --> 00:36:11,602
to have the spacecraft,
as it was diving through,

849
00:36:11,635 --> 00:36:13,470
take pictures of the rings
from the inside out,

850
00:36:13,503 --> 00:36:15,973
and create this movie where
we got to see the lit side,

851
00:36:16,006 --> 00:36:18,375
the unlit side,
and even neater,

852
00:36:18,408 --> 00:36:20,945
we got to see the entire ring
system in one frame

853
00:36:20,978 --> 00:36:24,181
because of
the foreshortening.

854
00:36:24,214 --> 00:36:30,387
See, as you watch
it go by again.

855
00:36:30,420 --> 00:36:34,558
So there, the entire ring
system in one camera frame.

856
00:36:34,591 --> 00:36:37,728
Pretty neat.

857
00:36:37,761 --> 00:36:41,298
Okay, an orbit later,
we got to watch one of

858
00:36:41,331 --> 00:36:44,468
the protected bodies
of the Saturn system.

859
00:36:44,501 --> 00:36:46,003
So this is
in Enceladus.

860
00:36:46,036 --> 00:36:48,305
Again, it has that global
subsurface ocean and contact

861
00:36:48,338 --> 00:36:50,741
with an active
rocky core.

862
00:36:50,774 --> 00:36:54,445
And as it orbits Saturn,
squeezes it, and it creates

863
00:36:54,478 --> 00:36:57,414
these geysers that shoot
out of its south pole.

864
00:36:57,447 --> 00:37:00,150
So these are water geysers
shooting out of the south pole.

865
00:37:00,183 --> 00:37:02,453
This is about 14 hours
of observation

866
00:37:02,486 --> 00:37:07,358
and it was taken from
half a million miles away.

867
00:37:07,391 --> 00:37:15,432
And this was our last dedicated
observation of Enceladus.

868
00:37:15,465 --> 00:37:18,969
Okay, Grand Finale Orbit 21,
so just one and a half to go.

869
00:37:19,002 --> 00:37:20,771
We got some really
great pictures of

870
00:37:20,804 --> 00:37:22,339
the dawn side of
Saturn's atmosphere.

871
00:37:22,372 --> 00:37:24,908
So here you can see some of
the structure in the clouds,

872
00:37:24,941 --> 00:37:27,211
and once again,
like with the B Ring,

873
00:37:27,244 --> 00:37:28,312
we got
the images in color.

874
00:37:28,345 --> 00:37:29,947
And it's a little
hard to make out,

875
00:37:29,980 --> 00:37:32,016
but you actually have
these multi-hued bands

876
00:37:32,049 --> 00:37:33,951
of green and red
in the clouds.

877
00:37:33,984 --> 00:37:35,653
And again, this is
a true color image.

878
00:37:35,686 --> 00:37:41,992
That is actually what you
would see if you were there.

879
00:37:42,025 --> 00:37:44,595
All right, getting
close to the end now.

880
00:37:44,628 --> 00:37:47,965
On the final plunge, so
this is our last half orbit.

881
00:37:47,998 --> 00:37:52,136
Last trip from Titan's orbit
down into Saturn,

882
00:37:52,169 --> 00:37:56,173
we took a series
of seven image sets

883
00:37:56,206 --> 00:37:59,677
of different objects
in the rings.

884
00:37:59,710 --> 00:38:03,147
And so these are the final
seven sets of images

885
00:38:03,180 --> 00:38:04,948
that Cassini took.

886
00:38:04,981 --> 00:38:07,985
And this was about a day
before we plunged into Saturn.

887

00:38:08,018 --> 00:38:11,288
Also at the end of that,
we had Cassini image

888
00:38:11,321 --> 00:38:13,457
what would eventually
become its impact site,

889
00:38:13,490 --> 00:38:14,658
which was
a little bit morbid,

890
00:38:14,691 --> 00:38:16,060
but very
scientifically interesting.

891
00:38:16,093 --> 00:38:19,029
[laughter]

892
00:38:19,062 --> 00:38:21,031
So this gave us some
context for what we would

893
00:38:21,064 --> 00:38:25,135
later be seeing with our
other instruments as we were

894
00:38:25,168 --> 00:38:27,905
plunging into
Saturn's atmosphere.

895
00:38:27,938 --> 00:38:30,641
Okay, so a little
before 5 a.m.

896
00:38:30,674 --> 00:38:33,143
on September 15th, 2017,

897
00:38:33,176 --> 00:38:36,046
Cassini entered

Saturn's atmosphere.

898
00:38:36,079 --> 00:38:39,049
And within a minute,
our thrusters saturated

899
00:38:39,082 --> 00:38:41,118
and we couldn't point
the spacecraft anymore.

900
00:38:41,151 --> 00:38:43,220
It only took 20 more seconds
for our S band signal,

901
00:38:43,253 --> 00:38:47,391
which you can see there,
to completely disappear.

902
00:38:47,424 --> 00:38:49,893
And within
the next minute,

903
00:38:49,926 --> 00:38:53,397
Saturn's atmosphere
destroyed the spacecraft,

904
00:38:53,430 --> 00:38:57,201
and Cassini
became a part of Saturn.

905
00:38:57,234 --> 00:39:01,004
So end of mission was
called at 4:56 a.m. JPL time,

906
00:39:01,037 --> 00:39:03,374
September 15th,
2017 when we lost

907
00:39:03,407 --> 00:39:11,215
the S band carrier signal.

908
00:39:11,248 --> 00:39:12,216
Okay, so with that,

909
00:39:12,249 --> 00:39:14,485
I just want to say
thank you for coming.

910
00:39:14,518 --> 00:39:26,029
[applause]

911
00:39:26,062 --> 00:39:30,434
I would also like to thank
all of my Cassini family,

912
00:39:30,467 --> 00:39:31,602
all of my predecessors,

913
00:39:31,635 --> 00:39:35,272
and also everybody here
who helped put this on.

914
00:39:35,305 --> 00:39:37,975
It takes a lot of work,
and I get the easy part.

915
00:39:38,008 --> 00:39:39,610
I just come up here
and talk to you guys.

916
00:39:39,643 --> 00:39:40,577
So they all did
a lot of work,

917
00:39:40,610 --> 00:39:41,979
so give them
a round of applause too.

918
00:39:42,012 --> 00:39:53,690

[applause]

919
00:39:53,723 --> 00:39:55,592
Okay, so with that, I have
time for questions.

920
00:39:55,625 --> 00:39:56,860
However, if you want
to ask a question,

921
00:39:56,893 --> 00:39:59,096
I ask that
you go up,

922
00:39:59,129 --> 00:40:02,366
form a line at
that microphone there.

923
00:40:02,399 --> 00:40:03,700
That way everybody in
here can hear you,

924
00:40:03,733 --> 00:40:05,169
and also everybody online
can hear you.

925
00:40:05,202 --> 00:40:06,804
And I also
I will preface this with:

926
00:40:06,837 --> 00:40:08,439
I will answer these to
the best of my knowledge.

927
00:40:08,472 --> 00:40:11,341
If you remember those dates
at the beginning,

928
00:40:11,374 --> 00:40:14,545
2013 to 2017

is my reign of terror.

929
00:40:14,578 --> 00:40:16,046
[laughter]

930
00:40:16,079 --> 00:40:18,015
And it went all
the way back to 1991

931
00:40:18,048 --> 00:40:21,418
with Mission Planners and
even farther than that.

932
00:40:21,451 --> 00:40:22,719
Like I said, I was
a baby when it was born,

933
00:40:22,752 --> 00:40:24,288
so I will
do what I can.

934
00:40:24,321 --> 00:40:26,056
I may rely on some friendly
faces in the audience

935
00:40:26,089 --> 00:40:27,624
to help me out.

936
00:40:27,657 --> 00:40:29,593
- Well, the first one is
actually kind of a remark,

937
00:40:29,626 --> 00:40:31,028
not a question.

938
00:40:31,061 --> 00:40:34,298
The birth of Cassini goes
a bit back before 1982.

939

00:40:34,331 --> 00:40:36,934
In the mid-'70s,
Donna Pivirotto noticed

940
00:40:36,967 --> 00:40:39,570
that essentially every
Mariner was different.

941
00:40:39,603 --> 00:40:40,737
And she said, "We ought
to construct

942
00:40:40,770 --> 00:40:42,573
"some building blocks."

943
00:40:42,606 --> 00:40:45,776
And she proposed a project
called Mariner Block II.

944
00:40:45,809 --> 00:40:47,845
And then they stopped
calling it Mariner,

945
00:40:47,878 --> 00:40:49,580
because all the Mariners
were solar powered.

946
00:40:49,613 --> 00:40:52,683
And then later on they
were nuclear powered.

947
00:40:52,716 --> 00:40:55,752
But Mariner Block II is
where Cassini got started.

948
00:40:55,785 --> 00:40:57,254
And, of course, Cassini was
supposed to have a twin

949
00:40:57,287 --> 00:41:00,257

called CRAF, the Comet
Rendezvous Asteroid Flyby,

950
00:41:00,290 --> 00:41:02,459
and that got
axed long before

951
00:41:02,492 --> 00:41:05,195
Cassini actually
got going along.

952
00:41:05,228 --> 00:41:07,564
So Cassini's a bit
older than 1982.

953
00:41:07,597 --> 00:41:09,566
It goes back
to the mid-'70s.

954
00:41:09,599 --> 00:41:10,767
- Okay, we'll have to
update a couple books.

955
00:41:10,800 --> 00:41:12,202
And I'm going to keep telling
that story because

956
00:41:12,235 --> 00:41:14,404
my picture before 1982
was not as good.

957
00:41:14,437 --> 00:41:16,073
- No pictures of you
before then, yeah.

958
00:41:16,106 --> 00:41:19,042
Yeah.
No, the question I have:

959
00:41:19,075 --> 00:41:24,715

In the mid-'90s, before the
Neptune flyby for Voyager,

960
00:41:24,748 --> 00:41:28,352
I asked Fred Billingsley
with such a long baseline,

961
00:41:28,385 --> 00:41:30,954
are the Voyager cameras
good enough to do

962
00:41:30,987 --> 00:41:33,957
any decent astrometry, to
measure the distance

963
00:41:33,990 --> 00:41:36,193
to nearby stars
using parallax?

964
00:41:36,226 --> 00:41:38,662
And he said the cameras on
Voyager aren't good enough

965
00:41:38,695 --> 00:41:41,999
for astrometry even with
that enormous baseline.

966
00:41:42,032 --> 00:41:45,402
Were the Cassini cameras good
enough to get better parallax

967
00:41:45,435 --> 00:41:47,971
measurements with an enormous
baseline than we can get

968
00:41:48,004 --> 00:41:51,575
with just using the Earth
baseline for astrometry?

969
00:41:51,608 --> 00:41:53,143

- I don't know that we
ever did that with Cassini.

970
00:41:53,176 --> 00:41:54,211
I'm going to look at
a friendly face here.

971
00:41:54,244 --> 00:41:56,713
- Yeah, we never did that.

972
00:41:56,746 --> 00:41:59,583
- Yeah, I think we were
too busy with Saturn science.

973
00:41:59,616 --> 00:42:01,785
But, yeah, so I'm not
sure if the cameras

974
00:42:01,818 --> 00:42:03,887
are good enough or
not to do parallax.

975
00:42:03,920 --> 00:42:07,791
- No star images, huh?
- We can get back to you.

976
00:42:07,824 --> 00:42:10,761
- Thank you.
- Yeah.

977
00:42:10,794 --> 00:42:12,496
- I have an attitude
control question.

978
00:42:12,529 --> 00:42:13,730
- Yeah.

979
00:42:13,763 --> 00:42:15,933
- It looked like the tumble
boundaries that you showed

980
00:42:15,966 --> 00:42:17,901
for RCS thrusters
were not flat.

981
00:42:17,934 --> 00:42:19,870
- Right.
- Why is that?

982
00:42:19,903 --> 00:42:22,573
- So the tumble boundary
is not just a function

983
00:42:22,606 --> 00:42:25,042
of the density
of the atmosphere.

984
00:42:25,075 --> 00:42:27,544
It's also a function
of how fast you're going

985
00:42:27,577 --> 00:42:29,746
and the attitude
of the spacecraft.

986
00:42:29,779 --> 00:42:33,083
A good way to think about this
is if you're driving in a car,

987
00:42:33,116 --> 00:42:34,551
you put your hand
out the window,

988
00:42:34,584 --> 00:42:37,154
and put it face-on to the wind,
and start driving faster,

989
00:42:37,187 --> 00:42:39,289
it's going to
push you harder.

990
00:42:39,322 --> 00:42:41,325
Also if you change
the pointing of your hand

991
00:42:41,358 --> 00:42:43,727
so that it's like this,
it's going to push you less.

992
00:42:43,760 --> 00:42:45,629
So in that one
where it bumped up,

993
00:42:45,662 --> 00:42:47,264
we weren't necessarily
going any faster.

994
00:42:47,297 --> 00:42:48,665
They were all about
the same speed.

995
00:42:48,698 --> 00:42:50,667
But we were at an attitude
that was more like having

996
00:42:50,700 --> 00:42:53,070
an open palm out the window than
a closed palm out the window.

997
00:42:53,103 --> 00:42:56,239
And so the atmosphere
turned us harder,

998
00:42:56,272 --> 00:42:58,442
which meant the thrusters
had to fight it more.

999
00:42:58,475 --> 00:43:00,978
- Thank you.
- Yep.

1000
00:43:01,011 --> 00:43:04,047
- So what were some of the
most difficult decisions

1001
00:43:04,080 --> 00:43:08,118
that you had to make
as a planner?

1002
00:43:08,151 --> 00:43:11,822
- Well, I think the first
one was just coming up

1003
00:43:11,855 --> 00:43:13,790
with the fact that we could
have a contingency plan,

1004
00:43:13,823 --> 00:43:15,759
and not just Captain America it,
and just say,

1005
00:43:15,792 --> 00:43:18,261
"Hey, shields.
Shields everywhere!"

1006
00:43:18,294 --> 00:43:19,896
But to actually have to
prove that, you know what,

1007
00:43:19,929 --> 00:43:22,499
we could take data,
analyze it,

1008
00:43:22,532 --> 00:43:26,069
and make a decision
and uplink a contingency

1009
00:43:26,102 --> 00:43:29,039
to the spacecraft all
within six and a half days.

1010
00:43:29,072 --> 00:43:30,607
Because these orbits
were much, much shorter

1011
00:43:30,640 --> 00:43:32,476
than anything we'd
ever done before.

1012
00:43:32,509 --> 00:43:35,379
The ring-grazing orbits
were just over a week.

1013
00:43:35,412 --> 00:43:37,114
These were just
under a week.

1014
00:43:37,147 --> 00:43:39,516
The closest we got to that
before was nine days,

1015
00:43:39,549 --> 00:43:41,485
and we weren't inside
the ring system.

1016
00:43:41,518 --> 00:43:44,554
So proving that we could turn
something around fast enough

1017
00:43:44,587 --> 00:43:47,457
I think was the biggest
challenge as far as

1018
00:43:47,490 --> 00:43:48,692
mission planning goes.

1019
00:43:48,725 --> 00:43:50,927
- Thank you.
- Yeah.

1020
00:43:50,960 --> 00:43:52,729
- Thanks so much for
the awesome presentation.

1021
00:43:52,762 --> 00:43:53,930
- You're welcome.

1022
00:43:53,963 --> 00:43:56,400
- How do you know how many
orange peels you have left

1023
00:43:56,433 --> 00:43:58,502
in the tank
on a spacecraft?

1024
00:43:58,535 --> 00:43:59,736
[laughter]

1025
00:43:59,769 --> 00:44:00,871
- Yeah, that's
a good question.

1026
00:44:00,904 --> 00:44:03,774
I actually didn't say--
we have some uncertainty

1027
00:44:03,807 --> 00:44:06,243
in that estimate, right?

1028
00:44:06,276 --> 00:44:08,445
The uncertainty in that one
orange wedge was about

1029
00:44:08,478 --> 00:44:10,080
plus or minus
1.5 orange wedges.

1030
00:44:10,113 --> 00:44:13,216
[laughter]

1031
00:44:13,249 --> 00:44:17,788
So we really needed to--
We couldn't go any longer.

1032
00:44:17,821 --> 00:44:19,990
And so it really all
comes to two things.

1033
00:44:20,023 --> 00:44:22,459
First, it's very accurate
measurements on the ground

1034
00:44:22,492 --> 00:44:27,397
when we load up the spacecraft
and take its weight.

1035
00:44:27,430 --> 00:44:30,634
And so we have some idea with
a relatively small uncertainty

1036
00:44:30,667 --> 00:44:32,002
of how much fuel
we put in it.

1037
00:44:32,035 --> 00:44:34,404
Then that small uncertainty
actually just grows

1038
00:44:34,437 --> 00:44:36,406
and grows and grows,
because from there,

1039
00:44:36,439 --> 00:44:37,541
each time we
perform a maneuver,

1040
00:44:37,574 --> 00:44:39,476
we have a model on
the ground that says

1041
00:44:39,509 --> 00:44:41,411
about how much fuel
we thought we burned,

1042
00:44:41,444 --> 00:44:43,013
but that model has
some uncertainty.

1043
00:44:43,046 --> 00:44:46,216
So each time you use that
model, what may have been

1044
00:44:46,249 --> 00:44:48,585
a fraction of an orange wedge
of uncertainty is just

1045
00:44:48,618 --> 00:44:49,753
growing and growing
and growing.

1046
00:44:49,786 --> 00:44:52,289
So by the end, not only
is our uncertainty bigger,

1047
00:44:52,322 --> 00:44:55,092
but the amount of fuel
we have left is smaller.

1048
00:44:55,125 --> 00:44:59,563
And so things start
to look a lot scarier.

1049
00:44:59,596 --> 00:45:03,633
- Thank you.
- Yep.

1050
00:45:03,666 --> 00:45:07,971
- I guess my question
is there must've been

1051
00:45:08,004 --> 00:45:10,907
a lot of discussion
about what to do.

1052
00:45:10,940 --> 00:45:15,712
You know, what-- and there must
have been some observations

1053
00:45:15,745 --> 00:45:19,049
that would've been nice
that you couldn't do.

1054
00:45:19,082 --> 00:45:21,051
Could you tell us
about some of those?

1055
00:45:21,084 --> 00:45:24,020
- Yeah, I can
tell you a little.

1056
00:45:24,053 --> 00:45:25,388
So that's all
science planning,

1057
00:45:25,421 --> 00:45:27,224
which is right after
mission planning happens.

1058
00:45:27,257 --> 00:45:29,292
I'm the bigger picture,
and then science planners

1059
00:45:29,325 --> 00:45:31,228
go down and divvy up
the individual orbits.

1060
00:45:31,261 --> 00:45:33,530
But what I can say is that
science was split up

1061
00:45:33,563 --> 00:45:35,499
into different disciplines.

1062
00:45:35,532 --> 00:45:37,501
And each of those disciplines
and instruments were given

1063
00:45:37,534 --> 00:45:40,003
the opportunity to say
what they thought they needed

1064
00:45:40,036 --> 00:45:43,740
in the Grand Finale in order to
get this really great science

1065
00:45:43,773 --> 00:45:45,709
that we were
promising everyone.

1066
00:45:45,742 --> 00:45:48,545
And luckily when we added
all those orbits up,

1067
00:45:48,578 --> 00:45:51,181
it came out to
35 out of 22.

1068
00:45:51,214 --> 00:45:53,416
And so that's a
little bit over.

1069
00:45:53,449 --> 00:45:56,153
But at JPL, we know how
to make 35 fit into 22.

1070
00:45:56,186 --> 00:45:57,320
[laughter]

1071

00:45:57,353 --> 00:45:59,322
We were able to get

1072
00:45:59,355 --> 00:46:01,691
the instrument scientists
together to talk things out

1073
00:46:01,724 --> 00:46:03,326
and figure out where we
could share orbits,

1074
00:46:03,359 --> 00:46:04,661
where we could have more
than one instrument on

1075
00:46:04,694 --> 00:46:06,696
at the same time and
both get the same science.

1076
00:46:06,729 --> 00:46:08,465
And then we also had to push
back a little bit and say,

1077
00:46:08,498 --> 00:46:10,300
"Do you really need
that many orbits?

1078
00:46:10,333 --> 00:46:11,668
"Could you do
with one less?"

1079
00:46:11,701 --> 00:46:14,371
And so, it was just
a series of negotiations

1080
00:46:14,404 --> 00:46:17,140
with the project and the science
teams that went back and forth

1081
00:46:17,173 --> 00:46:20,744

like that to get it all fit
into the 22.5 orbits.

1082
00:46:20,777 --> 00:46:24,815
- Thank you.
- Yeah.

1083
00:46:24,848 --> 00:46:32,556
- Hi, my question would be
for future missions,

1084
00:46:32,589 --> 00:46:37,260
what sort of guidance
do you have for people

1085
00:46:37,293 --> 00:46:39,162
that will be in
your shoes five years,

1086
00:46:39,195 --> 00:46:41,231
ten years
and fifteen years from now.

1087
00:46:41,264 --> 00:46:44,000
What sort of-- maybe you can
think of, like, one, or two,

1088
00:46:44,033 --> 00:46:46,469
or three things that-- what
sort of guidance do you have

1089
00:46:46,502 --> 00:46:50,707
for them learning what you
learned on this mission

1090
00:46:50,740 --> 00:46:54,077
where it seemed like there
were a lot of options that

1091
00:46:54,110 --> 00:46:58,915

you may not have thought
you had that you did have?

1092
00:46:58,948 --> 00:47:02,786
- Yeah, so the first one is:
plan for what you think

1093
00:47:02,819 --> 00:47:06,523
you're never going to do,
because you're going to do it.

1094
00:47:06,556 --> 00:47:08,992
We never thought we'd fly
inside the ring system,

1095
00:47:09,025 --> 00:47:13,330
and so being able to do that
was actually a pretty big deal.

1096
00:47:13,363 --> 00:47:14,764
It took
a lot of work.

1097
00:47:14,797 --> 00:47:16,533
We had to change a lot of
tools in order to

1098
00:47:16,566 --> 00:47:19,336
actually get them to
function inside the rings,

1099
00:47:19,369 --> 00:47:20,971
because we never
thought we'd be there.

1100
00:47:21,004 --> 00:47:23,506
But what that
really gets to is--

1101
00:47:23,539 --> 00:47:25,475

I'd say a couple
other lessons, it's:

1102
00:47:25,508 --> 00:47:29,846
you got to keep the spacecraft
simple and robust.

1103
00:47:29,879 --> 00:47:33,450
And that makes it so that
you have something that lasts

1104
00:47:33,483 --> 00:47:36,586
a long time so that you can just
keep doing this great science.

1105
00:47:36,619 --> 00:47:38,755
And also, you need to keep
your system flexible,

1106
00:47:38,788 --> 00:47:40,991
so that you can react
to new discoveries

1107
00:47:41,024 --> 00:47:42,425
and going new places.

1108
00:47:42,458 --> 00:47:43,560
And so I think those are
the two key things about

1109
00:47:43,593 --> 00:47:46,963
the Cassini spacecraft
and the project

1110
00:47:46,996 --> 00:47:48,465
that made it so that
we could do this.

1111
00:47:48,498 --> 00:47:49,833
- Got you.

Thank you so much.

1112
00:47:49,866 --> 00:47:52,235
- Yeah.

1113
00:47:52,268 --> 00:47:56,573
- How come some of the
pictures that Cassini took

1114
00:47:56,606 --> 00:47:59,342
were black and white
and others were color?

1115
00:47:59,375 --> 00:48:01,978
- Yeah, so Cassini's
cameras actually

1116
00:48:02,011 --> 00:48:03,780
are just black and white.

1117
00:48:03,813 --> 00:48:05,749
And the way it works is we
put different color filters

1118
00:48:05,782 --> 00:48:08,151
in front of them, so that just
that color of light

1119
00:48:08,184 --> 00:48:09,386
comes through.

1120
00:48:09,419 --> 00:48:11,187
And depending on
the science we're doing,

1121
00:48:11,220 --> 00:48:12,923
and how much
time we have,

1122

00:48:12,956 --> 00:48:14,291
that determines
how many filters

1123
00:48:14,324 --> 00:48:16,426
we're able to put in
front of the camera

1124
00:48:16,459 --> 00:48:17,928
when we make
a given observation.

1125
00:48:17,961 --> 00:48:20,530
In order to get one
in color as we see it,

1126
00:48:20,563 --> 00:48:23,466
we need three filters, the red,
the green, and the blue.

1127
00:48:23,499 --> 00:48:25,335
And so for those particular
ones, we were able to get

1128
00:48:25,368 --> 00:48:27,370
all three filters in
front of the camera

1129
00:48:27,403 --> 00:48:33,143
and reproduce
true to life images.

1130
00:48:33,176 --> 00:48:34,277
- Hello, thanks for
your lecture tonight.

1131
00:48:34,310 --> 00:48:35,312
- Yeah.

1132
00:48:35,345 --> 00:48:36,246

- You showed a beautiful
picture of the moon,

1133
00:48:36,279 --> 00:48:37,981
Daphne going through
the ring plane.

1134
00:48:38,014 --> 00:48:39,049
- Yeah.

1135
00:48:39,082 --> 00:48:40,083
- How big is that moon
in comparison to ours

1136
00:48:40,116 --> 00:48:42,085
or something else that
we can reference.

1137
00:48:42,118 --> 00:48:45,221
- Ooh!
- It's about 150 miles across.

1138
00:48:45,254 --> 00:48:48,024
- Okay, my friendly face
says that's it's about

1139
00:48:48,057 --> 00:48:49,559
150 miles across.

1140
00:48:49,592 --> 00:48:51,161
- So it's tiny.
- It's tiny, yes.

1141
00:48:51,194 --> 00:48:55,298
- Thank you.
- Yeah.

1142
00:48:55,331 --> 00:48:57,467
Okay, I'm getting some blue
card questions from online,

1143
00:48:57,500 --> 00:48:58,935
but yeah?

1144
00:48:58,968 --> 00:49:02,305
- So as Cassini
gets extended

1145
00:49:02,338 --> 00:49:06,276
over all these years,
does it have an arc?

1146
00:49:06,309 --> 00:49:08,912
Like, did you know you were
going to dive into the rings

1147
00:49:08,945 --> 00:49:10,981
this-- you know, all these
years later as the mantle

1148
00:49:11,014 --> 00:49:14,217
gets passed, they're making up
new missions as they're

1149
00:49:14,250 --> 00:49:16,219
seeing what kind of
science they're gathering?

1150
00:49:16,252 --> 00:49:17,554
Could you talk a
little bit about that?

1151
00:49:17,587 --> 00:49:22,525
- Yeah, so, I think it was 2008
or 2009 when we first thought

1152
00:49:22,558 --> 00:49:26,463
of doing this Grand Finale,
so, you know,

1153
00:49:26,496 --> 00:49:28,198
eight or nine
years before it.

1154
00:49:28,231 --> 00:49:30,367
As far as how Cassini
kept getting extended,

1155
00:49:30,400 --> 00:49:32,435
we would
submit a proposal

1156
00:49:32,468 --> 00:49:35,438
and go through a review
process every two years.

1157
00:49:35,471 --> 00:49:37,874
And that would say, "Hey,
here's what we're doing.

1158
00:49:37,907 --> 00:49:38,775
"Here's our status.

1159
00:49:38,808 --> 00:49:40,010
"Here's all this
great stuff we did.

1160
00:49:40,043 --> 00:49:41,077
"And if you give us
this much more money,

1161
00:49:41,110 --> 00:49:42,779
"here's this much
more great stuff

1162
00:49:42,812 --> 00:49:44,914
"that we think we're
going to be able to do."

1163

00:49:44,947 --> 00:49:46,950
And so it was sort of on this
rolling two-year basis

1164
00:49:46,983 --> 00:49:48,718
that we were able
to try and plan out

1165
00:49:48,751 --> 00:49:51,021
what the next
two years would be.

1166
00:49:51,054 --> 00:49:52,155
- Thank you.

1167
00:49:52,188 --> 00:49:54,424
I'm just in awe of
what humans can do.

1168
00:49:54,457 --> 00:49:55,725
So thank you.
- Yeah.

1169
00:49:55,758 --> 00:50:02,198
[laughter]

1170
00:50:02,231 --> 00:50:04,134
- Okay, so now we have
questions from online.

1171
00:50:04,167 --> 00:50:07,303
So this one's from
YouTube from OneHeart.

1172
00:50:07,336 --> 00:50:13,376
"How small could Cassini be
made with today's technology?"

1173
00:50:13,409 --> 00:50:15,712
Actually interestingly, I

don't think it could be made

1174
00:50:15,745 --> 00:50:18,615
too much smaller.

1175
00:50:18,648 --> 00:50:20,316
Yeah, that graphic that
I showed you where it was

1176
00:50:20,349 --> 00:50:23,586
filled up with propellant,
that wasn't accurate,

1177
00:50:23,619 --> 00:50:25,021
but it was
a lot closer to accurate

1178
00:50:25,054 --> 00:50:27,157
than you may
think it was.

1179
00:50:27,190 --> 00:50:30,226
Most of that spacecraft body
that you see there

1180
00:50:30,259 --> 00:50:31,928
is filled with fuel.

1181
00:50:31,961 --> 00:50:33,730
And so that's really
where it gets its size.

1182
00:50:33,763 --> 00:50:35,031
The other thing
that sizes it

1183
00:50:35,064 --> 00:50:37,700
I'd say is
the antenna up on top,

1184
00:50:37,733 --> 00:50:40,403
and Saturn hasn't gotten
any closer to Earth as far as

1185
00:50:40,436 --> 00:50:43,706
I know, and so the antenna
would need to be about

1186
00:50:43,739 --> 00:50:45,642
the same size in order to
communicate with Earth.

1187
00:50:45,675 --> 00:50:47,911
So the part that would get
smaller, if you look at

1188
00:50:47,944 --> 00:50:50,480
the spacecraft, there's a ring
going around the top,

1189
00:50:50,513 --> 00:50:52,515
below the antenna,
but above the probe.

1190
00:50:52,548 --> 00:50:54,551
That's where all
our electronics are.

1191
00:50:54,584 --> 00:50:59,556
And those could probably
get a little bit smaller.

1192
00:50:59,589 --> 00:51:01,791
Okay, yes, taking them
from-- here we go.

1193
00:51:01,824 --> 00:51:04,861
Okay, also from YouTube,
from AstronomyNation.

1194
00:51:04,894 --> 00:51:08,198
"Was the contamination of
Titan by the Huygens probe

1195
00:51:08,231 --> 00:51:09,299
"taken into consideration."

1196
00:51:09,332 --> 00:51:13,069
Yes, so we knew that
the Huygens probe

1197
00:51:13,102 --> 00:51:15,605
was going to Titan.

1198
00:51:15,638 --> 00:51:18,174
And so we built it
with that in mind.

1199
00:51:18,207 --> 00:51:21,177
And so it went through
a much more stringent

1200
00:51:21,210 --> 00:51:23,546
planetary protection process
than the orbiter did.

1201
00:51:23,579 --> 00:51:26,716
And so that made it safe
to go down to Titan,

1202
00:51:26,749 --> 00:51:28,818
but Cassini-- it's very
expensive to do that.

1203
00:51:28,851 --> 00:51:31,020
And so Cassini was not
built to those standards.

1204
00:51:31,053 --> 00:51:32,722

It wasn't going to
go down to Titan.

1205
00:51:32,755 --> 00:51:38,094
And so that's why it could
not be crashed on Titan.

1206
00:51:38,127 --> 00:51:43,166
Okay...

1207
00:51:43,199 --> 00:51:45,668
Okay, YouTube from
Eric Lamplanta, "What was

1208
00:51:45,701 --> 00:51:50,840
"the biggest surprise that came
out of Cassini's discoveries?"

1209
00:51:50,873 --> 00:51:52,709
I think this is an opinion,
but in my opinion,

1210
00:51:52,742 --> 00:51:54,577
the biggest surprise
was Enceladus.

1211
00:51:54,610 --> 00:51:57,847
I don't think anybody
expected to find

1212
00:51:57,880 --> 00:51:59,782
this global
subsurface ocean

1213
00:51:59,815 --> 00:52:01,985
that actually had, like,
activity where you have

1214
00:52:02,018 --> 00:52:04,087
these jets coming

out of the south pole,

1215
00:52:04,120 --> 00:52:05,221
and then
we later find out,

1216
00:52:05,254 --> 00:52:07,123
hey, it's in contact
with a rocky core.

1217
00:52:07,156 --> 00:52:08,691
Oh, and guess what?

1218
00:52:08,724 --> 00:52:10,827
We think there's actually
evidence that there could be

1219
00:52:10,860 --> 00:52:14,564
the chemicals in that ocean
necessary to support life.

1220
00:52:14,597 --> 00:52:17,700
And so that is definitely
by far the biggest surprise.

1221
00:52:17,733 --> 00:52:22,505
Also because Enceladus at
Saturn is very much

1222
00:52:22,538 --> 00:52:24,274
like Europa at Jupiter.

1223
00:52:24,307 --> 00:52:28,311
It's almost identical in
that it's an icy moon

1224
00:52:28,344 --> 00:52:30,680
with a subsurface ocean in
contact with a rocky core.

1225
00:52:30,713 --> 00:52:34,284
And discovering two of these
in one solar system means that

1226
00:52:34,317 --> 00:52:37,120
these potentially habitable
environments outside

1227
00:52:37,153 --> 00:52:41,391
of the sun's habitable zone
is-- are not rare.

1228
00:52:41,424 --> 00:52:43,660
If you have it twice in one
solar system, it means

1229
00:52:43,693 --> 00:52:45,962
in the whole universe it
could be occurring a lot.

1230
00:52:45,995 --> 00:52:47,697
So it really increases
the probability

1231
00:52:47,730 --> 00:52:54,637
that we could someday
find life beyond Earth.

1232
00:52:54,670 --> 00:52:58,241
Okay, on YouTube
from Claudia.

1233
00:52:58,274 --> 00:53:02,078
"What kind of--

1234
00:53:02,111 --> 00:53:04,547
"Oh, what kind of
cameras were on Cassini?"

1235

00:53:04,580 --> 00:53:08,818
So the cameras on Cassini
were basically telescopes.

1236
00:53:08,851 --> 00:53:10,887
So, like I said, that one
picture of Enceladus

1237
00:53:10,920 --> 00:53:12,889
was taken from half
a million miles away.

1238
00:53:12,922 --> 00:53:16,626
So the cameras are
digital cameras.

1239
00:53:16,659 --> 00:53:19,562
The highest resolution
one is what?

1240
00:53:19,595 --> 00:53:20,797
One megapixel?
- Yeah.

1241
00:53:20,830 --> 00:53:23,733
- Yeah, one megapixel camera.
It was launched in '97.

1242
00:53:23,766 --> 00:53:25,034
Give us a break.

1243
00:53:25,067 --> 00:53:27,170
[laughter]

1244
00:53:27,203 --> 00:53:29,405
- Operates in
the freezing cold.

1245
00:53:29,438 --> 00:53:31,674
- But then it has this huge

lens put on it so that

1246
00:53:31,707 --> 00:53:33,576
the fields of view are
really, really small.

1247
00:53:33,609 --> 00:53:35,411
Like you could not
use them in this room.

1248
00:53:35,444 --> 00:53:37,680
It'd be like using
binoculars in your bedroom.

1249
00:53:37,713 --> 00:53:39,349
You're not going
to see a whole lot.

1250
00:53:39,382 --> 00:53:40,383
So yeah, so that's
what it was.

1251
00:53:40,416 --> 00:53:44,654
It was a one
megapixel telescope.

1252
00:53:44,687 --> 00:53:48,858
All right, any other questions
from the room, from online?

1253
00:53:48,891 --> 00:53:50,793
Oh, I'll repeat it, yes.

1254
00:53:50,826 --> 00:53:55,031
- What's the baud rate that
data was transmitted at?

1255
00:53:55,064 --> 00:53:58,167
- Okay, so he asked what the
baud rate or the data rate

1256
00:53:58,200 --> 00:54:01,037
that Cassini was
able to transmit at.

1257
00:54:01,070 --> 00:54:03,439
And again, I'm going to
look at my friendly face.

1258
00:54:03,472 --> 00:54:04,707
[laughter]

1259
00:54:04,740 --> 00:54:06,509
- Look at your
other friend.

1260
00:54:06,542 --> 00:54:07,577
That one back there.

1261
00:54:07,610 --> 00:54:09,145
- Oh, yeah, yeah, I have
another friendly face.

1262
00:54:09,178 --> 00:54:14,550
You want to come
to the microphone?

1263
00:54:14,583 --> 00:54:16,152
- So the highest data rate
we could transmit at

1264
00:54:16,185 --> 00:54:20,156
was 142,000 bits
per second.

1265
00:54:20,189 --> 00:54:21,758
From a billion
miles away.

1266

00:54:21,791 --> 00:54:22,692
- Yeah.

1267
00:54:22,725 --> 00:54:23,693
[laughter]

1268
00:54:23,726 --> 00:54:24,827
- It may not seem
like fast, but from

1269
00:54:24,860 --> 00:54:30,733
a billion miles away
that's doing pretty good.

1270
00:54:30,766 --> 00:54:32,201
- Okay, if there are
no more questions,

1271
00:54:32,234 --> 00:54:33,569
you're still
welcome to stay here.

1272
00:54:33,602 --> 00:54:34,671
You'll be warm and dry.

1273
00:54:34,704 --> 00:54:36,973
[laughter]

1274
00:54:37,006 --> 00:54:38,608
[applause]

1275
00:54:38,641 --> 00:54:44,180
Oh!

1276
00:54:44,213 --> 00:54:46,849
- How big was
your Cassini team?

1277
00:54:46,882 --> 00:54:50,053

And I'm talking your dates
when you were planner?

1278
00:54:50,086 --> 00:54:51,254
How many people?

1279
00:54:51,287 --> 00:54:54,157
- When I was the planner,
I think we had

1280
00:54:54,190 --> 00:54:56,526
50 to 100
part-time people.

1281
00:54:56,559 --> 00:55:00,096
We didn't have a whole
lot of full time.

1282
00:55:00,129 --> 00:55:02,632
- Well, there's
250 scientists.

1283
00:55:02,665 --> 00:55:04,100
- Oh, sure, yeah, sorry.

1284
00:55:04,133 --> 00:55:06,703
[laughter]

1285
00:55:06,736 --> 00:55:07,704
- Those other people.

1286
00:55:07,737 --> 00:55:10,206
- Yes, the project
people at JPL, sorry.

1287
00:55:10,239 --> 00:55:12,208
The project
people at JPL.

1288

00:55:12,241 --> 00:55:14,077
I believe there are about
100 part-timers that

1289
00:55:14,110 --> 00:55:20,283
all fit into about 50
full time equivalents.

1290
00:55:20,316 --> 00:55:22,018
All right, you can
clap again, if you want.

1291
00:55:22,051 --> 00:55:32,729
[applause]

1292
00:55:32,762 --> 00:55:36,499
- Outstanding, Erick.