Deep Space Atomic Clock

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NASA

Jet Propulsion Laboratory
California Institute of Technology

von Kármán Lecture Series

1
00:00:05,101 --> 00:00:07,370
NASA's
JET PROPULSION LABORATORY

2
00:00:07,370 --> 00:00:10,040
PRESENTS THE VON KARMAN
LECTURES.

3
00:00:10,040 --> 00:00:12,909
A SERIES OF TALKS BY SCIENTISTS
AND ENGINEERS WHO ARE

4
00:00:12,909 --> 00:00:16,196
EXPLORING OUR PLANET,
OUR SOLAR SYSTEM,

5
00:00:16,196 --> 00:00:33,079
AND ALL THAT LIES BEYOND.

6
00:00:33,079 --> 00:00:40,470
GOOD EVENING, LADIES AND
GENTLEMEN.

7
00:00:40,470 --> 00:00:42,222
HOW IS EVERYONE TONIGHT?

8
00:00:42,222 --> 00:00:43,540
THANK YOU FOR COMING OUT TO JOIN
US.

9
00:00:43,540 --> 00:00:47,494
ATOMIC CLOCKS ARE ALMOST
INVISIBLE TO MODERN LIFE.

10
00:00:47,494 --> 00:00:52,115
FOR EXAMPLE, THEY PROVIDE THE
FOUNDATION OF THE GLOBAL

11
00:00:52,115 --> 00:00:55,185

POSITIONING SYSTEM ENABLING AN
ENTIRE INDUSTRY OF LOCATION

12
00:00:55,185 --> 00:00:58,355
AWARE APPLICATIONS, AND THEY
UNDERPIN THE GLOBAL FINANCIAL

13
00:00:58,355 --> 00:01:05,161
AND TRADING SYSTEM WHERE
TRANSACTIONS HAVE TO BE TAGGED

14
00:01:05,161 --> 00:01:06,012
TO MILLISECOND PER SUGGESTION.

15
00:01:06,012 --> 00:01:10,066
THEY HAVE BEEN THE FREQUENT
STANDARD FOR THE DEEP SPACE

16
00:01:10,066 --> 00:01:20,060
NETWORK WHICH TRACKS THE
MULTITUDE OF THE SPACECRAF

17
00:01:20,060 --> 00:01:21,478
DEMONSTRATION MISSION HAS BEEN
MATURING THE LATEST TECHNOLOGIES

18
00:01:21,478 --> 00:01:25,165
INTO A SMALLER, LESS MASSIVE
PACKAGE SUITABLE FOR

19
00:01:25,165 --> 00:01:31,388
INSTALLATION ON A VARIETY OF
DEEP SPACE PROBES TO ENHANCE

20
00:01:31,388 --> 00:01:34,241
NAVIGATION PRECISION ACROSS THE
SOLAR SYSTEM.

21
00:01:34,241 --> 00:01:39,479
WE'RE LUCKY TO HAVE TWO GUESTS

TELL US.

22
00:01:39,479 --> 00:01:48,121
DR. TODD ELLIE IS A GRADUATE OF
PERDUE UNIVERSITY AND FORMER AIR

23
00:01:48,121 --> 00:01:51,057
FORCE OFFICER.

24
00:01:51,057 --> 00:01:55,495
HE'S BEEN AT THE JET PROPULSION
LABORATORY SINCE 1999 DEVELOPING

25
00:01:55,495 --> 00:01:59,165
NAVIGATION SYSTEMS AND
ARCHITECTURES FOR MANY PROJECTS

26
00:01:59,165 --> 00:02:05,288
BE AND SMALL INCLUDING THE MARS
NETWORK, FORMER CONSTELLATION

27
00:02:05,288 --> 00:02:18,201
PROGRAM, AND LUNAR LANDER.

28
00:02:18,201 --> 00:02:22,272
DR. FORRINGTON IS A GRADUATE OF
CAL TECH.

29
00:02:22,272 --> 00:02:25,191
HE HAS DEGREES IN ELECT CALL
ENGINEERING AND MORE THAN 25

30
00:02:25,191 --> 00:02:29,362
YEARS OF EXPERIENCE IN HARDWARE
AND SOFTWARE DEVELOPMENT.

31
00:02:29,362 --> 00:02:33,466
ALMOST 20% IN SPACE
APPLICATIONS.

32
00:02:33,466 --> 00:02:36,519
PLANETARY SCIENCE, AND
SPACECRAFT TECHNOLOGY

33
00:02:36,519 --> 00:02:37,237
DEVELOPMENT.

34
00:02:37,237 --> 00:02:42,042
OTHER THAN SPACE THAT RIGHT,
ALAN'S INTERESTS TEND TOWARD

35
00:02:42,042 --> 00:02:44,477
COLLEGE HOOPS AND BALLROOM
DANCING.

36
00:02:44,477 --> 00:02:49,215
LADIES AND GENTLEMEN, PLEASE
HELP ME WELCOME TONIGHT'S GUESTS

37
00:02:49,215 --> 00:02:55,305
DR. TODD ELY AND ALAN
FAIRINGTON.

38
00:02:55,305 --> 00:02:56,323
[APPLAUSE]
>> THANK YOU, MARK.

39
00:02:56,323 --> 00:02:58,241
THANK YOU FOR COMING.

40
00:02:58,241 --> 00:03:04,264
ALAN AND I EXCITED TO TALK ABOUT
THE ATOMIC CLOCK PROJECT TODAY.

41
00:03:04,264 --> 00:03:07,167
THE DEEP SPACE ATOMIC CLOCK
PROJECT IS DEVELOPING AN

42
00:03:07,167 --> 00:03:14,057

ADVANCED PROTOTYPE OF A NEW TYPE
OF ATOMIC CLOCK THAT WE HOPE TO

43
00:03:14,057 --> 00:03:16,076
DEMONSTRATE IN LOWER ORBIT IN
THE NEAR FUTURE.

44
00:03:16,076 --> 00:03:22,132
NOW THE ATOMIC CLOCK, OBVIOUSLY,
CAN TELL TIME VERY ACCURATELY.

45
00:03:22,132 --> 00:03:26,052
BUT THAT'S NOT HOW WE'RE
INTENDING TO USE IT FOR.

46
00:03:26,052 --> 00:03:26,486
NAVIGATION AND SCIENCE.

47
00:03:26,486 --> 00:03:31,341
IT'S A KEY COMPONENT TO THE
ASPECTS, AND SO OVER THE COURSE

48
00:03:31,341 --> 00:03:35,178
OF THE NEXT HOUR OR SO, WE WOULD
LIKE TO TALK ABOUT HOW CLOCKS

49
00:03:35,178 --> 00:03:41,067
AND TIME PLAY A ROLE TO THE
SCIENCE WE DO IN DEEP SPACE, AND

50
00:03:41,067 --> 00:03:49,459
TO BEGIN THAT WE HAVE A VIDEO TO
SET THE STAGE.

51
00:03:49,459 --> 00:03:56,399
>> TIME SEEMS TO RULE EVERYTHING
WE DO.

52
00:03:56,399 --> 00:03:58,268
IT'S IMPORTANT TO US.

53
00:03:58,268 --> 00:04:05,992
THE HOURS AND MINUTES OF OUR DAY
IS --

54
00:04:05,992 --> 00:04:10,380
■ ■
OFTEN OVERLOOKED IT'S A CRUCIAL

55
00:04:10,380 --> 00:04:15,268
PART IN ANOTHER AREA OF HUMAN
PROGRESS.

56
00:04:15,268 --> 00:04:16,086
NAVIGATION.

57
00:04:16,086 --> 00:04:19,139
WHAT DOES TIME HAVE TO DO WITH
NAVIGATION, YOU ASK?

58
00:04:19,139 --> 00:04:26,413
WELL, GOT A SECOND TO FIND OUT?

59
00:04:26,413 --> 00:04:30,050
SEA EXPLORERS CARRIED CLOCKS ON
TOP THEIR SHIPS.

60
00:04:30,050 --> 00:04:34,070
THE CLOCKS WERE SET TO THE EXACT
TIME TO THE CLOCK ON LAND AND

61
00:04:34,070 --> 00:04:38,041
TOGETHER WITH OBSERVING THE
MOON, SUN, AND THE CLOCK THEY

62
00:04:38,041 --> 00:04:42,095
COULD DETERMINE THE LONGITUDE
AND LATITUDE.

63

00:04:42,095 --> 00:04:46,499
OTHER SHIPS COULD KNOW WHERE
THEY WERE GOING.

64
00:04:46,499 --> 00:04:48,301
AMAZING.

65
00:04:48,301 --> 00:04:52,388
HOWEVER, CLOCKS BACK THEN
WEREN'T VERY ACCURATE.

66
00:04:52,388 --> 00:04:56,392
IF THE SHIPS DRIFTED OFF FROM
THE MAIN CLOCK IT COULD MEAN THE

67
00:04:56,392 --> 00:05:04,200
DIFFERENCE OF FINDING THEIR
DESTINATION AND BEING HOPELESSLY

68
00:05:04,200 --> 00:05:04,350
LOST.

69
00:05:04,350 --> 00:05:13,243
TODAY TIME IS PRECISE IN THE
GLOBAL POSITIONING SYSTEM OR

70
00:05:13,243 --> 00:05:14,294
GPS.

71
00:05:14,294 --> 00:05:18,431
BOATS, PLANES, CARS REPEAT DATA
BACK FROM THE ORBITING SATELLITE

72
00:05:18,431 --> 00:05:24,354
TO CALCULATE THE LONGITUDE AND
LATITUDE.

73
00:05:24,354 --> 00:05:28,358
IT ALLOWS YOU TO ARRIVE TO A
DESTINATION WITHIN FEET.

74
00:05:28,358 --> 00:05:31,394
IT'S ONLY BECAUSE OF TIME THAT
WE CAN KNOW WHERE WE ARE AND

75
00:05:31,394 --> 00:05:40,086
WHERE WE'RE GOING.

76
00:05:40,086 --> 00:05:42,255
WHAT ABOUT IN SPACE?

77
00:05:42,255 --> 00:05:44,440
NOT JUST SPACE BUT DEEP SPACE.

78
00:05:44,440 --> 00:05:50,413
HOW DO YOU NAVIGATE AND EXPLORE
A PLACE WHERE THERE ARE NO

79
00:05:50,413 --> 00:05:53,149
LONGITUDE OR LATITUDE.

80
00:05:53,149 --> 00:05:57,403
RIGHT NOW SCIENTISTS NAVIGATE BY
USING GIANT ANTENNA HERE ON

81
00:05:57,403 --> 00:05:58,054
EARTH.

82
00:05:58,054 --> 00:06:02,408
NOT THOSE KIND.

83
00:06:02,408 --> 00:06:03,226
THESE KIND.

84
00:06:03,226 --> 00:06:07,046
JUST LIKE THE OLD SEA EXPLORERS.

85
00:06:07,046 --> 00:06:11,301

THESE ANTENNA SEND OUT A SIGNAL
BOUNCED OFF THE SPACECRAFT

86
00:06:11,301 --> 00:06:14,020
STRAIGHT BACK TO THE EARTH.

87
00:06:14,020 --> 00:06:23,146
THAT DETERMINES THE SPACECRAFT'S
DISTANCE AND SPEED.

88
00:06:23,146 --> 00:06:24,430
THE SIGNALS OF THE SPACECRAFT
ARE THE MOST EFFICIENT WAY TO

89
00:06:24,430 --> 00:06:25,331
NAVIGATE SPACE.

90
00:06:25,331 --> 00:06:29,052
THEY CAN ONLY TALK TO ONE
SPACECRAFT AT A TIME LEAVING

91
00:06:29,052 --> 00:06:29,419
OTHERS WAITING.

92
00:06:29,419 --> 00:06:35,108
BY THE TIME THE SIGNAL IS
CALCULATED AND SENT BACK, THE

93
00:06:35,108 --> 00:06:38,127
SPACECRAFT ISN'T THE SAME SPOT
ANYMORE AND THE RESULT HAS TO BE

94
00:06:38,127 --> 00:06:38,311
ADJUSTED.

95
00:06:38,311 --> 00:06:43,249
HOW CAN DEEP SPACE EXPLORATION
BECOME EVEN MORE PRECISE.

96

00:06:43,249 --> 00:06:46,469
HOW CAN A PATTERN HAVE A FURTHER
AND FURTHER INTO SPACE BE MORE

97
00:06:46,469 --> 00:06:50,290
IMMEDIATE AND INDEPENDENT OF
HAVING TO CHECK IN WITH --

98
00:06:50,290 --> 00:06:53,493
WHAT'S THAT, SAMMY?

99
00:06:53,493 --> 00:06:57,413
OF COURSE, THE DEEP SPACE ATOMIC
CLOCK.

100
00:06:57,413 --> 00:07:00,099
ENGINEERS HAVE DEVELOPED A WAY
FOR THE SPACECRAFT TO HAVE THE

101
00:07:00,099 --> 00:07:01,050
ON BOARD CLOCK.

102
00:07:01,050 --> 00:07:04,037
IT NO LONGER HAS TO CHECK IN
WITH THE COORDINATES.

103
00:07:04,037 --> 00:07:09,409
THIS THE BREAKTHROUGH DEVICE IS
SELF-SUFFICIENT AND CAN HANDLE

104
00:07:09,409 --> 00:07:12,462
THE HARSH CONDITIONS OF DEEP
SPACE.

105
00:07:12,462 --> 00:07:15,465
NOW THE SPACECRAFT CAN MAKE
IMMEDIATE CORRECTIONS ON ITS

106
00:07:15,465 --> 00:07:16,115
OWN.

107
00:07:16,115 --> 00:07:22,222
A MAN WITH INCREDIBLE PRECISION.

108
00:07:22,222 --> 00:07:23,439
FINALLY GETTING HIS DUE.

109
00:07:23,439 --> 00:07:30,413
PAVING THE WAY FOR MORE PRECISE
SPACE EXPLORATION.

110
00:07:30,413 --> 00:07:36,169
ONE TICK, TOCK, TICK AT A TIME.

111
00:07:36,169 --> 00:07:47,247
[APPLAUSE]
>> SO ALLEN AND I ARE GOING TO

112
00:07:47,247 --> 00:07:50,116
ATTEMPT TO ELABORATE A LITTLE
BIT FURTHER.

113
00:07:50,116 --> 00:07:56,372
WE CAN BEGIN OUR JOURNEY TALKING
ABOUT GOING BACK IN TIME AND

114
00:07:56,372 --> 00:07:57,290
TALKING ABOUT NAVIGATION.

115
00:07:57,290 --> 00:08:00,159
ONE OF THE KEY COMPONENTS OF A
NAVIGATION IS MAP.

116
00:08:00,159 --> 00:08:05,248
TO NAVIGATE ON EARTH, MAPS HAVE
BEEN DRAWN FOR A MILLENNIA AND

117
00:08:05,248 --> 00:08:10,169
HERE'S AN EXAMPLE OF A MAP DROWN

IN 1630.

118
00:08:10,169 --> 00:08:14,374
WHAT IS NOTABLE, IT'S THE FIRST
MAP TO IDENTIFY 15 DEGREES OF

119
00:08:14,374 --> 00:08:20,196
LONGITUDE WITH ONE HOUR OF
ROTATION OF THE EARTH ABOUT THE

120
00:08:20,196 --> 00:08:20,346
AXIS.

121
00:08:20,346 --> 00:08:25,151
SO HOW WE USE MAPS IS NOT ONLY
TO DEFINE, OBVIOUSLY, THE POINTS

122
00:08:25,151 --> 00:08:31,257
OF INTEREST THAT WE WOULD LIKE
TO TRAVEL TO, BUT A REFERENCE

123
00:08:31,257 --> 00:08:31,424
SYSTEM.

124
00:08:31,424 --> 00:08:38,448
IN THIS CASE THE LINES ARE
LATITUDE AND LINES OF LONGITUDE.

125
00:08:38,448 --> 00:08:43,486
SEA FAIRERS HAVE KNOWN FOR
MILLENNIA.

126
00:08:43,486 --> 00:08:52,312
WE CITE THE NORTH STAR.

127
00:08:52,312 --> 00:08:53,413
LONGITUDE IS TRICKIER PROBLEM.

128
00:08:53,413 --> 00:08:57,333

THERE ARE A NUMBER OF METHODS
DEVISED OVER THE MANY THOUSANDS

129
00:08:57,333 --> 00:09:00,186
OF YEARS.

130
00:09:00,186 --> 00:09:04,023
THE EARLIEST OF WHICH IS THE
SAILORS WOULD DROP A ROPE WITH

131
00:09:04,023 --> 00:09:11,114
KNOTS AT THE BOW OF THE SHIP AND
SEE HOW LONG IT TOOK FOR THE

132
00:09:11,114 --> 00:09:14,317
KNOTS TO ARRIVE AT THE STERN OF
THE SHIP AND YOU CAN COMPUTE

133
00:09:14,317 --> 00:09:17,070
VELOCITY AND WITH THE TIME YOU
CAN COMPUTE DISTANCE.

134
00:09:17,070 --> 00:09:18,321
NOT A VERY ACCURATE METHOD.

135
00:09:18,321 --> 00:09:25,978
AT THE TIME THERE ARE OTHER
METHODS, THE MED OF LUNAR

136
00:09:25,978 --> 00:09:26,162
DISTANCES.

137
00:09:26,162 --> 00:09:31,351
IT'S COMPETING WITH USING CLOCKS
TO DETERMINE LONGITUDE.

138
00:09:31,351 --> 00:09:36,089
NOW, HOW WE CAN USE A CLOCK TO
DETERMINE OUR LONGITUDE IS AT

139
00:09:36,089 --> 00:09:37,206
YOUR POINT DEPARTURE.

140
00:09:37,206 --> 00:09:39,008
LET'S SAY IT'S BRITAIN.

141
00:09:39,008 --> 00:09:42,362
YOUR SET YOUR TIME TO THE GROUND
CLOCK THERE.

142
00:09:42,362 --> 00:09:44,364
YOU KNOW THE LONGITUDE BECAUSE
YOU HAVE THE MAP AND YOU SET OFF

143
00:09:44,364 --> 00:09:46,265
ON THE TRAVELS.

144
00:09:46,265 --> 00:09:50,386
EACH DAY AT HIGH NOON, YOU CHECK
THE TIME ON THE CLOCK.

145
00:09:50,386 --> 00:09:53,156
YOU COMPETE THE DIFFERENCE
BETWEEN THAT CLOCK TIME AND HIGH

146
00:09:53,156 --> 00:09:57,226
NOON AND YOU HAVE A MEASURE OF
YOUR LONGITUDE DISTANCE YOU HAVE

147
00:09:57,226 --> 00:09:58,478
TRAVELED DURING YOUR TRAVELS.

148
00:09:58,478 --> 00:10:03,449
AND SO THAT, ACTUALLY, IS THE
METHOD THAT HAS ESTABLISHED

149
00:10:03,449 --> 00:10:11,290
ITSELF AS A NORM, AT LEAST BACK
IN THE 18th CENTURY, AND, IN

150
00:10:11,290 --> 00:10:16,362
FACT, IN 1714, THE BRITISH
PARLIAMENT WAS SO DESPERATE TO

151
00:10:16,362 --> 00:10:20,216
FIGURE OUT A SOLUTION TO THE
LONGITUDE PROBLEM, THEY SET UP A

152
00:10:20,216 --> 00:10:25,154
PRIZE TO 20,000 POUND TO THE
PERSON WHO CAN FIGURE OUT HOW TO

153
00:10:25,154 --> 00:10:26,038
SOLVE THIS.

154
00:10:26,038 --> 00:10:29,525
JOHN HARRISON TOILED FOR DECADES
BUILDING MANY CLOCKS.

155
00:10:29,525 --> 00:10:34,313
THE CHALLENGE THAT HE HAD WAS TO
TAKE THE ACCURACY OF THE GROUND

156
00:10:34,313 --> 00:10:37,316
CLOCK OF THE DAY, WHICH WERE
BIG, AND TRY TO DEVELOP

157
00:10:37,316 --> 00:10:41,187
SOMETHING THAT WAS PORTABLE ON A
SHIP THAT COULD WITHSTAND THE

158
00:10:41,187 --> 00:10:44,140
HARSH ENVIRONMENT THAT A SHIP
PRESENTS TO A CLOCK'S STABILITY.

159
00:10:44,140 --> 00:10:48,394
SO WHAT I MEAN BY CLOCK
STABILITY IS, AS THE CLOCK TICKS

160
00:10:48,394 --> 00:10:52,281
EVERY SECOND, THE CLOCK IS VERY
STABLE AT EACH SECOND IT'S THE

161
00:10:52,281 --> 00:10:53,399
SAME LENGTH IN TIME.

162
00:10:53,399 --> 00:10:56,436
IF THAT LENGTH IN TIME VARIES,
YOU HAVE AN INSTABILITY.

163
00:10:56,436 --> 00:11:06,262
AND SO ON A SHIP, THINGS LIKE
HUMIDITY CHANGES OR MOTION CAN

164
00:11:06,262 --> 00:11:08,064
AFFECT THE STABILITY.

165
00:11:08,064 --> 00:11:11,267
ON THE FOURTH TRY, HE BUILT THIS
WATCH RIGHT HERE.

166
00:11:11,267 --> 00:11:17,273
IT'S ABOUT 5 INCHES IN DIAMETER,
AND IT WAS SUCCESSFUL AT

167
00:11:17,273 --> 00:11:21,077
ACHIEVING THE OBJECTIVE WITH THE
LONGITUDE PRIZE.

168
00:11:21,077 --> 00:11:26,265
1762 A SHIP SET OUT ON A COURSE
FROM BRITAIN TO THE WEST INDIES.

169
00:11:26,265 --> 00:11:29,452
IN THAT 62-DAY JOURNEY IT LOST
FIVE SECONDS OF TIME.

170
00:11:29,452 --> 00:11:33,456

THE STABILITY OF THAT CLOCK WAS
1/10th OF A SECOND PER DAY AND

171
00:11:33,456 --> 00:11:37,360
THAT YIELDED ABOUT A 2 KILOMETER
ERROR LONGITUDE.

172
00:11:37,360 --> 00:11:43,182
THAT WAS GOOD ENOUGH TO NAVIGATE
AND SET ABOUT THE WAY IN WHICH

173
00:11:43,182 --> 00:11:47,186
THE MARINERS WOULD FIGURE OUT
THE LONGITUDE.

174
00:11:47,186 --> 00:11:51,224
BUT CIVILIZATION EVOLVES AND
TECHNOLOGY IMPROVES THE

175
00:11:51,224 --> 00:11:53,276
NAVIGATIONAL NEEDS AND DEMANDS
INCREASE.

176
00:11:53,276 --> 00:11:59,081
SO FAST FORWARD TO THE 1960S AND
THE NAVY NEEDED A WAY TO FIGURE

177
00:11:59,081 --> 00:12:03,102
OUT WHERE THEIR SHIPS AND
SUBMARINES ARE TO MUCH GREATER

178
00:12:03,102 --> 00:12:05,071
ACCURACY THAN PROVIDED.

179
00:12:05,071 --> 00:12:07,373
A SYSTEM WAS BUILD CALLED
TRANSIT.

180
00:12:07,373 --> 00:12:10,309
IT'S ABOUT TEN ORBITING

SATELLITES.

181
00:12:10,309 --> 00:12:14,163
LOW ALTITUDE ABOUT 1100
KILOMETERS, AND IT WAS DESIGNED

182
00:12:14,163 --> 00:12:18,134
SO THAT AS SATELLITES WOULD
OVERFLY THE U.S., THEY WOULD BE

183
00:12:18,134 --> 00:12:18,301
TRACKED.

184
00:12:18,301 --> 00:12:22,305
THOSE TRACKING STATIONS WOULD
COMPUTE THE ORBITS OF THE

185
00:12:22,305 --> 00:12:26,392
SPACECRAFT, AND THEN THAT WOULD
BE UPLOADED TO THE SPACECRAFT.

186
00:12:26,392 --> 00:12:30,479
WHEN THAT SATELLITE WOULD FLY
OVER A SHIP OR SUBMARINE, IT

187
00:12:30,479 --> 00:12:35,384
WOULD SEND A SIGNAL TO THE SHIP
OR SUBMARINE AND USING KNOWLEDGE

188
00:12:35,384 --> 00:12:39,088
OF WHERE THE SPACECRAFT WAS AT,
BECAUSE IT WOULD BROADCAST THE

189
00:12:39,088 --> 00:12:43,376
LOCATION, IT WOULD MEASURE THE
FREQUENCY SHIFT OF THIS SIGNAL

190
00:12:43,376 --> 00:12:47,046
TRANSITTING FROM THE SATELLITE
TO THE SHIP.

191
00:12:47,046 --> 00:12:50,449
NOW YOU CAN USE THE INFORMATION
TO FIGURE OUT HOW YOUR LOCATION.

192
00:12:50,449 --> 00:12:56,305
BUT WHAT IT REQUIRES IN THIS
ONE-WAYAL IS THAT THE CLOCK ON

193
00:12:56,305 --> 00:13:00,109
BOARD THE SATELLITE AND THE
CLOCK ON BOARD THE SHIP ARE VERY

194
00:13:00,109 --> 00:13:00,293
ACCURATE.

195
00:13:00,293 --> 00:13:02,311
AND SO THEY WEREN'T GOOD ENOUGH.

196
00:13:02,311 --> 00:13:11,254
TO RESPOND TO THAT, THE
TECHNOLOGY FOR CLOCKS SHIFTED TO

197
00:13:11,254 --> 00:13:14,006
USING SOMETHING LIKE A KWAURZ
-- QUARTZ CRYSTAL.

198
00:13:14,006 --> 00:13:18,210
HERE IS A PICTURE OF THE USO
TRANSIT SATELLITES IN 1960.

199
00:13:18,210 --> 00:13:23,299
AND THE WAY THE QUARTZ CRYSTAL
OSCILLATOR WORKS IS THAT IT USES

200
00:13:23,299 --> 00:13:31,357
THE MECHANICAL VIBRATION OF THE
QUARTZ TO DO THE TICKING.

201

00:13:31,357 --> 00:13:35,061
THIS DRAMATICALLY IMPROVE THE
ACCURACY OF THE NAVIGATION

202
00:13:35,061 --> 00:13:38,314
SYSTEMS ON THE TIME TRANSIT TO
DETERMINE THE LOCATION OF A

203
00:13:38,314 --> 00:13:42,501
SHIFT OF ABOUT 200 METERS.

204
00:13:42,501 --> 00:13:44,520
WE USE USO IN DEEP SPACE.

205
00:13:44,520 --> 00:13:51,527
HERE IS A PICTURE OF A USO WE
INTEND TO FLY ON OUR MISSION.

206
00:13:51,527 --> 00:13:56,198
THEY'RE OFTEN USED IN DEEP
SPACES FOR A LOT OF USES

207
00:13:56,198 --> 00:13:56,399
NAVIGATION.

208
00:13:56,399 --> 00:13:58,050
SOMETIMES, BUT THEY'RE STILL NOT
GOOD ENOUGH.

209
00:13:58,050 --> 00:14:03,189
ON OUR MISSION WE BUILT A USO
THAT IS STABLE BETTER THAN A

210
00:14:03,189 --> 00:14:04,123
MICROSECOND PER DAY.

211
00:14:04,123 --> 00:14:04,407
IT'S GOOD.

212

00:14:04,407 --> 00:14:08,327
BUT IT'S NOT GOOD ENOUGH FOR
DEEP SPACE NAVIGATION.

213
00:14:08,327 --> 00:14:12,031
IN FACT, THE TRANSIT SYSTEM
RESPONDED TO THE NEED OF THE

214
00:14:12,031 --> 00:14:15,434
TIME, BUT IT WASN'T GOOD ENOUGH
FOR GLOBAL POSITIONING.

215
00:14:15,434 --> 00:14:18,270
WE'RE FAMILIAR WITH THIS
CONSTELLATION THAT GLOBAL

216
00:14:18,270 --> 00:14:19,288
POSITIONING SYSTEM.

217
00:14:19,288 --> 00:14:24,193
IT'S A SYSTEM OF 32 SATELLITES,
AND THIS RESPONDED TO THE

218
00:14:24,193 --> 00:14:31,200
CHALLENGES PRESENTED BY TRANSIT
BY OFFERING MORE COVERAGE 32

219
00:14:31,200 --> 00:14:34,203
SATELLITES YIELD OVER FOUR
SATELLITES AT MOST LOCATIONS ON

220
00:14:34,203 --> 00:14:38,074
THE EARTH ALL THE TIME AND OFTEN
MORE THAN FOUR SATELLITES.

221
00:14:38,074 --> 00:14:41,460
SO THIS COVERAGE ALLOWS US TO
GET POSITIONING TO A MUCH

222
00:14:41,460 --> 00:14:46,032

GREATER ACCURACY THAN A HUNDRED
METERS.

223
00:14:46,032 --> 00:14:49,402
AND ANOTHER FUNDAMENTAL ASPECT
THERE ARE ATOMIC CLOCKS ON BOARD

224
00:14:49,402 --> 00:14:50,369
THE SPACE SATELLITE.

225
00:14:50,369 --> 00:14:56,509
AND THOSE ATOMIC CLOCKS ARE
NEEDED TO ENSURE THAT THE

226
00:14:56,509 --> 00:14:58,227
SIGNALS SENT FROM EACH SATELLITE
ARE EXTREMELY PRECISE AND

227
00:14:58,227 --> 00:14:58,411
ACCURATE.

228
00:14:58,411 --> 00:15:02,114
THE FACT THERE ARE 32 SATELLITES
MEANS THAT THE USERS CLOCK

229
00:15:02,114 --> 00:15:04,016
DOESN'T NEED TO BE NEARLY AS
ACCURATE.

230
00:15:04,016 --> 00:15:05,317
YOU DON'T NEED A USO.

231
00:15:05,317 --> 00:15:08,037
YOU DON'T NEED AN ATOMIC CLOCK.

232
00:15:08,037 --> 00:15:12,074
EVERYBODY WHO HAS A SMARTPHONE
HAS A GPS RECEIVER INSIDE THEIR

233

00:15:12,074 --> 00:15:14,360
PHONE, AND THEY DON'T HAVE AN
ATOMIC CLOCK.

234
00:15:14,360 --> 00:15:19,081
HOW DO WE DETERMINE OUR POSITION
MORE ACCURATELY GIVEN THAT WE

235
00:15:19,081 --> 00:15:22,301
HAVE A WORSE PERFORMING CLOCK
THAN OUR PHONE OR OTHER GROUND

236
00:15:22,301 --> 00:15:24,487
GPS RECEIVERS?

237
00:15:24,487 --> 00:15:28,057
SO I'M GOING TO DO A LITTLE
EXPERIMENT WITH YOU ALL TO TRY

238
00:15:28,057 --> 00:15:30,126
TO ILLUSTRATE HOW THE PROCESS
WORKS.

239
00:15:30,126 --> 00:15:37,066
IT'S A SIMPLIFIED EXAMPLE, BUT
THE FUNDAMENTALS ARE TRUE FOR

240
00:15:37,066 --> 00:15:40,419
THE MORE COMPLICATED SITUATIONS
WE USE NAVIGATIONAL GPS.

241
00:15:40,419 --> 00:15:45,107
I'M GOING TO FLAT LAND.

242
00:15:45,107 --> 00:15:47,376
A TWO DIMENSIONAL SPACE.

243
00:15:47,376 --> 00:15:50,296
I HAVE THREE GPS SATELLITES
INDICATED HERE IN THE CORNER.

244
00:15:50,296 --> 00:15:51,514
I'M SOMEWHERE IN HERE.

245
00:15:51,514 --> 00:15:53,482
I'M TRYING TO FIGURE OUT WHERE
I'M AT.

246
00:15:53,482 --> 00:15:58,437
I'M GOING TO TAKE MEASUREMENTS
OF MY GPS RECEIVER THAT IS IN MY

247
00:15:58,437 --> 00:15:59,088
PHONE.

248
00:15:59,088 --> 00:16:04,193
THE WAY IT WORKS I'LL GET
SIGNALS FROM EACH ONE OF THESE

249
00:16:04,193 --> 00:16:08,114
SATELLITES INSTANTANEOUSLY AND
SIMULTANEOUSLY.

250
00:16:08,114 --> 00:16:10,099
WITH THE FIRST MEASUREMENT, I'LL
GET A MEASURE OF RANGE.

251
00:16:10,099 --> 00:16:17,356
THE WAY IT WORKS IS THE
SATELLITE ESSENTIALLY SEND A

252
00:16:17,356 --> 00:16:19,308
SIGNAL ON THE TIME AND WHEN I
RECEIVE IT, WHENEVER I'M AT,

253
00:16:19,308 --> 00:16:26,182
I'LL HAVE A MEASURE OF RANGE AS
WELL AS A MEASURE OF HOW FAR OFF

254

00:16:26,182 --> 00:16:27,166
MY LOCAL CLOCK IS.

255
00:16:27,166 --> 00:16:33,072
SO THE GPS SATELLITE IS ABOUT
20,000 KILOMETERS IN ALTITUDE.

256
00:16:33,072 --> 00:16:36,275
IT TAKES ABOUT 70 MILLISECOND
FOR THE SIGNAL TO ARRIVE ON

257
00:16:36,275 --> 00:16:36,442
EARTH.

258
00:16:36,442 --> 00:16:43,215
I'M GOING TO COMPARE THAT TIME
TO WHAT MY PHONE SAYS AND I'LL

259
00:16:43,215 --> 00:16:46,068
HAVE A MEASURE OF THE DISTANCE
PLUS THE AIR IN THE CLOCK.

260
00:16:46,068 --> 00:16:49,371
WITH THE SINGULAR MEASUREMENT, I
CAN BE ANYWHERE IN THE BAND

261
00:16:49,371 --> 00:16:52,508
WHERE THE BAND REPRESENTS MY
CLOCK HERE.

262
00:16:52,508 --> 00:16:55,311
SO WITH THE SECOND GPS
MEASUREMENT, WE HAVE THIS

263
00:16:55,311 --> 00:16:59,348
MEASURE OF RANGE AND I CAN BE
ANYWHERE IN THIS BAN.

264
00:16:59,348 --> 00:17:03,185
BUT IF I COMBINE THE TWO, I'M

SOMEWHERE IN THE FOOTBALL SHAPED

265
00:17:03,185 --> 00:17:03,402
REGION.

266
00:17:03,402 --> 00:17:07,223
SO I'VE NOW ACTUALLY FIXED
MYSELF SOMEWHERE HERE, WHICH IS

267
00:17:07,223 --> 00:17:08,390
TWO MEASUREMENTS.

268
00:17:08,390 --> 00:17:10,242
I STILL DON'T KNOW MY TIME.

269
00:17:10,242 --> 00:17:12,077
I NEED A THIRD MEASUREMENT.

270
00:17:12,077 --> 00:17:17,016
WITH THAT THIRD MEASUREMENT, MY
LOCATION GETS MORE PRECISE AND I

271
00:17:17,016 --> 00:17:19,251
HAVE ANOTHER PIECE OF
INFORMATION THAT SAYS YOUR

272
00:17:19,251 --> 00:17:24,206
CLOCK'S TIME IS X.

273
00:17:24,206 --> 00:17:27,142
THAT'S, IN A NUTSHELL HOW OUR
RECEIVERS IN OUR PHONES AND

274
00:17:27,142 --> 00:17:28,994
OTHER GPS RECEIVERS WORK TODAY.

275
00:17:28,994 --> 00:17:31,347
BUT IT'S STILL NOT GOOD ENOUGH
FOR DEEP SPACE NAVIGATION.

276
00:17:31,347 --> 00:17:39,171
WE DON'T HAVE A PLETHORA OF
SATELLITES ZRUBTED ACROSS THE

277
00:17:39,171 --> 00:17:41,390
SOLAR SYSTEM TO DID DO THAT
NAVIGATION SYSTEM.

278
00:17:41,390 --> 00:17:43,375
WE HAVE THE DEEP SPACE NETWORK.

279
00:17:43,375 --> 00:17:47,179
IT WAS FORMED ABOUT THE TIME
THAT NASA WAS FORMED AT THE END

280
00:17:47,179 --> 00:17:51,483
OF THE 1950s, AND THE WAY IN
WHICH WE GET TRACKING DATA TO

281
00:17:51,483 --> 00:17:57,156
OUR SATELLITE AND OUR PROBES AND
SPACECRAFT ARE THROUGH THE

282
00:17:57,156 --> 00:17:59,291
RATHER HUGE ANTENNA.

283
00:17:59,291 --> 00:18:05,347
THIS PICTURE OVER HERE, THIS IS
THE FEED HORN OF THIS 70 METER

284
00:18:05,347 --> 00:18:07,166
ANTENNA IN CALIFORNIA.

285
00:18:07,166 --> 00:18:11,220
THAT'S A PERSON STANDING ON THE
END.

286
00:18:11,220 --> 00:18:12,388

THEY'RE BIG.

287
00:18:12,388 --> 00:18:17,192
THE REASON WHY THEY'RE BIG, THEY
NEED TO TRANSSUBMIT A POWERFUL

288
00:18:17,192 --> 00:18:19,461
SYSTEM TO SPACECRAFT IN
SATELLITES THAT ARE HUNDRED OF

289
00:18:19,461 --> 00:18:21,080
MILLIONS OF KILOMETERS AWAY.

290
00:18:21,080 --> 00:18:25,200
THE SATELLITES DON'T HAVE THE
TRANSMISSION POWER TO RETURN IT.

291
00:18:25,200 --> 00:18:29,305
THESE ANTENNAS -- EXCUSE ME,
THEY HAVE THE POWER TO RETURN

292
00:18:29,305 --> 00:18:29,438
IT.

293
00:18:29,438 --> 00:18:32,207
THEY HAVE HIGH GAIN ANTENNA ON
THEM AS WELL.

294
00:18:32,207 --> 00:18:40,115
BUT IT STARTS WITH A LARGE
TRANSMISSION FROM ONE OF THE

295
00:18:40,115 --> 00:18:40,299
STATIONS.

296
00:18:40,299 --> 00:18:46,372
YOU CAN IMAGINE THERE ARE ONLY
THREE COMPLEXES ON EARTH.

297

00:18:46,372 --> 00:18:52,011
THEY'RE SEPARATED LONGITUDELY BY
122 DEGREES SO TYPICALLY THERE'S

298
00:18:52,011 --> 00:18:56,165
ALWAYS ONE STATION IN VIEW OF A
SPACECRAFT OR SPACECRAFT IN THE

299
00:18:56,165 --> 00:18:58,100
SOLAR SYSTEM.

300
00:18:58,100 --> 00:19:01,120
AND THE WAY IN WHICH THIS SYSTEM
WORKS IT USES RANGING LIKE THE

301
00:19:01,120 --> 00:19:04,240
GPS, BUT WE USE TWO-WAY RANGING,
TYPICALLY, TODAY.

302
00:19:04,240 --> 00:19:08,961
AND THE REASON WE USE TWO-WAY
RANGING AND DOPPLER IS THAT THE

303
00:19:08,961 --> 00:19:11,130
SPACECRAFT CLOCKS AREN'T GOOD
ENOUGH.

304
00:19:11,130 --> 00:19:15,301
AT BEST THEY HAVE USO TODAY.

305
00:19:15,301 --> 00:19:18,120
AND THOSE AREN'T STABLE ENOUGH
SO THAT THE ONE-WAY SIGNALS WE

306
00:19:18,120 --> 00:19:22,358
GET WITH THEM WILL ALLOW US TO
NAVIGATE ACCURATELY AND

307
00:19:22,358 --> 00:19:23,058
PRECISELY.

308
00:19:23,058 --> 00:19:28,213
SO THE WAY THE TWO-WAY SIGNAL
WORKS IS THEY'LL SEND THAT TONE

309
00:19:28,213 --> 00:19:29,164
AT A CERTAIN TIME.

310
00:19:29,164 --> 00:19:31,283
IT WILL SEND IT UP TO THE
SPACECRAFT.

311
00:19:31,283 --> 00:19:36,405
THE SPACECRAFT WILL TURN IT
AROUND AND BE RECEIVED BACK HERE

312
00:19:36,405 --> 00:19:39,391
AT EARTH AND THAT'S WHERE THE
MEASUREMENT TAKES PLACE.

313
00:19:39,391 --> 00:19:43,112
ON THE GROUND WE'LL PROCESS THE
DATA TO FIGURE OUT THE

314
00:19:43,112 --> 00:19:44,196
TRAJECTORY OF THE SPACECRAFT.

315
00:19:44,196 --> 00:19:48,334
NOW YOU CAN IMAGINE THAT YOU
NEED PRECISION CLOCKS AND

316
00:19:48,334 --> 00:19:50,035
FREQUENCY SOURCES IN THE
STATIONS.

317
00:19:50,035 --> 00:19:51,070
WE DO.

318
00:19:51,070 --> 00:19:54,490

WE HAVE VERY PRECISE STABLE
STANDARDS.

319
00:19:54,490 --> 00:19:59,094
ALAN WILL TALK TO YOU AND SHOW
YOU PICTURES OF HOW BIG THEY

320
00:19:59,094 --> 00:19:59,228
ARE.

321
00:19:59,228 --> 00:20:00,362
THEY'RE STABLE AND PRECISE.

322
00:20:00,362 --> 00:20:05,451
THEY ONLY DRIFT ABOUT A TENTH OF
A MECHANIC KNOW SECOND PER DAY.

323
00:20:05,451 --> 00:20:07,286
IT'S A EXTREMELY TINY NUMBER.

324
00:20:07,286 --> 00:20:09,488
THIS IS GOOD ENOUGH FOR DEEP
SPACE NAVIGATION.

325
00:20:09,488 --> 00:20:14,276
I'M GOING TO DO ANOTHER
EXPERIMENT AND ILLUSTRATE HOW WE

326
00:20:14,276 --> 00:20:22,067
DO DEEP SPACE NAVIGATION WITH
THESE KINDS OF SIGNALS.

327
00:20:22,067 --> 00:20:27,072
WE HAVE TO KEEP IN MIND ABOUT
THE EARTH-BASED AND A HALF

328
00:20:27,072 --> 00:20:27,272
NAVIGATION.

329

00:20:27,272 --> 00:20:28,440
WE'RE IN THE SOLAR SYSTEM.

330
00:20:28,440 --> 00:20:30,442
WE HAVE TO FIGURE OUT WHAT WE
NEED.

331
00:20:30,442 --> 00:20:32,177
IT'S A REFERENCE SYSTEM.

332
00:20:32,177 --> 00:20:34,313
ON EARTH WE HAVE LATITUDE AND
LONGITUDE.

333
00:20:34,313 --> 00:20:40,069
IN DEEP SPACE WE HAVE A THREE
DIMENSIONAL SYSTEM WE DEFINE AT

334
00:20:40,069 --> 00:20:41,103
THE CENTER NEAR THE CENTER OF
THE SUN.

335
00:20:41,103 --> 00:20:44,139
WE NEED A MAP.

336
00:20:44,139 --> 00:20:46,342
WE NEED A MAP OF WHERE THE
DESTINATIONS ARE.

337
00:20:46,342 --> 00:20:49,511
THE TRAJECTORIES OF THE PLANETS
AND MOONS ANDS A STROIDS.

338
00:20:49,511 --> 00:20:54,416
WITH THIS MAP AND THIS SYSTEM
AND THE TRACKING DATA, WE CAN

339
00:20:54,416 --> 00:21:01,457
RESOLVE LOCATIONS AND
TRAJECTORIES AND SPACECRAFT.

340
00:21:01,457 --> 00:21:07,079
UNLIKE GPS WHERE WE DIDN'T NEED
PRECISION MODELS OF HOW

341
00:21:07,079 --> 00:21:08,013
SPACECRAFT MOVES.

342
00:21:08,013 --> 00:21:13,218
BECAUSE OF ONLY HAVING A SINGLE
STATION AT ANY GIVEN TIME, WE

343
00:21:13,218 --> 00:21:16,472
NEED PRECISE MODELS OF HOW
SPACECRAFT MOVEMENTS FACE.

344
00:21:16,472 --> 00:21:21,443
FOR THOSE THAT HAD A COLLEGE
PHYSICS CLASS, THESE ARE THE

345
00:21:21,443 --> 00:21:24,079
EQUATIONS OF MOTION YOU WERE
TAUGHT BACK IN THAT DAY.

346
00:21:24,079 --> 00:21:30,169
THERE A NUMBER OF FORCES THAT
ARE TRANSITING THROUGH THE SOLAR

347
00:21:30,169 --> 00:21:30,369
SYSTEM.

348
00:21:30,369 --> 00:21:35,390
OF COURSE, THE GRAVITATIONAL
PARTS OF THE PLANETS NEED TO BE

349
00:21:35,390 --> 00:21:36,108
ACCOUNTED FOR.

350
00:21:36,108 --> 00:21:39,078

THE FACT THAT THE GRAVITY FEEL
THAT ANY GIVEN PLANET IS

351
00:21:39,078 --> 00:21:42,247
NONUNIFORM TUGS ON THE
SPACECRAFT.

352
00:21:42,247 --> 00:21:45,084
THE FACT THAT THE SUN BEAMS
ENERGY ON THE SPACECRAFT PUSHES

353
00:21:45,084 --> 00:21:46,518
IT AROUND, TOO.

354
00:21:46,518 --> 00:21:48,087
WE NEED TO ACCOUNT FOR THAT.

355
00:21:48,087 --> 00:21:51,223
WE NEED TO ACCOUNT FOR THE FACT
THAT SPACE ISN'T FLAT.

356
00:21:51,223 --> 00:21:54,209
EINSTEIN TOLD US IT'S CURVED.

357
00:21:54,209 --> 00:21:58,363
SO TIME WILL CHANGE ITS RATE
BASED ON WHERE WE'RE AT IN THE

358
00:21:58,363 --> 00:22:01,416
GRAVITY WALLS OF EACH OF THESE
SOLAR SYSTEM BODIES.

359
00:22:01,416 --> 00:22:03,085
WE HAVE TO ACCOUNT FOR THAT.

360
00:22:03,085 --> 00:22:08,240
WE HAVE TO ACCOUNT FOR GASES
THAT ARE EMANATING FROM OUR

361

00:22:15,047 --> 00:22:08,440
SPACECRAFT.

362
00:22:15,047 --> 00:22:17,132
WE COUPLE IT WITH THE TRACKING
DATA WE GET.

363
00:22:17,132 --> 00:22:19,134
THIS IS HOW IT WORKS.

364
00:22:19,134 --> 00:22:25,407
AT LEAST IN THE LITTLE TWO-DAY
EXAMPLE, AND NOW, LIKE BEFORE, I

365
00:22:25,407 --> 00:22:30,479
HAVE A SPACE WITH THE REFERENCE
SYSTEM, AND THIS EXAMPLE I'M

366
00:22:30,479 --> 00:22:35,300
GOING IT LOOK AT ONE WAY DATA
WITH A BAD CLOCK.

367
00:22:35,300 --> 00:22:36,451
WE DON'T HAVE THAT NOW.

368
00:22:36,451 --> 00:22:41,156
AND I HAVE A SINGLE STATION IS
IN VIEW OF THE SATELLITE AND THE

369
00:22:41,156 --> 00:22:46,178
OTHER THING I KNOW IN THIS
LITTLE EXPERIMENT IS I'M ON A

370
00:22:46,178 --> 00:22:50,449
TRAJECTORY THAT IS A STRAIGHT
LINE TRAVELING AT A CONSTANT

371
00:22:50,449 --> 00:22:51,166
VELOCITY.

372
00:22:51,166 --> 00:22:53,418
IT'S A KEY INFORMATION FOR IT TO
WORK.

373
00:22:53,418 --> 00:22:57,272
IT WILL GET THE FIRST
MEASUREMENT TO MY SPACECRAFT.

374
00:22:57,272 --> 00:23:04,279
TO MEASURE OF RANGE AND, LIKE
BEFORE, I CAN BE ANYWHERE ON

375
00:23:04,279 --> 00:23:05,013
THAT CURVE.

376
00:23:05,013 --> 00:23:08,233
IT'S THE SAME RANGE AS HERE AS
HERE.

377
00:23:08,233 --> 00:23:12,304
THE BAN REPRESENTS THIS.

378
00:23:12,304 --> 00:23:15,073
I GET ANOTHER ONE AT SOME LATER
TIME.

379
00:23:15,073 --> 00:23:17,459
IT'S NOT FOUR MEASUREMENTS AT
THE SAME TIME, IT'S AT A

380
00:23:17,459 --> 00:23:20,062
DIFFERENT TIME.

381
00:23:20,062 --> 00:23:20,312
SO I'VE MOVED.

382
00:23:20,312 --> 00:23:23,131
AND SO NOW THE RANGE TO THE
SPACECRAFT HAS CHANGED.

383
00:23:23,131 --> 00:23:25,450
AND I CAN BE ANYWHERE HERE.

384
00:23:25,450 --> 00:23:30,038
AND I CAN TAKE ANOTHER ONE AND
ANOTHER ONE.

385
00:23:30,038 --> 00:23:32,090
I HAVE FOUR PIECES OF
INFORMATION NOW.

386
00:23:32,090 --> 00:23:35,194
AND FOR MY SIMPLE MODEL OF A
STRAIGHT LINE MOTION WITH A

387
00:23:35,194 --> 00:23:36,094
CONSTANT VELOCITY.

388
00:23:36,094 --> 00:23:38,113
THAT'S ENOUGH TO FIGURE OUT
WHERE I'M AT.

389
00:23:38,113 --> 00:23:39,097
I HAVE A PROBLEM.

390
00:23:39,097 --> 00:23:41,416
I HAVE THIS LARGE CLOCK HERE.

391
00:23:41,416 --> 00:23:43,285
I CAN PICK A SOLUTION LIKE THIS.

392
00:23:43,285 --> 00:23:51,276
AND THIS IS PERFECTLY
SATISFACTIONLY.

393
00:23:51,276 --> 00:23:53,245
BOTH OF THESE SOLUTIONS ARE
WRONG.

394
00:23:53,245 --> 00:23:55,247
THE RIGHT SOLUTION IS THAT.

395
00:23:55,247 --> 00:23:59,084
BUT MY DATA IS NOT GOOD ENOUGH
TO TELL ME THAT SOLUTION.

396
00:23:59,084 --> 00:24:02,020
SO LET'S SWITCH THE SCENARIO A
LITTLE BIT.

397
00:24:02,020 --> 00:24:04,006
NOW WE'RE GETTING TWO-WAY DATA.

398
00:24:04,006 --> 00:24:05,407
THAT'S THE WAY WE DO TODAY.

399
00:24:05,407 --> 00:24:11,296
WE'RE GETTING ONE-WAY DATA ON
BOARD THAT SPACECRAFT.

400
00:24:11,296 --> 00:24:15,033
SAME THING WE GET OUR FIRST
RANGE MEASUREMENT, OUR SECOND,

401
00:24:15,033 --> 00:24:16,368
THIRD, AND FOURTH.

402
00:24:16,368 --> 00:24:20,355
BUT NOW YOU'LL NOTICE THAT MY
LINE IS VERY NARROW.

403
00:24:20,355 --> 00:24:23,392
THAT'S BECAUSE MY CLOCK IS VERY
ACCURATE.

404
00:24:23,392 --> 00:24:26,194
OR MY TWO-WAY MEASUREMENT IS

ACCURATE.

405
00:24:26,194 --> 00:24:31,300
THE ONE-WAY DATA IS AS ACCURATE
AS THE TWO-WAY DATA WE GET

406
00:24:31,300 --> 00:24:31,466
TODAY.

407
00:24:31,466 --> 00:24:33,168
NOW I'M GOING SET MY LINE.

408
00:24:33,168 --> 00:24:34,419
I KNOW IT'S A STRAIGHT LINE.

409
00:24:34,419 --> 00:24:37,189
I KNOW IT'S A CONSTANT VELOCITY.

410
00:24:37,189 --> 00:24:39,391
THAT'S THE ONLY LINE THAT WORKS
IN THIS LITTLE EXAMPLE.

411
00:24:39,391 --> 00:24:44,246
AND THE REASON WHY IT WORKS IS
BECAUSE I HAVE THIS PRECISION

412
00:24:44,246 --> 00:24:48,300
MEASUREMENT OF RANGE.

413
00:24:48,300 --> 00:24:51,470
YOU CAN IMAGINE IT'S A SIMPLE
EXACT.

414
00:24:51,470 --> 00:24:53,372
IT'S MORE COMPLICATED IN REAL
LIFE.

415
00:24:53,372 --> 00:24:56,108
BUT FUNDAMENTALLY THIS IS HOW IT

WORKS.

416
00:24:56,108 --> 00:25:00,445
WHAT DOES IT MEAN FOR THE FUTURE
OF NAVIGATION IN DEEP SPACE?

417
00:25:00,445 --> 00:25:04,349
THIS IS A WAY IT WORKS TODAY.

418
00:25:04,349 --> 00:25:06,385
SO I'VE CHOSEN ANOTHER EXAMPLE
TO ILLUSTRATE THE FLEXIBILITY

419
00:25:06,385 --> 00:25:14,226
AND THE SCALEABILITY THAT D SACK
IMPLIES FOR THE DEEP SPACE

420
00:25:14,226 --> 00:25:14,426
NAVIGATION.

421
00:25:14,426 --> 00:25:19,464
WE HAVE A LOT OF ORBITERS AND
ROVERERS ON THE SURFACE OF MARRS

422
00:25:19,464 --> 00:25:20,132
TODAY.

423
00:25:20,132 --> 00:25:21,333
HERE IS AN EXAMPLE.

424
00:25:21,333 --> 00:25:23,435
WE'VE GOT FOUR ORBITERS AT
MARRS.

425
00:25:23,435 --> 00:25:29,408
WE HAVE A SPACECRAFT THAT IS
GOING TO LAND ON MARS.

426
00:25:29,408 --> 00:25:32,344

WE'RE GOING TO TRACK IT USING
TWO-WAY TRACKING.

427
00:25:32,344 --> 00:25:36,298
TODAY YOU HAVE AN TEN THAT, AND
IT WILL COMMUNICATE WITH THE

428
00:25:36,298 --> 00:25:38,367
SPACECRAFT AND GET THE TWO-WAY
TRACKING.

429
00:25:38,367 --> 00:25:43,155
BECAUSE OF THE TWO-WAY LENGTH
IT'S THE ONLY VEHICLE THAT IS

430
00:25:43,155 --> 00:25:44,373
GETTING IN TRACKING.

431
00:25:44,373 --> 00:25:51,096
SO TO GET TRACKING ON THAT
ORBITER, YOU NEED ANOTHER

432
00:25:51,096 --> 00:25:52,197
ANTENNA.

433
00:25:52,197 --> 00:25:53,448
UNFORTUNATELY THEY AREN'T
GETTING ANY TRACKING.

434
00:25:53,448 --> 00:25:54,366
THEY HAVE THE TIMESHARE.

435
00:25:54,366 --> 00:26:01,206
ALL THE VEHICLES AT D-SACK AND
USING ONE-WAY TRACKING QUESTION

436
00:26:01,206 --> 00:26:04,042
TAKE ADVANTAGE THAT THEY CAN
LISTEN TO MORE THAN ONE

437
00:26:04,042 --> 00:26:05,143
SPACECRAFT AT THE TIME.

438
00:26:05,143 --> 00:26:08,263
THEY CAN LISTEN TO TWO AND THERE
ARE PLANS TO UPGRADE TO FOUR.

439
00:26:08,263 --> 00:26:13,418
IN THIS EXAMPLE, THE SPACECRAFT
AND THAT SPACECRAFT CAN GET THE

440
00:26:13,418 --> 00:26:20,042
NEEDED TRACKING FOR ORBIT
DETERMINATION OR NAVIGATION.

441
00:26:20,042 --> 00:26:23,311
IN FACT, THIS ANTENNA THERE'S AN
ANTENNA BROADCASTING TO MARS.

442
00:26:23,311 --> 00:26:26,048
YOU CAN TRACK A SIGNAL ON THE UP
LENGTH.

443
00:26:26,048 --> 00:26:30,218
WHAT IS NEAT ABOUT THIS TRACKING
IT'S LIKE A BROADCAST SIGNAL

444
00:26:30,218 --> 00:26:34,272
LIKE GPS OR TRANSIT.

445
00:26:34,272 --> 00:26:39,094
IT DOESN'T REQUIRE THIS
SATELLITE TO TALK BACK.

446
00:26:39,094 --> 00:26:42,114
SO ANYBODY LISTENING IN CAN GET
ONE-WAY TRACKING.

447
00:26:42,114 --> 00:26:45,233

THAT'S GOOD ENOUGH FOR
NAVIGATION.

448
00:26:45,233 --> 00:26:48,070
AND FURTHER MORE, THIS IS
LEADING TO THE LATTER PART OF

449
00:26:48,070 --> 00:26:52,190
THE TALK IS NOT ONLY COULD YOU
COLLECT THAT DATA ON BOARD, NOW

450
00:26:52,190 --> 00:26:58,413
YOU HAVE THE POSSIBILITY OF
PROCESSING IT ON BOARD.

451
00:26:58,413 --> 00:27:04,069
SO I'M GOING LET ALLEN TALK NOW
ABOUT HOW ATOMIC CLOCKS WORK.

452
00:27:04,069 --> 00:27:09,307
WHEN HE'S DONE WE'LL TALK ABOUT
HOW IT CAN BE USED FOR FUTURE

453
00:27:09,307 --> 00:27:11,193
NAVIGATION AND EXPLORATION.
>> THANK YOU.

454
00:27:11,193 --> 00:27:14,379
THIS IS NOT AN ATOMIC CLOCK.

455
00:27:14,379 --> 00:27:16,114
THIS IS SUN DIAL.

456
00:27:16,114 --> 00:27:20,185
SUN DIALS HAVE BEEN USED FOR THE
LAST 2700 YEARS, AS FAR AS WE

457
00:27:20,185 --> 00:27:23,188
CAN TELL, PROBABLY EVEN EARLIER
THAN THAT.

458
00:27:23,188 --> 00:27:27,109
UNTIL THE 1800 SUN DIALS WERE
CONSIDERED THE CORRECT TIME.

459
00:27:27,109 --> 00:27:30,462
EVEN THOUGH WE HAD PENDULUM
CLOCKS AFTER THAT.

460
00:27:30,462 --> 00:27:42,107
UNTIL THE 1800S PENDULUM CLOCKS
WEREN'T CONSIDERED ACCURATE

461
00:27:42,107 --> 00:27:47,245
ENOUGH.

462
00:27:47,245 --> 00:27:48,396
THERE'S A LOT OF SUN DIALS.

463
00:27:48,396 --> 00:27:52,033
THERE ARE MORE SUN DIALS THAN
TYPES OF CLOCKS, PROBABLY.

464
00:27:52,033 --> 00:27:55,253
THEY WERE INVENTED OVER THE
CENTURIES TO SOLVE PROBLEMS AS

465
00:27:55,253 --> 00:27:59,157
SUN DIALS HAVE LIKE THEIR
ACCURACY VARIES WITH THE TIME OF

466
00:27:59,157 --> 00:27:59,307
YEAR.

467
00:27:59,307 --> 00:28:04,329
BECAUSE THE EARTH IS NOT IN A
CIRCULAR ORBIT AROUND THE SUN.

468
00:28:04,329 --> 00:28:06,148

IT'S ACTUALLY AN ELLIPSE.

469
00:28:06,148 --> 00:28:12,170
AND THE SHADOW MOVES AROUND A
LITTLE BIT.

470
00:28:12,170 --> 00:28:20,378
IN THE 1800S OR THE CHRISTIAN --
THE SAME OF SATURN AND TIE TAN

471
00:28:20,378 --> 00:28:26,234
FAME INVENTED THE FIRST
PRACTICAL PENDULUM CLOCK IN THE

472
00:28:26,234 --> 00:28:27,152
1600s.

473
00:28:27,152 --> 00:28:31,139
THESE CLOCKS WORK BY MEASURING
HOW MUCH TIME IT TAKES FOR

474
00:28:31,139 --> 00:28:32,073
PENDULUMS TO SWING.

475
00:28:32,073 --> 00:28:35,310
THAT'S A THING THAT IS A
PROPERTY.

476
00:28:35,310 --> 00:28:39,164
OF PENDULUMS IT DOESN'T MATTER
HOW HEAVY THEY ARE IT MATTERS

477
00:28:39,164 --> 00:28:40,248
HOW LONG THEY ARE.

478
00:28:40,248 --> 00:28:44,319
AND IT DETERMINES HOW MUCH TIME
THEY TAKE TO SWING BACK AND

479

00:28:44,319 --> 00:28:44,469
FORTH.

480
00:28:44,469 --> 00:28:46,404
IT'S AN EXAMPLE OF AN ABSOLUTE
CLOCK.

481
00:28:46,404 --> 00:28:49,124
YOU DON'T HAVE TO DO ANY ADDING.

482
00:28:49,124 --> 00:28:51,359
JUST READ OFF THE FACE WHAT TIME
IT IS.

483
00:28:51,359 --> 00:28:55,063
A PENDULUM CLOCK YOU HAVE TO ADD
UP THE SWINGS.

484
00:28:55,063 --> 00:28:57,432
LIKE YOU HEARD TODD TALKING
ABOUT THE BARS BEING WIDE, THE

485
00:28:57,432 --> 00:29:00,352
CLOCKS WHERE YOU HAVE TO ADD UP
THE SWINGS HAVE ERRORS.

486
00:29:00,352 --> 00:29:05,991
AND EVERY TIME YOU ADD THE
SWINGS TOGETHER YOU ADD MORE AND

487
00:29:05,991 --> 00:29:06,341
MORE ERRORS.

488
00:29:06,341 --> 00:29:10,395
PENDULUMS WERE NOT GOOD ENOUGH
UNTIL THEY WERE ENGINEERED TO BE

489
00:29:10,395 --> 00:29:14,432
BETTER THAN SUN DIALS ONLY ABOUT
200 YEARS AGO.

490
00:29:14,432 --> 00:29:25,310
SO AFTER PENDULUM CLOCKS IN THE
1920s, QUARTZ CRYSTAL CLOCK WAS

491
00:29:25,310 --> 00:29:26,044
INCONVENIENTED.

492
00:29:26,044 --> 00:29:30,148
IT'S THE PROBABLY IN THE
WRISTWATCH OR ALARM CLOCK.

493
00:29:30,148 --> 00:29:32,017
IF YOU STILL HAVE ONE.

494
00:29:32,017 --> 00:29:33,435
EVERYBODY USES THEIR PHONES NOW.

495
00:29:33,435 --> 00:29:37,305
THEY RELY ON A DIFFERENT
PRINCIPLE THAN A PENDULUM.

496
00:29:37,305 --> 00:29:41,226
IT'S A LITTLE PIECE OF ROCK,
QUARTZ, WHEN IT'S PLACED IN AN

497
00:29:41,226 --> 00:29:43,194
ELECTRICITY FIELD IT VIBRATES.

498
00:29:43,194 --> 00:29:45,363
BECAUSE OF THE SHAPE, IT'S
PRECISELY SHAPED.

499
00:29:45,363 --> 00:29:49,251
BECAUSE OF THE SHAPE, IT ONLY
VIBRATES AT A CERTAIN FREQUENCY

500
00:29:49,251 --> 00:29:51,169
OR CERTAIN NUMBER OF TICKS.

501
00:29:51,169 --> 00:29:56,241
JUST LIKE A PENDULUM CLOCK, A
KWAURDS CLOCK, WHICH IS AN ORDER

502
00:29:56,241 --> 00:29:59,177
MAGNITUDE OVER TEN TIMES MORE
ACCURATE THAN A PENDULUM CLOCK.

503
00:29:59,177 --> 00:30:01,046
IT'S ADDING UP THE TICKS.

504
00:30:01,046 --> 00:30:04,249
AS TODD SAID IT'S NOT GOOD
ENOUGH FOR NAVIGATION.

505
00:30:04,249 --> 00:30:08,219
SO WE MOVE INTO ATOMIC CLOCKS.

506
00:30:08,219 --> 00:30:09,404
AND AN ATOMIC CLOCK.

507
00:30:09,404 --> 00:30:12,374
IT'S A CLASSIC ATOMIC CLOCK.

508
00:30:12,374 --> 00:30:13,241
THIS IS A CLOCK.

509
00:30:13,241 --> 00:30:18,330
IT'S A TYPE OF CLOCK USED IN
REFERENCE CLOCKS AND TELEVISION

510
00:30:18,330 --> 00:30:22,050
STATIONS, BANKS, IN BANKS, YES.

511
00:30:22,050 --> 00:30:23,285
THEY DO TIME EVERYTHING.

512

00:30:23,285 --> 00:30:26,154
AND ALL OVER THE WORLD.

513
00:30:26,154 --> 00:30:31,426
BANKS ARE USED TOGETHER TO
CREATE WHAT WE USUALLY REFER TO

514
00:30:31,426 --> 00:30:33,295
AS UNIVERSAL COORDINATED TIME.

515
00:30:33,295 --> 00:30:35,347
THEY'RE KNOWN AS PRIMARY
STANDARD.

516
00:30:35,347 --> 00:30:36,431
THEY DON'T VARY MUCH AT ALL.

517
00:30:36,431 --> 00:30:38,249
WHAT IS AN ATOMIC CLOCK?

518
00:30:38,249 --> 00:30:41,403
IT'S ATOMIC BUT IT'S NOT ATOMIC
LIKE THIS.

519
00:30:41,403 --> 00:30:44,205
THIS IS ACTUALLY IS CALLED A
NUCLEAR.

520
00:30:44,205 --> 00:30:46,474
AN ATOMIC CLOCK IS AN ATOMIC
DEVICE.

521
00:30:46,474 --> 00:30:52,330
BUT THEY SHARE THE SAME HERITAGE
AND THEY CAME ABOUT AT ROUGHLY

522
00:30:52,330 --> 00:30:56,167
THE SAME TIME IN THE '40s.

523

00:30:56,167 --> 00:30:57,552
WE USE A MERCURY TRAP CLOCK.

524
00:30:57,552 --> 00:31:00,105
AND I'M GOING TO TELL YOU ABOUT
THAT A LITTLE BIT.

525
00:31:00,105 --> 00:31:04,059
THERE ARE OTHER TYPES OF ATOMIC
CLOCKS, BUT THE PRINCIPLE IS

526
00:31:04,059 --> 00:31:08,396
REASONABLY THE SAME EVEN THOUGH
THE DETAILS ARE IMMENSELY MORE

527
00:31:08,396 --> 00:31:11,282
COMPLEX DEPENDING ON THE
DIFFERENT ONES.

528
00:31:11,282 --> 00:31:13,201
WE USE A MERCURY AT TOM HERE.

529
00:31:13,201 --> 00:31:17,022
IT HAS 80 ELECTRONS SPINNING
AROUND IN THE SHELLS.

530
00:31:17,022 --> 00:31:20,308
THE ONE WE CARE ABOUT IS THE TWO
ON THE OUTSIDE SHELL BECAUSE

531
00:31:20,308 --> 00:31:22,494
THOSE ARE THE ONES WE INTERACT
WITH.

532
00:31:22,494 --> 00:31:28,083
AND WE IONIZE THESE, WHICH MEANS
WE USE AN ELECTRIC CURRENT TO

533
00:31:28,083 --> 00:31:30,285
KNOCK OFF THE ELECTRON.

534
00:31:30,285 --> 00:31:32,103
THEN WE ONLY WORRY ABOUT THE
ONE.

535
00:31:32,103 --> 00:31:33,455
WE CALL IT MERCURY AT TOM.

536
00:31:33,455 --> 00:31:39,227
WE REFER TO IT AS A QUANTUM
TUNING FORK.

537
00:31:39,227 --> 00:31:42,497
IT WILL RESPOND TO CERTAIN RADIO
SIGNALS.

538
00:31:42,497 --> 00:31:44,532
BUT ONLY CERTAIN ONES.

539
00:31:44,532 --> 00:31:47,068
SO THIS IS OUR TUNING FORK.

540
00:31:47,068 --> 00:31:53,074
WHAT WE DO IS WE SEND A RADIO
FREQUENCY AT THIS AT TOM, AND

541
00:31:53,074 --> 00:31:56,394
THIS RADIO FREQUENCY INTERACTS
WITH THE ELECTRON.

542
00:31:56,394 --> 00:32:07,122
IF THE FREQUENCY IS NOT RIGHT,
THE TUNING FORK DOESN'T DO

543
00:32:07,122 --> 00:32:07,305
ANYTHING.

544
00:32:07,305 --> 00:32:08,139
THE ATOM IS NOT PER TRUSHED.

545
00:32:08,139 --> 00:32:09,224
IF IT'S FASTER IT WILL VIBRATE
WITH IT.

546
00:32:09,224 --> 00:32:12,177
IT'S NOT VIBRATING.

547
00:32:12,177 --> 00:32:15,246
IT'S DOING A MAGNETIC PULL
NUCLEAR SPIN THING.

548
00:32:15,246 --> 00:32:21,386
IF THE FREQUENCY IS EXACTLY 40.5
AND ABOUT 50 DECIMAL POINTS

549
00:32:21,386 --> 00:32:26,224
FREQUENCY, THIS ATOM WILL REACT
IN A WAY WE CAN MEASURE WITH

550
00:32:26,224 --> 00:32:29,194
ULTRA VIOLET LIGHT.

551
00:32:29,194 --> 00:32:32,514
ONE OF THE DIFFICULTIES WITH
ATOMIC CLOCKS THE ATOMS ARE NOT

552
00:32:32,514 --> 00:32:35,383
JUST AFFECTED BY THE FREQUENCY
YOU'RE HITTING THEM WITH.

553
00:32:35,383 --> 00:32:37,469
THEY'RE AFFECTED BY THE WORLD
AROUND THEM.

554
00:32:37,469 --> 00:32:40,405
WE TRY TO DISCONNECT THEM FROM
THE UNIVERSE.

555

00:32:40,405 --> 00:32:42,457
WE DO THAT BY TRAPPING THEM.

556
00:32:42,457 --> 00:32:48,096
AND SO WE PUT THEM INSIDE THIS
LITTLE DEVICE WHICH IS ABOUT THE

557
00:32:48,096 --> 00:32:49,414
SIZE OF A THREE MUSKETEERS BAR.

558
00:32:49,414 --> 00:32:50,398
THE BIG BAR.

559
00:32:50,398 --> 00:32:54,085
NOT THE BITE SIZE ONE.

560
00:32:54,085 --> 00:32:57,355
WE BASICALLY INSIDE THE GOLD
RODS HERE WE FORM AN ELECTRIC

561
00:32:57,355 --> 00:33:01,242
FIELD AND PUT A BUNCH OF MERCURY
ATOMS IN THERE.

562
00:33:01,242 --> 00:33:04,129
WE IONIZE THEM AND THEY STAY IN
A BOTTLE.

563
00:33:04,129 --> 00:33:05,230
THEY'RE IN THE LITTLE BOTTLE.

564
00:33:05,230 --> 00:33:07,482
THEY DON'T INTERACT WITH THE
METAL.

565
00:33:07,482 --> 00:33:10,318
THEY DON'T BOUNCE OFF ANYTHING.

566
00:33:10,318 --> 00:33:12,270

THEY FLY AROUND IN LAZY CIRCLES.

567
00:33:12,270 --> 00:33:14,305
AND IT MAKES THEM VERY QUALM.

568
00:33:14,305 --> 00:33:19,194
WHEN THEY'RE CALM THEY CAN REACT
VERY NICELY TO THE RADIO WAVES

569
00:33:19,194 --> 00:33:24,082
THAT WE PUMP IN INTO THE PORTS
HERE.

570
00:33:24,082 --> 00:33:24,232
OKAY.

571
00:33:24,232 --> 00:33:31,256
NOW YOU MIGHT THINK, OKAY, IT'S
MERCURY.

572
00:33:31,256 --> 00:33:35,410
IS IT DANGEROUS?

573
00:33:35,410 --> 00:33:37,295
THE AMOUNT OF MERCURY WE HAVE.

574
00:33:37,295 --> 00:33:40,415
THERE'S MORE MERCURY IN TWO CANS
OF TUNA FISH.

575
00:33:40,415 --> 00:33:47,222
THERE'S ONLY ABOUT 1500,000
ATOMS OF MERCURIED IN THE TUBE,

576
00:33:47,222 --> 00:33:49,073
WHICH IS A VERY SMALL AMOUNT OF
MERCURY.

577
00:33:49,073 --> 00:33:51,242

IT'S VERY PRECISE WAY.

578
00:33:51,242 --> 00:33:53,478
IT TAKES MONTHS TO GET THE
BALANCE JUST RIGHT IN THE

579
00:33:53,478 --> 00:33:59,434
MERCURY AS WE BUILD UP THE
CLOCKS.

580
00:33:59,434 --> 00:34:03,988
SO TODD WAS TALKING ABOUT HOW IN
THE DSN WE USE THE ATOMIC

581
00:34:03,988 --> 00:34:04,155
CLOCKS.

582
00:34:04,155 --> 00:34:08,259
YOU MAY HAVE HEARD RECENTLY THE
NATIONAL INSTITUTE OF STANDARDS

583
00:34:08,259 --> 00:34:13,064
AND TECHNOLOGY, THEY'RE SORT OF
THE UNITED STATES KEEPER OF

584
00:34:13,064 --> 00:34:13,214
TIME.

585
00:34:13,214 --> 00:34:18,069
THEY HAVE A CLOCK THE F 1.

586
00:34:18,069 --> 00:34:21,172
IT'S THE MOST ACCURATE CLOCK IN
THE WORLD NOW.

587
00:34:21,172 --> 00:34:23,424
IT IS SORT OF LIKE WHO IS THE
BEST QUARTERBACK?

588

00:34:23,424 --> 00:34:26,144
IT'S FLIPPING AROUND BETWEEN
DIFFERENT ORGANIZATIONS.

589
00:34:26,144 --> 00:34:27,362
IT'S THE SIZE OF A KITCHEN.

590
00:34:27,362 --> 00:34:32,133
IT'S THE SIZE OF AN INDUSTRIAL
KITCHEN.

591
00:34:32,133 --> 00:34:32,317
OKAY.

592
00:34:32,317 --> 00:34:34,202
IT IS QUITE ACCURATE.

593
00:34:34,202 --> 00:34:38,089
IT'S A DIFFERENT TECHNOLOGY THEY
USE IT'S WHERE WE THROW THE

594
00:34:38,089 --> 00:34:40,358
ATOMS IN THE AIR AND THEY COME
DOWN AND THEY'RE NOT CONNECTED

595
00:34:40,358 --> 00:34:45,246
TO ANYTHING AND THEY MEASURE
THEM.

596
00:34:45,246 --> 00:34:51,152
OUR TECHNOLOGY HAS BEEN USED IN
THE DSN AND IT STAND FOR LINEAR

597
00:34:51,152 --> 00:34:55,240
ION TRAP -- SOMETHING.

598
00:34:55,240 --> 00:34:57,408
IT'S ABOUT THE SIZE OF A
REFRIGERATOR.

599
00:34:57,408 --> 00:34:59,193
IT'S A FANCY REFRIGERATOR.

600
00:34:59,193 --> 00:35:02,113
EACH ONE IS THE SIZE OF A
REGULAR REFRIGERATOR.

601
00:35:02,113 --> 00:35:08,102
YOU GET THE IDEA FROM A KITCHEN
TON A FRIDGE RATER TO ABOUT THE

602
00:35:08,102 --> 00:35:09,320
SIZE OF THE TOASTER OVEN.

603
00:35:09,320 --> 00:35:12,373
IT'S NOT ALL THAT HEAVY EITHER.

604
00:35:12,373 --> 00:35:14,175
THAT'S THE THING THE PROJECT HAS
BEEN DOING.

605
00:35:14,175 --> 00:35:17,228
WE HAVE BEEN TAKING A TECHNOLOGY
THAT HAS BEEN IN THE WORKS AND

606
00:35:17,228 --> 00:35:23,418
BEEN DEPLOYED FOR THE LAST FIVE
TO TEN YEARS.

607
00:35:23,418 --> 00:35:26,404
IT'S BEEN IN THE WORKS EVEN
LONGER.

608
00:35:26,404 --> 00:35:33,177
WE CAN SHRINK IT DOWN TO PUT IT
ON A SPACECRAFT AND USE IT IN

609
00:35:33,177 --> 00:35:35,096
SPACE LIKE THE WAY TODD HAS BEEN

TALKING ABOUT.

610
00:35:35,096 --> 00:35:38,449
IT'S A LITTLE DIFFERENT THAN THE
NORMAL TYPE OF MISSION.

611
00:35:38,449 --> 00:35:42,086
OUR GOAL IS NOT TO GO AND GO TO
A CERTAIN PLACE AND COLLECT

612
00:35:42,086 --> 00:35:45,240
SCIENCE ABOUT A CERTAIN TARGET,
AS WE CALL IT.

613
00:35:45,240 --> 00:35:49,460
IT'S TO TEST THE CLOCK IN THE
ENVIRONMENT OF SPACE AND ON A

614
00:35:49,460 --> 00:35:52,380
SPACECRAFT AND SEE HOW WELL IT
WORKS.

615
00:35:52,380 --> 00:35:58,136
AND SEE WHERE THE WARTS ARE SO
WE CAN DESIGN THE REAL ONE TO GO

616
00:35:58,136 --> 00:36:04,976
TO JUPITER OMR MARS.

617
00:36:04,976 --> 00:36:07,345
IT'S A NEW CLASS THAT NASA HAS
BEEN DOING.

618
00:36:07,345 --> 00:36:09,030
WE'RE BUILDING THE PAYLOAD.

619
00:36:09,030 --> 00:36:09,447
THERE'S THE DLOK.

620

00:36:09,447 --> 00:36:13,334
THERE'S THE USO THAT TODD SHOWED
YOU EARLIER.

621
00:36:13,334 --> 00:36:16,404
IT'S A MEASUREMENT DEVICE A GPS
SIVER WE USE TO MEASURE THE

622
00:36:16,404 --> 00:36:17,305
CLOCK IN SPACE.

623
00:36:17,305 --> 00:36:20,258
WE PUT IT ON A SMALL SPACECRAFT.

624
00:36:20,258 --> 00:36:22,360
IT'S ABOUT THE SIZE OF THIS
PODIUM.

625
00:36:22,360 --> 00:36:28,249
IT'S VERY SMALL COMPARED TO
NORMAL JPL SPACECRAFT THAT WOULD

626
00:36:28,249 --> 00:36:29,434
REACH TO THE CEILING HERE.

627
00:36:29,434 --> 00:36:34,355
AND WE FLY THAT SPACECRAFT WITH
A BUNCH OF OTHER SPACECRAFT ON A

628
00:36:34,355 --> 00:36:36,240
MISSION THAT THE AIR FORCE IS
RUNNING.

629
00:36:36,240 --> 00:36:40,078
NOW WHEN I WAS A KID, I USED TO
PLAY MONOPOLY WITH MY SISTERS.

630
00:36:40,078 --> 00:36:44,432
YOU SIT THERE AND YOU'VE GOT
BALTIC AVENUE AND YOU WANT NORTH

631
00:36:44,432 --> 00:36:45,266
CAROLINA AVENUE.

632
00:36:45,266 --> 00:36:48,386
AND YOUR SISTER'S GOT IT SO YOU
OFFER HERE, YOU KNOW, A

633
00:36:48,386 --> 00:36:52,390
RAILROAD, AND BALTIC, AND A
LITTLE BIT OF CASH TO SWEETEN

634
00:36:52,390 --> 00:36:53,274
THE DEAL.

635
00:36:53,274 --> 00:36:55,159
MY OTHER SISTER WANTS IT, TOO.

636
00:36:55,159 --> 00:36:58,463
WE WORK OUT THE THREE WAY DEAL
WHERE THERE'S THE MONEY AND

637
00:36:58,463 --> 00:37:00,415
PROPERTY CHANGING HAND.

638
00:37:00,415 --> 00:37:06,254
THAT'S THE WAY WE GET ON THE
MISSIONS.

639
00:37:06,254 --> 00:37:09,323
WHAT HAPPENS IS A UNITED STATES
SATELLITE PROVIDER HAS A MISSION

640
00:37:09,323 --> 00:37:12,360
WHERE THEY WANT TO FLY A LOT OF
DEMONSTRATION PAYLOAD.

641
00:37:12,360 --> 00:37:17,982
WE'RE PAYING THEM FOR SEATS ON

THEIR SPACECRAFT.

642
00:37:17,982 --> 00:37:20,318
IT'S LIKE PIEING AN AIRLINE
TICKET.

643
00:37:20,318 --> 00:37:22,353
THEY'VE GOT OTHER PAYLOADS.

644
00:37:22,353 --> 00:37:25,256
AND THIS THEN WE'RE ALSO PAYING
FOR TWO AIR FORCE PAYLOADS TO BE

645
00:37:25,256 --> 00:37:27,175
ON THIS SPACECRAFT.

646
00:37:27,175 --> 00:37:30,078
SO THE AIR FORCE WILL TURN
AROUND AND GIVE US A RIDE ON

647
00:37:30,078 --> 00:37:30,378
THEIR ROCKET.

648
00:37:30,378 --> 00:37:34,248
WE START TRADING THINGS AROUND
AND IT MAKES FOR AN INTERESTING

649
00:37:34,248 --> 00:37:36,200
AND COMPLEX ARRANGEMENT.

650
00:37:36,200 --> 00:37:39,103
IT SAVES THE TAXPAYERS A LOT OF
MONEY.

651
00:37:39,103 --> 00:37:41,189
WE'RE NOT PAYING ANYTHING AT ALL
FOR THE ROCKET.

652
00:37:41,189 --> 00:37:44,358

THE AIR FORCE IS FLYING THE
ROCKET FOR ANOTHER REASON.

653
00:37:44,358 --> 00:37:47,211
ALL OF THE SATELLITES THAT ARE
ON THE ROCKET ARE SORT OF

654
00:37:47,211 --> 00:37:49,180
GETTING A FREE RIDE.

655
00:37:49,180 --> 00:37:51,165
BECAUSE THE AIR FORCE WANTS TO
CHECK IT OUT.

656
00:37:51,165 --> 00:37:53,317
IT'S A FALCON HEAVY, BY THE WAY.

657
00:37:53,317 --> 00:38:01,959
WHICH IS THE NEXT VERSION OF THE
FALCON THAT IS SPACEX IS

658
00:38:01,959 --> 00:38:03,277
PLANNING TO FLY LATER THIS YEAR.

659
00:38:03,277 --> 00:38:06,330
IT'S BASICALLY THREE FALCON
NINES TIED TOGETHER.

660
00:38:06,330 --> 00:38:07,965
IT'S A POWERFUL ROCKET.

661
00:38:07,965 --> 00:38:09,200
THE AIR FORCE WANTS TO CHECK IT
OUT.

662
00:38:09,200 --> 00:38:13,387
WE GET TO RIDE PRETTY MUCH FOR
FREE FOR CARRYING A COUPLE OF

663

00:38:13,387 --> 00:38:14,338
THEIR OTHER PAYLOAD.

664
00:38:14,338 --> 00:38:16,157
THAT'S HOW WE WORK THE DEALS
OUT.

665
00:38:16,157 --> 00:38:18,126
I'M GOING TO HAND IT OVER TO
TODD HERE.

666
00:38:18,126 --> 00:38:22,196
HE'S GOING TO SWITCH BACK NOW TO
WHAT WE DO WITH THE CLOCK AND

667
00:38:22,196 --> 00:38:28,252
FANCY WAYS.
>> THANKS.

668
00:38:28,252 --> 00:38:33,374
>> SO THE ROCKET PUTS US IN
SPACE.

669
00:38:33,374 --> 00:38:42,083
IT'S A LOW-EARTH ORBIT IN WHICH
ALLEN TALKED ABOUT.

670
00:38:42,083 --> 00:38:44,469
WE'LL SEE IF THAT'S THE DATE WE
FLY.

671
00:38:44,469 --> 00:38:55,363
BUT ONCE WE ARE IN SPACE, SIRI
NEEDS TO CHECK THE SPACECRAFT.

672
00:38:55,363 --> 00:38:59,100
AFTER A MONTH WE CHECK IT OUT
AND SEE IF IT'S WORKING OKAY.

673
00:38:59,100 --> 00:39:02,053

WE'RE READY TO START THE NOMINAL
MISSION.

674
00:39:02,053 --> 00:39:03,304
THAT'S ABOUT FIVE MONTHS LONG.

675
00:39:03,304 --> 00:39:06,340
THE WAY IN WHICH WE OPERATE THE
MISSION IS THAT RECEIVER THAT

676
00:39:06,340 --> 00:39:12,146
ALLEN TALKED ABOUT IS GOING TO
RECEIVE GPS SIGNALS FROM THE

677
00:39:12,146 --> 00:39:12,363
CONSTELLATION.

678
00:39:12,363 --> 00:39:16,300
SO THIS SPACECRAFT IS IN ABOUT A
700 KILOMETER ORBIT.

679
00:39:16,300 --> 00:39:20,071
THE GPS SATELLITES ARE ABOUT
20,000 KILOMETER ORBIT.

680
00:39:20,071 --> 00:39:22,089
WE SEE A LOT OF GPS SATELLITES.

681
00:39:22,089 --> 00:39:25,042
WE SEE ON AVERAGE ABOUT 12
CONTINUOUSLY.

682
00:39:25,042 --> 00:39:26,377
THAT'S A LOT OF DATA.

683
00:39:26,377 --> 00:39:28,362
AND IT'S FAIR TO ASK.

684
00:39:28,362 --> 00:39:29,013

OKAY.

685
00:39:29,013 --> 00:39:32,116
YOU'RE A NEW TYPE OF ATOMIC
CLOCK.

686
00:39:32,116 --> 00:39:35,086
YOU SAID GPS HAS ATOMIC CLOCKS.

687
00:39:35,086 --> 00:39:36,170
IT'S SUPPOSED TO BE BETTER.

688
00:39:36,170 --> 00:39:37,405
HOW IS IT GOING TO WORK?

689
00:39:37,405 --> 00:39:44,345
IT TURNS OUT THERE ARE OVER 400
TRACKING STATIONS ON EARTH

690
00:39:44,345 --> 00:39:47,381
TRACKING THE GPS CONSTELLATION
ALL THE TIME.

691
00:39:47,381 --> 00:39:51,118
AND THE TRACKING STATIONS HAVE
DETERMINED THE LOCATION OF EACH

692
00:39:51,118 --> 00:39:53,321
SATELLITE CONTINUOUSLY TO ABOUT
2 CENTIMETERS.

693
00:39:53,321 --> 00:39:58,192
AND THE CLOCK ON BOARD TO ABOUT
50 -- EVEN THOUGH THE GPS CLOCK

694
00:39:58,192 --> 00:40:08,052
ISN'T AS STABLE AS OUR CLOCK,
IT'S MOVING AROUND WE KNOW HOW.

695

00:40:08,052 --> 00:40:10,438
WE CAN DETERMINE HOW WELL THE
CLOCK OPERATES.

696
00:40:10,438 --> 00:40:14,075
SO OUR REQUIREMENT IS TO SHOW
THAT THE STABILITY IS BETTER

697
00:40:14,075 --> 00:40:16,177
THAN TWO NANO SECOND PER DAY.

698
00:40:16,177 --> 00:40:20,364
AND OUR GOAL IS ABOUT 3/10 OF A
MECHANIC KNOW SECOND PER DAY.

699
00:40:20,364 --> 00:40:24,068
IF YOU REMEMBER WHEN I WAS
TALKING ABOUT THE DSN, IT'S

700
00:40:24,068 --> 00:40:26,270
ABOUT A TENTH OF A MECHANIC KNOW
SECOND PER DAY.

701
00:40:26,270 --> 00:40:30,224
WE'RE IN THE BALLPARK OF WHAT
THE DSN IS ABLE TO PROVIDE.

702
00:40:30,224 --> 00:40:35,213
IN FACT, AT THESE LEVELS OTHER
ERRORS IN THE DOPPLER

703
00:40:35,213 --> 00:40:38,416
MEASUREMENTS START TO DOMINATE
THE MEASUREMENTS AND THE CLOCK

704
00:40:38,416 --> 00:40:40,484
AREA ESSENTIALLY GOES AWAY.

705
00:40:40,484 --> 00:40:46,257
WITH THAT WE'RE HOPING TO

DEMONSTRATE THE UTILITIES FOR

706
00:40:46,257 --> 00:40:50,161
FUTURE MISSIONS TO SHOW IT CAN
NAVIGATE THE TV QUITE WELL.

707
00:40:50,161 --> 00:40:56,500
AND THEN AFTER THAT FIRST FIVE
MONTHS, WE'RE NOT A BIG MISSION

708
00:40:56,500 --> 00:41:02,039
AND WE'RE TRYING TO DO THIS AS
EFFICIENTLY AND I DON'T WANT TO

709
00:41:02,039 --> 00:41:06,093
SAY CHEAPLY BUT, YOU KNOW, AS
ECONOMICALLY AS WE CAN.

710
00:41:06,093 --> 00:41:12,300
SO WE'VE GOT THE DATA AND NOW
WHAT WE'RE INTERESTED IN IS

711
00:41:12,300 --> 00:41:14,135
MAKING SURE THE THINGS STILL
TICKS.

712
00:41:14,135 --> 00:41:17,505
FOR LONG LIFE DURATION MISSIONS,
YOU NEED TO WORK FOR MORE THAN A

713
00:41:20,124 --> 00:41:18,155
YEAR.

714
00:41:20,124 --> 00:41:24,278
BUT WE CAN OPERATE LONGER AS
LONG AS WE KEEP PAYING THE RENT

715
00:41:24,278 --> 00:41:27,131
ON THE SIRI SPACECRAFT.

716
00:41:27,131 --> 00:41:28,332
SO COOL STUFF.

717
00:41:28,332 --> 00:41:32,320
THIS IS OUR DEMONSTRATION CLOCK.

718
00:41:32,320 --> 00:41:34,038
IT'S A PROTOTYPE CLOCK.

719
00:41:34,038 --> 00:41:37,341
IT'S NOT THE FINAL CLOCK THAT
WOULD GO ON A FUTURE MISSION.

720
00:41:37,341 --> 00:41:41,495
WHAT YOU WOULD DO NEXT IS --
WHAT WE'RE LEARNING AS PART OF

721
00:41:41,495 --> 00:41:47,435
OUR PROJECT HOW WE WOULD SHRINK
IT FURTHER.

722
00:41:47,435 --> 00:41:53,240
WE'VE GOT LOTS OF IDEAS HOW TO
CUT THAT BY A QUARTER AND MAKE

723
00:41:53,240 --> 00:41:54,392
IT ABOUT THIS BIG.

724
00:41:54,392 --> 00:41:57,295
IT'S VERY REASONABLE TO FLY ON
FUTURE SPACE MISSIONS.

725
00:41:57,295 --> 00:42:03,034
SOME OF THE WAYS IN WHICH WE CAN
USE IT FOR FUTURE MISSIONS IN

726
00:42:03,034 --> 00:42:06,203
THE ARENA OF SCIENCE AND
NAVIGATION, LET'S TALK ABOUT

727
00:42:06,203 --> 00:42:07,371
THAT FOR A LITTLE BIT.

728
00:42:07,371 --> 00:42:12,093
HERE IS AN ILLUSTRATION OF
TRANSMITTING A SIGNAL THROUGH

729
00:42:12,093 --> 00:42:14,478
THE RINGS AND RECEIVED HERE AT
THE DSN.

730
00:42:14,478 --> 00:42:20,151
THIS IS THAT ONE WAY SIGNAL
AGAIN AND THEY HAVE TO USE TODAY

731
00:42:20,151 --> 00:42:21,185
ARE USO.

732
00:42:21,185 --> 00:42:25,406
AND USOS ARE GREAT.

733
00:42:25,406 --> 00:42:29,243
YOU GET A LOT OF DATA TO PROBE
THE RINGS BUT IT'S ABOUT TEN TO

734
00:42:29,243 --> 00:42:31,395
A HUNDRED TIMES MORE ACCURATE
THAN THE MEASUREMENT.

735
00:42:31,395 --> 00:42:36,367
WE CAN LEARN A LOT MORE ABOUT
THE RINGS IF IT WERE ON BOARD.

736
00:42:36,367 --> 00:42:40,454
PLACES LIKE MARS, SPACECRAFT
TRANSMIT SIGNALS THROUGH THE

737
00:42:40,454 --> 00:42:45,192

ATMOSPHERE AS THE SATELLITE
RISES AND SET, AND THAT SIGNAL

738
00:42:45,192 --> 00:42:47,044
GETS AFFECTED BY THE ATMOSPHERE.

739
00:42:47,044 --> 00:42:51,165
WE CAN LEARN A LOT ABOUT THE
ATMOSPHERE BY MEASURING THESE

740
00:42:51,165 --> 00:42:51,332
SIGNALS.

741
00:42:51,332 --> 00:42:54,185
AGAIN, THIS IS A ONE WAY SIGNAL.

742
00:42:54,185 --> 00:42:59,390
SO MARS ORBITERS HAVE USO AND
IT'S RECEIVED BACK HERE.

743
00:42:59,390 --> 00:43:02,159
AND THE USO IS THE LIMITING
ERROR SOURCE.

744
00:43:02,159 --> 00:43:06,464
IF IT WERE ON BOARD, IT WOULD BE
TEN TO A HUNDRED TIMES MORE

745
00:43:06,464 --> 00:43:07,148
ACCURATE.

746
00:43:07,148 --> 00:43:13,287
OTHER WAYS IN WHICH WE CAN USE
IT IS PUT IT ON BOARD THE

747
00:43:13,287 --> 00:43:16,407
ORBITER TO RECALL THAT
ILLUSTRATION I HAD EARLIER WHERE

748

00:43:16,407 --> 00:43:19,443
THE SATELLITES WERE GETTING A
LOT OF DATA.

749
00:43:19,443 --> 00:43:21,278
ALMOST CONTINUOUSLY.

750
00:43:21,278 --> 00:43:26,467
QUESTION TAKE ADVANTAGE OF THAT
OR AN ORBIT AROUND MARS AND

751
00:43:26,467 --> 00:43:33,374
USING IT WITH THE DATA AND USING
THE FACT THAT WE CAN DIAL INTO

752
00:43:33,374 --> 00:43:34,075
THE KSN AT.

753
00:43:34,075 --> 00:43:38,095
TODAY WE USE X BAN.

754
00:43:38,095 --> 00:43:40,481
IT'S ABOUT 40 GIG HERTZ.

755
00:43:40,481 --> 00:43:44,518
THE DATA WE GET IS TEN TIMES
MORE ACCURATE THAN THE X BAND.

756
00:43:44,518 --> 00:43:48,189
IT YOU DOUBLE THE DATA AND
IMPROVE DATA, WE CAN DETERMINE

757
00:43:48,189 --> 00:43:50,074
THINGS LIKE THE GRAVITY FIELD.

758
00:43:50,074 --> 00:43:53,377
THE LONG-TERM GRAVITY FIELD AT
MARRS VERY ACCURATELY.

759

00:43:53,377 --> 00:43:59,083
ONE OF THE THINGS THAT WE LEARN
RECENTLY IS THAT THERE'S A LOT

760
00:43:59,083 --> 00:44:05,439
OF ICE MASS REDISTRIBUTION OVER
THE COURSE OF A YEAR.

761
00:44:05,439 --> 00:44:09,443
THEY MIGHT BE ABLE TO CONTRIBUTE
TO UNDERSTANDING THAT BETTER.

762
00:44:09,443 --> 00:44:15,399
OTHER WAYS IN WHICH WE CAN USE
IT IS NASA IS DEVELOPING A

763
00:44:15,399 --> 00:44:21,439
SPACECRAFT TO EXPLORE YOU ROW
PA.

764
00:44:21,439 --> 00:44:23,107
A MOON OF JUPITER.

765
00:44:23,107 --> 00:44:24,492
IT'S ENCASED IN AN ICE SHELL.

766
00:44:24,492 --> 00:44:29,196
ALL THE DATA SAID THERE'S AN
OCEAN UNDERNEATH THAT ICE.

767
00:44:29,196 --> 00:44:35,186
ONE OF THE KEY THINGS THAT THE
MISSION WILL DO IS PROBE THE

768
00:44:35,186 --> 00:44:38,339
CHARACTERS OF THE ICE AND THE
OCEAN UNDERNEATH USING A VARIETY

769
00:44:38,339 --> 00:44:39,340
OF INSTRUMENTS.

770
00:44:39,340 --> 00:44:43,194
AND ONE OF THOSE INVESTIGATIONS
IS GOING TO INVOLVE DETERMINING

771
00:44:43,194 --> 00:44:46,030
THE GRAVITY FIELD AROUND IT.

772
00:44:46,030 --> 00:44:50,134
AND MUCH LIKE BEFORE, THIS
EXAMPLE WE'RE PROBING THE

773
00:44:50,134 --> 00:44:51,252
GRAVITY FIELD HERE.

774
00:44:51,252 --> 00:44:57,458
WE'RE PROBING THE GRAVITY FIELD
OF UROPA AND THROUGH THAT WE CAN

775
00:44:57,458 --> 00:45:01,195
DETECT AND CONFIRM THE OCEAN
UNDERNEATH THE ICE.

776
00:45:01,195 --> 00:45:06,317
UNFORTUNATELY, TO GET THAT DATA
WE EITHER HAVE TO POINT THE HIGH

777
00:45:06,317 --> 00:45:13,991
GAIN ANTENNA AT EARTH, OR DEPLOY
MEDIUM ANTENNAS ON THIS AND

778
00:45:13,991 --> 00:45:16,160
OTHER FACETS OF THE SPACECRAFT
AND POINT THE VEHICLE TO EARTH

779
00:45:16,160 --> 00:45:17,077
TO GET IT.

780
00:45:17,077 --> 00:45:21,332

AND WHAT IT MEANS IS ALL THE
INSTRUMENTS THAT ARE ORIENTED

781
00:45:21,332 --> 00:45:26,103
TOWARD UROPA GET POINTED AWAY.

782
00:45:26,103 --> 00:45:26,370
THAT'S NOT GOOD.

783
00:45:26,370 --> 00:45:29,423
WE CAN TAKE ADVANTAGE OF THE
FACT THAT ON BOARD EVERY

784
00:45:29,423 --> 00:45:32,443
SPACECRAFT ARE THE LITTLE
ANTENNA.

785
00:45:32,443 --> 00:45:40,217
WHAT IS NIFTY THEY HAVE A LARGE
VIEW OF SPACE AROUND THEM.

786
00:45:40,217 --> 00:45:43,270
THESE ANTENNA HAVE A VERY NARROW
VIEW.

787
00:45:43,270 --> 00:45:47,341
WE TAKE THE LOW GAIN ANTENNA AND
YOU REMEMBER THE ANTENNA THAT

788
00:45:47,341 --> 00:45:50,027
WAS BIG WITH ALL THE POWER
TRANSMITTING?

789
00:45:50,027 --> 00:45:54,164
WE CAN ACTUALLY TRACK THOSE
SIGNALS WITH LOW GAIN ANTENNA ON

790
00:45:54,164 --> 00:45:56,166
BOARD A VEHICLE.

791
00:45:56,166 --> 00:46:00,971
IF YOU ADD IT TO THAT MIX, NOW
THAT DATA WE'RE COLLECTING IS

792
00:46:00,971 --> 00:46:01,171
ACCURATE.

793
00:46:01,171 --> 00:46:03,290
ACCURATE ENOUGH TO DETERMINE THE
GRAVITY FIELD.

794
00:46:03,290 --> 00:46:08,112
IF WE WERE TO BE ON BOARD THE
VEHICLE, WE WOULD DELIVER ABOUT

795
00:46:08,112 --> 00:46:12,416
THREE TIMES MORE DATA THAN WE
WOULD GET VERSUS USING THE THIS

796
00:46:12,416 --> 00:46:13,100
ANTENNA.

797
00:46:13,100 --> 00:46:17,054
OTHER MISSIONS THAT NASA IS
CONTEMPLATING IS SENDING

798
00:46:17,054 --> 00:46:17,471
BALLOONS TO TIE TAN.

799
00:46:17,471 --> 00:46:22,059
TIE TAN HAS AN ATMOSPHERE OF
NITROGEN.

800
00:46:22,059 --> 00:46:24,295
WE SPECULATE THERE ARE SEAS OF
METHANE.

801
00:46:24,295 --> 00:46:28,399
IT'S A VERY OCEANY WORLD, AND

ONE OF THE WAYS IN WHICH WE CAN

802
00:46:28,399 --> 00:46:31,368
EXPLORE THE SET OF BALLOONS TO
FLOAT IN THE ATMOSPHERE AND LET

803
00:46:31,368 --> 00:46:33,420
IT DRIFT.

804
00:46:33,420 --> 00:46:37,141
BUT ONE OF THE THINGS THAT WOULD
BE DIFFICULT IS TO TRACK WHERE

805
00:46:37,141 --> 00:46:44,431
THE BALLOON IS AT AS IT'S
COURSING OVERTY TAN.

806
00:46:44,431 --> 00:46:48,252
IF YOU HAD A SMALL VERSION AND
TAKE ADVANTAGE OF THE HIGH POWER

807
00:46:48,252 --> 00:46:49,486
TRANSMITTING TO THE VEHICLE.

808
00:46:49,486 --> 00:46:57,094
YOU PROBABLY HAVE FOUR 30-METERS
ANTENNA TO GET ENOUGH POWER.

809
00:46:57,094 --> 00:47:00,381
YOU CAN TRACK THE BALLOON AND
CHART THE COURSE.

810
00:47:00,381 --> 00:47:04,335
YOU CAN CORRELATE THE COURSE
WITH THE SCIENCE DATA THE

811
00:47:04,335 --> 00:47:07,171
BALLOON IS COLLECTING AND
TRANSMITTING BACK TO EARTH.

812
00:47:07,171 --> 00:47:10,057
SO THOSE ARE NIFTY SCIENCE
APPLICATIONS.

813
00:47:10,057 --> 00:47:11,158
LET'S GET BACK TO NAVIGATION.

814
00:47:11,158 --> 00:47:13,978
AND I'M GOING TO LOOK AT MARS.

815
00:47:13,978 --> 00:47:17,264
ONE OF THE NEXT MISSIONS THAT
WE'RE ENVISIONING GOING TO MARS

816
00:47:17,264 --> 00:47:21,118
IS AN ORBITER IN 2022.

817
00:47:21,118 --> 00:47:26,240
AND ONE OF THE WAYS IN WHICH
WE'RE HOPING OR PLANNING NOW IS

818
00:47:26,240 --> 00:47:32,446
TO INSERT INTO THE LOW ORBIT
USING SOLAR ELECTORATE

819
00:47:32,446 --> 00:47:33,163
PROPULSION.

820
00:47:33,163 --> 00:47:38,469
IT IMPARTS A SMALL ACCELERATION
AND THE SPACECRAFT WILL SLOWLY

821
00:47:38,469 --> 00:47:40,421
SPIRAL INTO THE ORBIT.

822
00:47:40,421 --> 00:47:43,107
NAVIGATION WISE IT'S A PRETTY
INTENSE PERIOD OF TIME.

823
00:47:43,107 --> 00:47:44,308
IT TAKES A LONG TIME.

824
00:47:44,308 --> 00:47:47,394
IF YOU HAD D SACK ON BOARD, YOU
COULD TAKE ADVANTAGE OF THE

825
00:47:47,394 --> 00:47:53,267
ABILITY TO GET THE DATA WITHOUT
IMPACTING OTHER MISSIONS THAT

826
00:47:53,267 --> 00:47:54,418
MEET THE DATA AT THE SAME TIME.

827
00:47:54,418 --> 00:47:59,306
YOU CAN COLLECT IT AND PROCESS
IT AND IMPROVE OUR ABILITY TO DO

828
00:47:59,306 --> 00:47:59,506
NAVIGATION.

829
00:47:59,506 --> 00:48:06,130
ANOTHER WAY IN WHICH IT COULD BE
HELPFUL IS THINKING FORWARD TO

830
00:48:06,130 --> 00:48:07,414
HUMANS GOING TO MARS.

831
00:48:07,414 --> 00:48:11,251
THERE'S GOING TO BE PROBABLY
VEHICLES GOING TO MARS.

832
00:48:11,251 --> 00:48:18,409
IF YOU HAD IT ON BOARD, ON
TRANSMISSIONS ON THE SPACECRAFT

833
00:48:18,409 --> 00:48:22,229
AND COUPLE IT WITH ON BOARD
COMPUTERS YOU CAN COMPUTE THE

834
00:48:22,229 --> 00:48:27,267
TRAJECTORY IN REAL TIME THAT
ASTRONAUTS TO USE TO SAFELY AND

835
00:48:27,267 --> 00:48:33,323
ROBUSTLY MAKE THEIR WAY TO MARS.

836
00:48:33,323 --> 00:48:34,341
EITHER AN ORBIT OR LAND.

837
00:48:34,341 --> 00:48:36,477
THOSE ARE SO. APPLICATIONS
WE'RE ENVISIONINGS.

838
00:48:36,477 --> 00:48:38,379
I HOPE YOU LIKED OUR TALK TODAY.

839
00:48:38,379 --> 00:48:42,266
I THOUGHT I WOULD END WITH A FEW
PICTURES HERE ILLUSTRATING

840
00:48:42,266 --> 00:48:47,354
CLOCKS OVER THE PAST QUARTER
MILLENNIUM.

841
00:48:47,354 --> 00:48:50,257
AND NUMBERICALLY IMPROVING
STABILITY.

842
00:48:50,257 --> 00:48:56,030
THERE'S HARRISON'S WATCH AT A
TENTH OF A SECOND PER DAY.

843
00:48:56,030 --> 00:49:00,300
AND THEM CAME ALONG USO IN THE
1960s AND THEY'RE 2,000 TIMES

844
00:49:00,300 --> 00:49:04,955

MORE STABLE AT THE MICROSECOND
PER DAY.

845
00:49:04,955 --> 00:49:13,363
NOW WE HAVE THIS AT ABOUT 3/10
OF A NANO SECOND PER DAY.

846
00:49:13,363 --> 00:49:20,070
WE'RE HAPPY TO ANSWER ANY
QUESTIONS YOU MIGHT HAVE.

847
00:49:20,070 --> 00:49:29,413
[APPLAUSE]
IF ANYBODY HAS ANY QUESTIONS,

848
00:49:29,413 --> 00:49:33,367
COME DOWN TO THE MIKES.

849
00:49:33,367 --> 00:49:37,221
WE DID A GOOD JOB OF EXPLAINING
EVERYTHING.

850
00:49:37,221 --> 00:49:43,060
>> CRYSTAL CLEAR.
>> DON'T BE SHY.

851
00:49:43,060 --> 00:49:43,277
HERE'S ONE.

852
00:49:43,277 --> 00:49:44,378
>> I HAVE A QUESTION.

853
00:49:44,378 --> 00:49:48,415
SO THE MOST ACCURATE CLOCK IN
THE WHOLE WORLD.

854
00:49:48,415 --> 00:49:53,187
YOU SAID A LITTLE BIT ABOUT HOW
YOU CAN TRY TO MEASURE THE

855
00:49:53,187 --> 00:49:58,041
ACCURACY OF VERY ACCURATE CLOCKS
USING THIS CONSTELLATION OF GPS

856
00:49:58,041 --> 00:49:58,242
SATELLITES.

857
00:49:58,242 --> 00:50:04,481
HOW IS THE ERROR IN THE MOST
ACCURATE CLOCK IN THE WORLD

858
00:50:04,481 --> 00:50:07,367
MEASURED?

859
00:50:07,367 --> 00:50:08,185
>> YEAH.

860
00:50:08,185 --> 00:50:11,138
IT'S MORE ACCURATE THAN ANY
OTHER CLOCK.

861
00:50:11,138 --> 00:50:15,509
IT'S NOT MORE ACCURATE THAN A
BUNCH OF CLOCKS TOGETHER.

862
00:50:15,509 --> 00:50:20,164
SO MATHEMATICALLY YOU CAN
COMBINE THE ACCURACY OF AN

863
00:50:20,164 --> 00:50:23,050
ENSEMBLE OF CLOCKS AND COMPARE
IT AGAINST THAT.

864
00:50:23,050 --> 00:50:44,238
IT'S SIMILAR TO WHAT WE'RE DOING
WITH THE ECHO IN ORBIT.

865
00:50:44,238 --> 00:50:52,396
[INAUDIBLE]

>> I'LL LET ALLEN ANSWER THAT

866
00:50:52,396 --> 00:50:56,116
ONE.
>> I'M SORRY.

867
00:50:56,116 --> 00:50:57,317
WHAT WAS THAT?

868
00:50:57,317 --> 00:50:59,319
>> WHAT'S THE LIFETIME OF THE
CLOCK?

869
00:50:59,319 --> 00:51:02,089
HOW DO YOU KNOW IT'S GOING TO
WORK FOR MANY YEARS?

870
00:51:02,089 --> 00:51:08,412
>> THE LIMITATION FOR MOST SPACE
FARING EQUIPMENT ARE THE

871
00:51:08,412 --> 00:51:12,165
ELECTRONICS AND THE FACT THAT
IT'S ALTERNATELY EITHER VERY

872
00:51:12,165 --> 00:51:15,335
COLD AND HOT OR JUST VERY COLD
ALL THE TIME OR AS THE

873
00:51:15,335 --> 00:51:18,222
SPACECRAFT HEATS UP IT GETS COLD
AND THEN HOT.

874
00:51:18,222 --> 00:51:21,441
THAT MAKES ALL THE ELECTRONIC
BOARDS, SAME WAY THAT

875
00:51:21,441 --> 00:51:23,243
ELECTRONICS IN YOUR CAR GO OUT.

876
00:51:23,243 --> 00:51:26,463
THEY EXPAND AND CONTRACT AND
EVENTUALLY SOMETHING BREAKS.

877
00:51:26,463 --> 00:51:32,369
SO THAT'S THE FUNDAMENTAL LIMIT
TO THE LIFETIME OF THE CLOCK.

878
00:51:32,369 --> 00:51:36,523
WE HAVE TUBES, LIKE THE LITTLE
ION TRACK TUBES.

879
00:51:36,523 --> 00:51:37,324
THEY'RE SEALED.

880
00:51:37,324 --> 00:51:40,410
SOME HAVE LASTED WELL OVER FIVE
YEARS.

881
00:51:40,410 --> 00:51:42,446
GOSH, I GUESS IT'S NINE YEARS
NOW.

882
00:51:42,446 --> 00:51:44,448
IT WAS FIVE WHEN WE STARTED THIS
PROJECT.

883
00:51:44,448 --> 00:51:51,288
SO WE DON'T SEE -- WE CAN MAKE A
SEAL THAT LASTS A LONG, LONG

884
00:51:51,288 --> 00:51:51,538
TIME.

885
00:51:51,538 --> 00:51:55,242
THE MERCURY ATOMS AND THE THINGS
INSIDE OF THE TUBES DON'T

886
00:51:55,242 --> 00:51:56,193

ACTUALLY GO AWAY.

887
00:51:56,193 --> 00:52:00,097
SO IT'S REALLY JUST THE
ELECTRONICS.

888
00:52:00,097 --> 00:52:01,999
>> OKAY.

889
00:52:01,999 --> 00:52:06,370
SO MY QUESTION, THE ONE-WAY
TRACKING THAT YOU CAN DO WITH

890
00:52:06,370 --> 00:52:17,064
THE ACCURATE ATOMIC CLOCK,
YOU -- YOU'RE ONLY GETTING RADIO

891
00:52:17,064 --> 00:52:17,281
INFORMATION.

892
00:52:17,281 --> 00:52:22,052
YOU'RE ONLY GETTING VERY
ACCURATE --

893
00:52:22,052 --> 00:52:29,426
>> INSIDE INFORMATION.
>> WOULD -- AT SOME POINT IN THE

894
00:52:29,426 --> 00:52:34,431
FUTURE, COULD YOU HAVE A SECOND
MASTER STATION THAT MAY BE

895
00:52:34,431 --> 00:52:37,351
MONITORED OR SOMETHING AND THEN
YOU COULD GET, RANGING FROM TWO

896
00:52:37,351 --> 00:52:38,151
DIFFERENT DIRECTIONS?

897

00:52:38,151 --> 00:52:41,171
>> YOU COULD.
>> WOULDN'T THAT BE BETTER?

898
00:52:41,171 --> 00:52:46,226
>> ONE OF THE CONCEPTS FOR
HUMANS GOING TO MARS IS TO PUT A

899
00:52:46,226 --> 00:52:48,178
MARS AREA STATIONARY SATELLITE.

900
00:52:48,178 --> 00:52:53,367
THAT WOULD PROVIDE TRACKING
SERVICES WHILE AT MARS FOR THE

901
00:52:53,367 --> 00:52:55,452
ASTRONAUTS ON THE SURFACE AS
WELL AS APPROACHING VEHICLES.

902
00:52:55,452 --> 00:52:59,172
IN THE LITTLE CARTOON I SHOWED,
ACTUALLY TWO ARROWS GOING TO THE

903
00:52:59,172 --> 00:53:00,090
LITTLE ROCKET.

904
00:53:00,090 --> 00:53:03,176
THAT WAS DEMONSTRATING THAT VERY
POSSIBILITY.

905
00:53:03,176 --> 00:53:08,365
ANOTHER THING, WHICH WE HAVE
ACTUALLY DONE QUITE A BIT OF.

906
00:53:08,365 --> 00:53:13,153
JPL IS FAMOUS FOR DOING OPTICAL
NAVIGATION.

907
00:53:13,153 --> 00:53:18,008
WE TAKE IMAGES OF SLES TEAL

BODIES WITH A STAR BURST

908
00:53:18,008 --> 00:53:18,208
BACKGROUND.

909
00:53:18,208 --> 00:53:23,180
AND YOU CAN FIND YOUR LOCATION
RELATIVE TO THE BODIES AND

910
00:53:23,180 --> 00:53:26,099
COUPLE THAT PROCESS.

911
00:53:26,099 --> 00:53:28,502
IT'S LINE OF SIGHT INFORMATION
THAT THE RANGING PROVIDES.

912
00:53:28,502 --> 00:53:32,422
NOW YOU HAVE A MORE COMPLETE
KIND OF THREE DIMENSIONAL FIX OF

913
00:53:32,422 --> 00:53:34,174
YOUR LOCATION IN SPACE.

914
00:53:34,174 --> 00:53:38,228
SO THAT'S ANOTHER POSSIBILITY
THAT WE COULD -- THAT WE'RE

915
00:53:38,228 --> 00:53:39,279
ENVISIONING.
>> THANK YOU.

916
00:53:39,279 --> 00:53:40,113
>> OKAY.

917
00:53:40,113 --> 00:53:43,316
WE HAVE SOME -- I GUESS THESE
ARE SOCIAL MEDIA QUESTIONS.

918
00:53:43,316 --> 00:53:49,056

I HAVE BEEN HANDED.
>> SO THE FIRST ONE IS, IS FOR

919
00:53:49,056 --> 00:53:49,406
TODD.
>> OKAY.

920
00:53:49,406 --> 00:53:55,128
>> WHAT ARE THE EFFECTS OF
GENERAL RELATIVITY ON ATOMIC

921
00:53:55,128 --> 00:53:57,447
CLOCKS IN OUTER SPACE FOR FROM
EARTH'S GRAVITATIONAL FIELD?

922
00:53:57,447 --> 00:54:01,268
>> SO THE GPS SYSTEM ACTUALLY
HAS TO DEAL WITH THIS.

923
00:54:01,268 --> 00:54:05,222
THEY ACTUALLY -- THE FREQUENCY
THAT IT WOULD NATURALLY TRANSMIT

924
00:54:05,222 --> 00:54:09,009
IN ITS ORBIT, THEY ACTUALLY
ARTIFICIALLY REDUCE THAT

925
00:54:09,009 --> 00:54:13,130
FREQUENCY BECAUSE THE CLOCKS ON
EARTH TICK AT A DIFFERENT RATE

926
00:54:13,130 --> 00:54:16,166
THAN THE CLOCKS IN THE GPS
CONSTELLATION.

927
00:54:16,166 --> 00:54:18,201
SO THIS IS A FACT OF LIFE.

928
00:54:18,201 --> 00:54:19,453
THIS IS SOMETHING WE HAVE TO

DEAL WITH.

929
00:54:19,453 --> 00:54:23,473
WE HAVE TO DEAL WITH IT TODAY
REPEATEDLY, EVEN WITH TWO-WAY

930
00:54:23,473 --> 00:54:24,241
DATA.

931
00:54:24,241 --> 00:54:30,213
USING DSAC IN THE FUTURE WITH
ONE-WAY DATA WE'D HAVE TO

932
00:54:30,213 --> 00:54:32,232
CORRECT FOR CERTAIN EFFECTS.

933
00:54:32,232 --> 00:54:34,434
THEY'RE SMALL BUT SUBSTANTIAL.

934
00:54:34,434 --> 00:54:38,138
IF WE DIDN'T CORRECT FOR THEM
THEY WOULD BE THE LARGEST ERROR

935
00:54:38,138 --> 00:54:45,128
SOURCE THAT WE'D ENCOUNTER IN
GOING TO PLACES LIKE MARS AND

936
00:54:45,128 --> 00:54:48,181
JUPITER.
>> DO THEY CLICK FASTER OR

937
00:54:48,181 --> 00:54:51,501
SLOWER AT MARS.
>> THEY CLICK FASTER.

938
00:54:51,501 --> 00:54:54,421
>> WE SPENT AN HOUR THIS
AFTERNOON TRYING TO FIGURE OUT

939

00:54:54,421 --> 00:55:01,144
THE ANSWER TO THAT QUESTION IN
CASE SOMEBODY ANSWERED IT.

940
00:55:01,144 --> 00:55:02,262
>> IF YOU DON'T GET IT RIGHT,
YOU GET IT WRONG.

941
00:55:02,262 --> 00:55:04,314
>> I HAVE ANOTHER QUESTION.

942
00:55:04,314 --> 00:55:07,167
DSAC OPERATES AT THE LEVEL OF
ATOMS.

943
00:55:07,167 --> 00:55:12,022
ARE THERE ANY CHALLENGES BECAUSE
OF QUANTUM MECHANICS?

944
00:55:12,022 --> 00:55:14,991
ACTUALLY, WE USE QUANTUM
MECHANICAL EFFECTS.

945
00:55:14,991 --> 00:55:21,081
THAT'S EXACTLY HOW THIS I WAS
TALKING ABOUT WITH THIS ELECTRON

946
00:55:21,081 --> 00:55:23,116
IS A QUANTUM MECHANIC EFFECT.

947
00:55:23,116 --> 00:55:28,338
ONE OF OF THE REASON WE TRAP THE
IONS IN A FIELD IS REDUCE

948
00:55:28,338 --> 00:55:31,024
PROHIATIONS ON THE ATOMS.

949
00:55:31,024 --> 00:55:36,246
WE DON'T GET TO THE LEVEL OF
QUANTUM MECHANICAL EFFECTS IN

950
00:55:36,246 --> 00:55:36,396
THAT.

951
00:55:36,396 --> 00:55:40,400
SO THE CHALLENGES ARE TO DESIGN
A VERY MAGNETICALLY CLEAN CLOCK.

952
00:55:40,400 --> 00:55:42,436
THAT WHOLE CLOCK, ALL THAT
METAL.

953
00:55:42,436 --> 00:55:44,237
NONE OF IT IS MAGNETIC.

954
00:55:44,237 --> 00:55:47,140
IT'S ALL NON-MAGNETIC METALS.

955
00:55:47,140 --> 00:55:52,145
THE MAGNETIC FIELDS, THE STRAY
MAGNETIC FIELDS WOULD INDUCE A

956
00:55:52,145 --> 00:55:53,430
QUANTUM MECHANICAL EFFECT.

957
00:55:53,430 --> 00:55:57,317
THAT'S A CHALLENGE BECAUSE
NON-MAGNETIC SCREWS ARE HARD TO

958
00:55:57,317 --> 00:56:00,170
FIND.
>> TO FOLLOW UP ON THAT, WE TALK

959
00:56:00,170 --> 00:56:03,123
ABOUT THE HARSH ENVIRONMENT OF
SPACE AND PEOPLE'S PERCEPTIONS

960
00:56:03,123 --> 00:56:05,258
MIGHT BE THE SPACE AROUND THE

VEHICLE.

961
00:56:05,258 --> 00:56:08,411
BUT REALLY THE SPACE INSIDE THE
VEHICLE IS AN ENVIRONMENT WE

962
00:56:08,411 --> 00:56:11,998
HAVE TO DEAL WITH, THE CHANGING
TEMPERATURES INSIDE THE

963
00:56:11,998 --> 00:56:17,454
SPACECRAFT, THE MAGNETIC FIELDS
FROM THE OUTER ENVIRONMENT AS

964
00:56:17,454 --> 00:56:23,160
WELL AS FROM THE SPACE FIELD
ITSELF COULD IMPACT THE CLOCK.

965
00:56:23,160 --> 00:56:24,361
>> ANOTHER QUESTION.

966
00:56:24,361 --> 00:56:30,400
COULD NEARBY SPACECRAFT USE A
DSAC THAT IS CLOSE BY?

967
00:56:30,400 --> 00:56:36,106
>> SO, WHAT DSAC DOES, WE DIDN'T
REALLY GET INTO THIS -- IT TAKES

968
00:56:36,106 --> 00:56:41,211
A USO AND USES THE TUNING FORK
FEATURE, AND WE CONTROL THE

969
00:56:41,211 --> 00:56:45,332
OUTPUT OF THE USO TO GET A MORE
STABLE FREQUENCY ON LONGER TIME

970
00:56:45,332 --> 00:56:46,032
SCALES.

971
00:56:46,032 --> 00:56:50,020
IN TEN SECONDS WE'RE REALLY
ADOPTING THE STABILITY OF THE

972
00:56:50,020 --> 00:56:52,272
USO THAT IS PART OF THIS
PROCESS.

973
00:56:52,272 --> 00:56:57,510
AND IN FACT, USOs ARE USED
ROUTINELY FOR COMMUNICATING

974
00:56:57,510 --> 00:56:59,129
BETWEEN NEARBY SPACECRAFT.

975
00:56:59,129 --> 00:57:04,034
AN EXAMPLE THAT WE USE, EARTH
AND AT THE MOON, EARTH IS THE

976
00:57:04,034 --> 00:57:05,368
GRACE MISSION.

977
00:57:05,368 --> 00:57:09,089
THEY USE COMMUNICATION LINKS
BETWEEN TWO SPACECRAFT THAT ARE

978
00:57:09,089 --> 00:57:13,009
IN ORBIT.

979
00:57:13,009 --> 00:57:17,414
THEY'RE A FEW HUNDRED KILOMETERS
APART AND THE TIME FOR THE

980
00:57:17,414 --> 00:57:22,435
SIGNAL TO GO BACK AND FORTH IS
VERY SHORT.

981
00:57:22,435 --> 00:57:26,339
WHAT MATTERS FOR DSAC IS LOOKING

AT THE EVOLUTION OF THE

982
00:57:26,339 --> 00:57:29,442
FREQUENCY IN TIME OVER LONG
PERIODS OF TIME.

983
00:57:29,442 --> 00:57:33,296
YOU'RE TAKING MEASUREMENTS AT A
PERIOD OF TIME, AND THEN YOU'RE

984
00:57:33,296 --> 00:57:36,333
NOT TAKING MEASUREMENTS FOR A
DAY, AND YOU START TAKING THEM

985
00:57:36,333 --> 00:57:37,000
AGAIN.

986
00:57:37,000 --> 00:57:40,053
YOU DON'T WANT YOUR FREQUENCY
AND TIME SOURCE TO HAVE DRIFTED

987
00:57:40,053 --> 00:57:42,122
SIGNIFICANTLY AWAY FROM WHAT
IT'S SUPPOSED TO BE.

988
00:57:42,122 --> 00:57:45,475
THAT BECOMES AN ERROR THAT YOU
HAVE TO DEAL WITH IN THE

989
00:57:45,475 --> 00:57:46,493
TRAJECTORY DETERMINATION
PROCESS.

990
00:57:46,493 --> 00:57:50,380
REMEMBER, WE HAVE ONLY A LIMITED
AMOUNT OF DATA TO FIGURE OUT THE

991
00:57:50,380 --> 00:57:51,398
TRAJECTORY.

992
00:57:51,398 --> 00:57:53,216
ERRORS LIKE CLOCKS MAKE THAT
HARDER.

993
00:57:53,216 --> 00:57:53,383
>> OKAY.

994
00:57:53,383 --> 00:57:56,469
THIS ONE IS FROM AN USTREAM
CHAT.

995
00:57:56,469 --> 00:57:58,071
WE GOT YOU COVERED.

996
00:57:58,071 --> 00:58:03,209
COULDEN A EARTH ORBITING DSAC
AUGMENT THE DEEP SPACE NETWORK

997
00:58:03,209 --> 00:58:06,446
FOR NAVIGATING EXISTING PROBES
AND MISSIONS?

998
00:58:06,446 --> 00:58:09,449
>> THE CHALLENGE THERE IS, YOU
KNOW, ONE ANSWER WOULD BE YES.

999
00:58:09,449 --> 00:58:14,187
BUT ACTUALLY THE REAL CHALLENGE
FOR AN ORBITING SPACECRAFT IS

1000
00:58:14,187 --> 00:58:16,156
KNOWING ITS LOCATION PRECISELY.

1001
00:58:16,156 --> 00:58:23,213
SO, FOR THIS DSM ENTERPRISE TO
WORK, WE ACTUALLY DO LOCATION OF

1002
00:58:23,213 --> 00:58:36,476
THE -- OF MONUMENTS THAT DEFINE

THE CENTER TO WITHIN A

1003
00:58:36,476 --> 00:58:40,413
CENTIMETER OF WHERE THAT WILL IT
WILL THE ANTENNA.

1004
00:58:40,413 --> 00:58:45,201
WE WOULD BE CHALLENGED FOR A
SPACECRAFT TO HAVE THAT KIND OF

1005
00:58:45,201 --> 00:58:45,402
ACCURACY.

1006
00:58:45,402 --> 00:58:48,088
WHILE THE FREQUENCY AND TIME
STABILITY ON THE SATELLITE WOULD

1007
00:58:48,088 --> 00:58:51,391
BE GOOD AND COULD AUGMENT THE
DSN.

1008
00:58:51,391 --> 00:58:56,212
WE WOULD BE CHALLENGED KNOWING
WHERE THE SPACECRAFT IS AT TO

1009
00:58:56,212 --> 00:59:03,286
PARTICIPATE IN THIS NAVIGATION
ENTERPRISE.

1010
00:59:03,286 --> 00:59:08,224
>> FROM THE SOUND OF THINGS,
THERE IS KIND OF A LOG JAM OR A

1011
00:59:08,224 --> 00:59:11,277
TRAFFIC JAM, BOTTLE NECK, AT THE
DEEP SPACE NETWORK.

1012
00:59:11,277 --> 00:59:18,268
CAN YOU COMMENT ABOUT ANY PLANS
TO EXPAND THE DSN TO -- BECAUSE,

1013
00:59:18,268 --> 00:59:21,254
UNLESS THE CURRENT MISSIONS ARE
BASICALLY GOING TO DIE OUT IN

1014
00:59:21,254 --> 00:59:26,159
THE NEXT FEW YEARS, WITH THE
NUMBER OF MISSIONS THAT WILL BE

1015
00:59:26,159 --> 00:59:32,248
COMING ONLINE, WE'RE GOING TO BE
NEEDING MORE DSN CAPABILITY.

1016
00:59:32,248 --> 00:59:35,218
>> THERE ARE CURRENTLY FIVE
MISSIONS AT MARS RIGHT NOW,

1017
00:59:35,218 --> 00:59:36,302
RIGHT?

1018
00:59:36,302 --> 00:59:37,270
IS IT FIVE?

1019
00:59:37,270 --> 00:59:44,361
>> FIVE -- YEAH.
>> MAVEN IS ON THE WAY.

1020
00:59:44,361 --> 00:59:46,396
>> MAVEN IS THERE.

1021
00:59:46,396 --> 00:59:48,448
XL MARS.

1022
00:59:48,448 --> 00:59:50,316
MRO, ODYSSEY.

1023
00:59:50,316 --> 00:59:52,085
TGO IS ON THE WAY.

1024
00:59:52,085 --> 00:59:54,054
THERE'S SIX AT MARS.

1025
00:59:54,054 --> 00:59:58,208
YES.
>> THERE'S A LOT.

1026
00:59:58,208 --> 01:00:02,178
I CAN'T REALLY SPECULATE AS TO
WHAT THE NASA PLANNERS ARE DOING

1027
01:00:02,178 --> 01:00:04,297
ABOUT ADDING ANTENNAS.

1028
01:00:04,297 --> 01:00:06,232
I'M SURE THERE ARE PLANS FOR
THAT.

1029
01:00:06,232 --> 01:00:09,486
DSAC IS ONE WAY IN WHICH WE CAN
USE THE EXISTING NETWORK A LOT

1030
01:00:09,486 --> 01:00:10,487
MORE EFFICIENTLY.

1031
01:00:10,487 --> 01:00:17,127
AND SO, IN THAT ARCHITECTURAL
TRADE, THE PLANNERS NEED TO

1032
01:00:17,127 --> 01:00:20,513
DECIDE IS IT MORE COST EFFECTIVE
TO PUT A DSAC ON BOARD A

1033
01:00:20,513 --> 01:00:24,517
SPACECRAFT AND EXPAND OUR USER
BASE THAT WAY OR ADDING MORE

1034
01:00:24,517 --> 01:00:25,201
ANTENNAS.

1035
01:00:25,201 --> 01:00:28,471
AND I'M SURE THE ANSWER TO THAT
WILL DEPEND ON HOW WELL WE ARE

1036
01:00:28,471 --> 01:00:34,127
AT REDUCING THE SIZE OF DSAC AND
MAKING IT MORE AFFORDABLE FOR

1037
01:00:34,127 --> 01:00:38,114
MIXED USERS AND PUTTING THAT
INTO THE MIX OF THE PLANNING.

1038
01:00:38,114 --> 01:00:44,070
>> SO OUR CURRENT FLEET IS NOT
TAXING DSN TO ITS LIMIT, THEN?

1039
01:00:44,070 --> 01:00:45,388
>> NOT RIGHT NOW.
>> OKAY.

1040
01:00:45,388 --> 01:00:49,375
>> WHEN I START LOOKING AT THE
ARMADA VEHICLES THAT THE HUMAN

1041
01:00:49,375 --> 01:00:52,228
PROGRAM IS CONTEMPLATING, I
DON'T KNOW.

1042
01:00:52,228 --> 01:00:58,134
MAYBE THAT COULD CHANGE.
>> THE DSN IS A LOT OF -- IT'S

1043
01:00:58,134 --> 01:00:58,284
BUSY.

1044
01:00:58,284 --> 01:01:01,488
DON'T -- THE ANTENNAS ARE --
THEY'RE ALWAYS ON.

1045
01:01:01,488 --> 01:01:04,140
AND THEY'RE ALWAYS TALKING TO
SOME SPACECRAFT.

1046
01:01:04,140 --> 01:01:07,460
I'M SURE, IF YOU TALK TO MISSION
MANAGERS FOR THESE DIFFERENT

1047
01:01:07,460 --> 01:01:10,430
MISSIONS, THEY WOULD WANT MORE
TRACKING TIME THAN THEY GET

1048
01:01:10,430 --> 01:01:11,247
RIGHT NOW.

1049
01:01:11,247 --> 01:01:16,052
SO IT'S DOABLE NOW, BUT IT'S
KIND OF GETTING TO BE AT

1050
01:01:16,052 --> 01:01:18,421
CAPACITY.
>> IN FACT, I HAVE AN ANECDOTAL

1051
01:01:18,421 --> 01:01:23,076
STORY THAT, WITH THE ARRIVAL OF
MAVEN, ODYSSEY WASN'T GETTING AS

1052
01:01:23,076 --> 01:01:27,330
MUCH TRACKING TIME AND THAT WAS
STRETCHING THEIR ABILITY TO

1053
01:01:27,330 --> 01:01:31,084
FIGURE OUT THEIR ORBITS TO THE
LEVEL THEY NEEDED TO.

1054
01:01:31,084 --> 01:01:33,503
>> THE QUESTION IS WHERE WILL
THE LAUNCH TAKE PLACE.

1055

01:01:33,503 --> 01:01:39,425
WE WILL BE LAUNCHED FROM THE
HISTORIC PAD 39-A AT THE KENNEDY

1056
01:01:39,425 --> 01:01:45,448
SPACE CENTER, SPACEX IS RENTING
THAT FORMER SATURN 5 SHUTTLE PAD

1057
01:01:45,448 --> 01:01:53,072
AND CONVERTING IT FOR THE FALCON
HEAVY.

1058
01:01:53,072 --> 01:01:53,256
QUESTION?

1059
01:01:53,256 --> 01:02:04,050
[INAUDIBLE QUESTION]
>> MERCURY --

1060
01:02:04,050 --> 01:02:07,036
>> THE QUESTION IS WHY DID WE
PICK MERCURY?

1061
01:02:07,036 --> 01:02:09,455
UNFORTUNATELY, I AM NOT AN
ATOMIC CLOCK PHYSICIST.

1062
01:02:09,455 --> 01:02:12,475
I CAN ONLY TELL YOU THAT THAT'S
WHAT THE GUY WHO KNOWS WHAT HE'S

1063
01:02:12,475 --> 01:02:17,046
DOING SAID TO USE.
>> SERIOUSLY, THERE ARE -- IT

1064
01:02:17,046 --> 01:02:23,219
HAS TO DO WITH THE WAY THE
ELECTRONS AND THE NUCLEUS TO THE

1065
01:02:23,219 --> 01:02:27,156

ATOM INTERACT AND THE
FREQUENCIES AND CAN YOU GET

1066
01:02:27,156 --> 01:02:29,108
PARTS TO GENERATE THE
FREQUENCIES.

1067
01:02:29,108 --> 01:02:34,380
IT'S A QUASI PRACTICAL DECISION
FOR AN ION TRACK CLOCK.

1068
01:02:34,380 --> 01:02:39,135
THE COMMON CLOCKS LIKE THE GPS
SATELLITES HAVE, THEY USE A

1069
01:02:39,135 --> 01:02:45,508
TRANSITION METAL CALLED ROBIDIUM
IN A GAS FORM.

1070
01:02:45,508 --> 01:02:50,246
THEY PICKED IT FOR A VARIETY OF
PRACTICAL AND PHYSICS REASONS.

1071
01:02:50,246 --> 01:02:54,217
IT USUALLY TURNS OUT TO BE
SOMETHING LIKE THAT.

1072
01:02:54,217 --> 01:02:58,371
CZM IS COMMONLY USED IN
EARTH-BASED CLOCKS AND LIKEWISE

1073
01:02:58,371 --> 01:03:00,290
THERE ARE PRACTICAL AND HISTORIC
REASONS FOR THAT.

1074
01:03:00,290 --> 01:03:03,409
BUT YOU CAN DO IT WITH A WIDE
VARIETY OF ATOMS.

1075
01:03:03,409 --> 01:03:07,330

IT JUST DEPENDS ON, REALLY,
WHETHER OR NOT YOU CAN -- HOW

1076
01:03:07,330 --> 01:03:12,051
HARD OR EASY IT IS TO ACTUALLY
BUILD IT, TO CONSTRUCT IT.

1077
01:03:12,051 --> 01:03:14,404
>> ONE MORE NOTE TO ADD ON
PERFORMANCE.

1078
01:03:14,404 --> 01:03:20,376
WE'RE ANTICIPATING THAT THE DSAC
THAT WE FLY IS MAYBE FIVE TIMES

1079
01:03:20,376 --> 01:03:25,131
MORE STABLE THAN THE ROBIDIUMS.

1080
01:03:25,131 --> 01:03:30,436
THE OTHER FEATURE OF THE MERCURY
CLOCK IS IT DOESN'T DRIFT.

1081
01:03:30,436 --> 01:03:35,441
ON TOP OF RANDOM INSTABILITIES
THERE IS USUALLY SOME PSEUDO

1082
01:03:35,441 --> 01:03:38,311
DETERMINISTIC DRIFT THAT PULLS
THE CLOCK AWAY.

1083
01:03:38,311 --> 01:03:41,297
ROW BID YUMS INTRINSICALLY HAVE
THAT.

1084
01:03:41,297 --> 01:03:42,248
DSAC WILL THAT.

1085
01:03:42,248 --> 01:03:46,185
FACTORING THAT WITH THE
INSTABILITY, WE'RE ABOUT 50

1086
01:03:46,185 --> 01:03:54,110
TIMES MORE ACCURATE THAN THE
FLYING GPS CLOCKS TODAY.

1087
01:03:54,110 --> 01:03:54,527
>> OKAY.

1088
01:03:54,527 --> 01:03:58,331
I ONLY SEE TWO PEOPLE WE'VE PUT
TO SLEEP, SO THAT'S PRETTY GOOD,

1089
01:03:58,331 --> 01:04:00,233
OUT OF THIS CROWD.

1090
01:04:00,233 --> 01:04:03,169
SO ANY OTHER QUESTIONS?