Precise Pointing for Radio Science Occultations and Radar Mapping during the Cassini Mission at Saturn

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This paper discusses the implementation challenges and lessons learned from radar and radio science pointing observations during the Cassini mission at Saturn. Implementation of the precise desired pointing reveals key issues in the ground system, the flight system, and the pointing paradigm itself. To achieve accurate pointing on some observations, specific workarounds had to be implemented and folded into the sequence development process. Underlying Cassini’s pointing system is a remarkable construct known as Inertial Vector Propagation.

Nomenclature

\begin{itemize}
  \item \textit{FSW} = Flight Software
  \item \textit{IVD} = Inertial Vector Definition
  \item \textit{IVP} = Inertial Vector Propagation
  \item \textit{RSS} = Radio Science Subsystem
  \item \textit{SCET} = Spacecraft Event Time
  \item \textit{SCLK} = Spacecraft Clock Time
\end{itemize}

I. Introduction

Some of the richest science gathered during the decade that the Cassini spacecraft has been orbiting Saturn are radar mapping of Titan and radio science during occultations of Titan, Saturn and the rings. Titan radar mapping has discovered lakes of liquid hydrocarbons near the north and south poles of this intriguing moon. Occultation radio science is an immensely fruitful technique of analyzing radio signals from Cassini after they pass through an intervening medium. Cassini radio signals pass through the atmosphere of Titan, for example, and these signals have been carefully analyzed on Earth. From these measurements scientists have gathered a rich understanding of the atmospheres of Titan and Saturn, along with detailed new knowledge of the rings of Saturn, the surface of Titan, and the icy water plumes emitted from the moon Enceladus.

Both radar and radio science occultation observations require very precise pointing to maximize the science return. Not only must the spacecraft estimate and control\textsuperscript{1} the inertial 3-axis attitude of Cassini precisely, but the commanded time-history of pointing the High-Gain Antenna must be carefully designed to get the most valuable radar mapping during Titan flybys and radio science during occultations of the atmospheres of Titan and Saturn.

This aspect of pointing – commanding the proper attitude over time – tends to get less emphasis in the technical literature than the control and stability aspects of achieving the pointing that science gathering requires. Certainly a camera exposure that is smeared due to undesired angular motion means a failure somewhere – either onboard or on the ground. Less well known is a camera that has a precise and stable exposure – but is pointing at the wrong object! Correct commanding of pointing is sometimes taken for granted, but is actually a subtle operational task, and there are many ways it can go wrong.

Cassini in particular has to have a robust pointing paradigm because there are so many instruments onboard and so many “users” of the Cassini pointing system. Cassini has a suite of Optical Remote Sensing instruments (including cameras), and a set of Fields, Particles, and Waves instruments (which often need multi-revolution slews for maximum science). But the microwave sensing and transmission instruments – the Radar and Radio Science subsystems – are actually the most demanding in terms of precise pointing requirements. Both synthetic aperture radar, radio science occultations, and bistatic scattering off Titan’s surface, require a very elaborate design of pointing.

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commands in order to maximize their science gathering. Radar and RSS share the High Gain Antenna for their science gathering, and they utilize the same type of pointing commands as any other instrument on Cassini. It is this “many users” aspect of the pointing system that required a new commanding paradigm during spacecraft development.

With no scan platform, the entire Cassini spacecraft must be slewed to bring a science instrument boresight to bear on a target of interest. One science observation team “hands off” to another and often both observations conclude by slew ing the spacecraft to a standard “waypoint” so that the next instrument team can reliably begin their observations from a known attitude. Building a seamless integrated series of commands that achieve the desired pointing goals of all users within the physical constraints of the spacecraft and without flight rule violation is hard. Ground operations require lots of tools, coordination meetings, and testing before a complete sequence of commands is ready to be uplinked to Cassini.

To achieve these objectives, the Cassini pointing system uses high-level, goal-oriented commands that alert the flight software that an activity needs to start. For example, a multi-revolution spacecraft slew for science fields and particle can be accomplished with just two commands: the first to command the angular rate and acceleration for the activity; the second to start the actual turn and tell the FSW the total magnitude and slew axis. The rest of the turn (profiling the acceleration, coasting, and deceleration phases) is handled by the flight software. A new spacecraft pointing attitude can be commanded with just two other commands: one to tell the spacecraft where to go and another how fast to get there.

Pointing commands do not reference underlying entities like right ascension, declination, or spacecraft body rates. On Cassini, pointing commands reference celestial objects themselves. If the target is Saturn, a single command causes the spacecraft to turn to Saturn. Once there, the spacecraft tracks Saturn until commanded to turn to another object. This means that target motion compensation is inherent in the design.

Cassini is able to explicitly point a science instrument boresight at a celestial object by use of an innovative pointing paradigm called Inertial Vector Propagation (IVP). A previous Cassini paper discussed IVP in detail. IVP has both a ground system component (to create commands and manage onboard IVP table contents) and a flight system component (to propagate active vectors placed into the IVP tables by ground command). These propagated vectors are then made available to the onboard attitude commander flight software object.

Cassini uses three types of time-varying IVP vectors: (1) conic vectors; (2) polynomial vectors; and (3) rotating-coordinate system vectors. Conic vectors are used when an object follows a purely Keplerian path in space dominated by a single gravitational body. Examples include Earth (and Saturn) with respect to the Sun and Cassini with respect to Saturn. Polynomial vectors are discussed in detail below. The third type, rotating-coordinate frames, is especially useful when a particular latitude/longitude of interest is to be tracked on a rotating body or the rings. Time-varying vectors “time out” (are autonomously deleted) from the inertial vector “table”, while fixed vectors must be explicitly deleted via command when no longer needed. Most Radar and RSS pointing involve polynomial time-varying vectors.

II. Cassini Polynomial Time-Varying Inertial Vectors

The time-varying pointing vector type used most frequently on Cassini is called a Chebyshev polynomial. The Cassini IVP flight software uses Chebyshev polynomials of the form:

\[ T_k(\tau) = \cos(k\theta) \quad \text{where } \tau = \cos \theta \]

These polynomials are defined as follows:

\[
\begin{align*}
T_0(\tau) &= 1 \\
T_1(\tau) &= \tau \\
T_k(\tau) &= 2 \tau T_{k-1}(\tau) - T_{k-2}(\tau) \quad k > 1
\end{align*}
\]

Where \( \tau \) is the normalized time, between -1 and 1 inclusive, and is given by:

\[
\tau = \frac{(2 t - t_f - t_e)}{(t_f - t_e)} \quad \text{where } t = 0 \text{ at the start time } t_e, \quad t = t_f - t_e \text{ at the end time } t_f
\]

Chebyshev polynomial propagation for both position and velocity can be done recursively and is especially well suited to “fit” spacecraft and celestial body ephemerides with a small maximum fit error. Let \( f(t) \) be the “true” time-
history of the ephemeris relative position or spatial pointing direction to be fitted by Chebyshev polynomials. Let the maximum allowable fit error be 40 μrad (= .00229 degrees, or 8.25 arcsec). So we want:

\[
\max_{-1 \leq r \leq 1} \left| f(t_j) - \sum_{i=0}^{n} C_i T_i(\tau_j) \right| < 40 \, \mu\text{rad}, \ j = 1, 2, 3, \ldots N
\]

where \( T_i \) are the Chebyshev polynomials, \( t_j \) are the time instants at which the data \( f(t) \) is available (there are \( N \) data points), \( C_i \) are the polynomial coefficients (to be computed), \( \tau_j \) is the \( \tau \) normalized time at each of the \( j \) time instances, and “\( n \)” is the “order” of the polynomial.

The Chebyshev expansion \( C_0 T_0 + C_1 T_1 + C_2 T_2 + \ldots + C_n T_n \) produces a sum that, over the range of time instants from the start time \( t_s \) to the end time \( t_f \), matches the actual desired pointing direction at each time instant within a maximum pointing error less than 40 μrad for any of the time instances in the range. Three separate fits are required for the three Cartesian axes and all use the same order polynomial fit. An \( n \)-th order fit therefore requires \( 3(n+1) \) polynomial coefficients. The fits are normally performed in the J2000 inertial reference frame.

This “vector fitting” process is performed on the ground in a tool called the IVP tool. This tool underlies all the pointing designs on the Cassini mission. The IVP tool ensures the commanded pointing is always within about 40 μrad of the ideal pointing, as defined by the ephemeris geometry that pertains during each science observation. The time-varying polynomial vectors are constructed as commands that are merged with the rest of the sequence to be uplinked.

In the Cassini implementation, a 12-th order polynomial is the largest allowed. Lower order polynomials are used if the pointing can be fit to less than 40 μrad across the range of the particular observation. Some observations can be fit using only a 2\(^{nd}\) order polynomial, while others, especially if they are longer observations, sometimes require one or more 12-th order polynomial. The IVP polynomial vector command used in uplinked sequences contains a vector name, a vector start time, a vector end time, and a series of polynomial coefficients (between 6 and 39 coefficients). The “duration” of a polynomial is the end time minus the start time.

An example of a high-order polynomial fit is a Saturn-to-Cassini vector during a Titan encounter (Fig. 1). When the spacecraft is very near Titan, the combined gravity of Saturn and Titan make it difficult for a single accurately-fit polynomial to have a duration of more than a day. Another vector “segment” is issued just before an active vector reaches its “end” time. Thus vector segment commands are stacked -- separated by hours or days -- but keep the onboard vector table populated with “currently” accurate pointing information. The 40 μrad fit criteria ensures that there is a smooth transition when a new polynomial takes over from a previous segment.

![Figure 1. Fit Error of Saturn-to-Cassini Polynomial near Titan Flyby](image_url)
Polynomial vectors have many advantages and a few disadvantages. Their great advantage is that they can fit a somewhat irregular path very accurately. The pointing from Cassini to Saturn in Figure 1, even though it gives the appearance of being very oscillatory, is actually a very accurate fit: by using this vector, the pointing is guaranteed to be within 40 μrad of the “ideal” pointing at every background polynomial propagation time point within the 20+ hour duration of the fit. The oscillatory rate is actually very small: less than 1.0e-7 rad/s. This is far below the noise level of the onboard controller.

Polynomials do have a few disadvantages. Up to 36 extended-precision coefficients makes for a large command. When a large polynomial command is issued, care must be taken that no other large command is issued nearby to avoid any chance of overflowing the command queue in the flight computer. Another disadvantage is that a polynomial is not well-behaved when propagated beyond its end time. Ground tools ensure that a new vector is always issued before a polynomial reaches its end time. In the event of spacecraft safe mode, the vector path back to Earth does not involve propagating polynomial vectors (other than the “short” distance from Cassini to Saturn).

III. Factors Affecting Accurate Pointing in Radar and Radio Science Observations

All time-varying vectors, fundamentally, are a function of time. If the current time is one hour after a vector’s “start” time, then the commanded pointing direction is, functionally, just a table-lookup: for that time, command that specific pointing direction in the J2000 inertial reference frame (X,Y,Z). Time is the independent variable. So an accurate clock is essential for the pointing system to operate accurately. And since vector propagation is like a table-lookup, the vector start time needs to be synchronized with the polynomial coefficients. If the ground system were to “truncate” or even “round off” the vector start time, even by a fraction of a second, this will introduce some small but non-zero error in the vector propagation.

Most science observations are designed using tools that present the science user with geometric targeting options. Examples include: (1) targeting the center of a celestial body; (2) targeting a fixed point on the surface of a body; (3) targeting a time-varying point on the surface of a body (perhaps at a constant viewing or lighting angle); (4) targeting the dust “RAM” direction (the relative velocity of Cassini with respect to dust orbiting in the rings); (5) targeting the limb (edge of visible disk) of a celestial body. For all these cases, the user is referencing some sort of geometric condition involving celestial objects. It is only the underlying “IVP fitting tool” that actually creates and utilizes a time-history of pointing vectors from Cassini to the target of interest. Polynomial vector fits are then made using this pointing-vector time-history. In all of these fits, the IVP fitting tool extracts position and velocity from navigation-supplied ephemeris files, which are a precise time-history of celestial body and Cassini states. The fitted polynomials correspond to actual position vectors in space (perhaps thousands or even millions of kilometers in magnitude) in the J2000 Cartesian inertial frame.

But radar and radio science pointing vector design is different. Radar swaths on Titan, for example, involve very complicated time-histories of look-angles, incidence angles, and other features like “pushbroom” tracking that adds an “along track” rotation rate. Radio science pointing involves modeling the layers of Titan’s atmosphere, for example, in order to bring about just the right amount of radio signal ray “bending” to permit the Cassini signal to travel through the Titan atmospheric medium and then continue on a precise path back to Earth. For these sorts of pointing designs, the science observation design teams build their own “table lookup” of pointing directions. Each entry in the Inertial Vector Definition file is a time stamp and a Cartesian 3-element unit vector in the J2000 inertial reference frame as seen in Table 1. These entries functionally are a finely spaced table of right ascension and declinations that vary with time.

| Time:       | 2005-046T06:22:04.000' |
| Position:   | 0.7647120458 0.6182384763 -0.1816498648 |
| Time:       | 2005-046T06:22:05.000' |
| Position:   | 0.7649437877 0.6179017803 -0.1818196679 |
| Time:       | 2005-046T06:22:06.000' |
| Position:   | 0.7651770010 0.6175628599 -0.1819897559 |

Table 1. Extract from Inertial Vector Definition file used to generate radar polynomials
The time stamps above are in Spacecraft Event Time (SCET), which is the Universal Coordinated Time (UTC) from the perspective of the spacecraft. The table spans the observation time and can run from 20 minutes up to several hours or more. The tables and associated targeting information are fed into the IVP fitting tool by the attitude control team, which is responsible for all IVP vectors created for Cassini. The output IVP polynomials are merged with all the other commands into an integrated sequence to be tested and ultimately uplinked to the spacecraft.

Prior to uplink an additional step is performed by the ground command system. The spacecraft clock has its own timing format (SCLK): it basically counts integer seconds relative to some T=0 reference time. It also divides a second into 256 equal chunks so that sub-second flight computer processing occurs properly. The Cassini project keeps track of the relationship between SCET and SCLK. The relationship is expressed as a table, which is a time-ordered series of SCETs, SCLKs, and a rate scale factor (very close to one). The table is updated throughout the mission and is the repository of the spacecraft clock drift time history as best estimated on the ground as seen in Table 2.

<table>
<thead>
<tr>
<th>SCLK</th>
<th>SCET</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1488155000.000</td>
<td>2005-057T23:56:49.263</td>
<td>1.000096576</td>
</tr>
<tr>
<td>1488156000.000</td>
<td>2005-058T00:13:29.360</td>
<td>0.999993695</td>
</tr>
<tr>
<td>1488577000.000</td>
<td>2005-062T21:10:06.706</td>
<td>0.999915371</td>
</tr>
</tbody>
</table>

This table is used by the ground system to convert all SCET command and IVP vector start and end times to SCLK in all uplinkable products. The ground system truncates fractions of a SCLK second in all uplinkable products. The practical effect of this is that some small error (up to one second) is introduced into IVP vector pointing due to this time conversion. It turns out that the observations that are most sensitive to this slight timing shift and pointing error are radar and radio science. And the error is maximized during periods where the pointing is changing rapidly – at the peak spacecraft body rates of an observation. In practice, radar and radio science observations tend to track at higher spacecraft body rates (sometimes above 2 mrad/s) than most other science observations. So a one second truncation timing error can result in pointing errors up to 2 mrad. This can be problematic for some radar and radio science observations.

**IV. Avoiding Pointing Errors – Examples from Cassini Flight Experience**

Several examples from Cassini’s orbital mission at Saturn are illustrative of the issues and testing required to minimize pointing error during observations. The Titan-16 flyby in July of 2006 involved synthetic aperture radar observations at altitudes as low as 950 km from the surface of Titan. Following the flyby, reconstructed pointing using attitude control telemetry showed an unexpected pointing error of 6 mrad. There were several factors that contributed to this large error. The attitude controller itself was responsible for up to 2.8 mrad of this error. Flying this close to Titan requires the use of RCS thrusters to counteract the Titan aerodynamic torques that occur at a closest approach altitude of 950 km. The RCS controller uses a “bang-off-bang” system that will reduce pointing errors in each spacecraft axis if the pointing error in that axis exceeds a “deadband”. Deadbands of 2 mrad are typical of radar observations and were in effect during T16 closest approach. Since each axis normal to the High Gain Antenna is permitted up to ±2 mrad before the RCS controller corrects the error, in the worst-case a pointing error of \(2\sqrt{2} = 2.8 \text{ mrad}\) does occur. The remainder of the pointing error turned out to be due to an error by the sequence integration lead team member who incorrectly selected an “old” SCLK/SCET conversion file. This led to a full second of error in the SCET to SCLK translation for all commands in the sequence including the IVP polynomial start time command argument. The SCLK truncation of fractional seconds led to an additional 0.8 seconds of timing error. The combined effects led to a pointing error of 6 mrad.

A lesson learned after T16 was to test in the Cassini hardware Integrated Test Laboratory the Titan flyby observations desired by radar and radio science. This would have uncovered the selection of the incorrect SCLK/SCET conversion file. Additionally, the radar team now is involved in the selection of the SCLK/SCET conversion so that, if a file selection decision needs to be made for SCLK/SCET for a sequence, the file that will minimize the timing error will be selected and used to build the uplinkable products.
Another pointing issue occurred recently during development of a radio science observation for the Titan-106 flyby in October of 2014. An early version of the T106 occultation sequence was tested in the Cassini hardware Integrated Test Laboratory. The reconstructed pointing from the test uncovered a pointing error that exceeded 2 mrad as shown in Fig. 2. For radio science, this error could significantly degrade their Ka-band downlink signal.

In this case, the attitude control deadbands were set at 0.5 mrad in each axis normal to the High Gain Antenna. So a 0.9 mrad pointing error compared to the RSS Inertial Vector Definition file would have been expected. Again, the peak error occurred right at the time of maximum spacecraft body rate (in this case, 2.5 mrad/s). And again the problem was related to the timing error (in this case, 0.6 s) introduced by the SCLK truncation of fractional seconds. The command translation system is not amenable to updates (to avoid the truncation), so a different workaround was devised in support of the T106 RSS observation. It involved adjusting the vectors specified in the RSS Inertial Vector Definition file. If the SCET time tag of each entry in the file could be adjusted by 0.4 seconds, and the corresponding 3-element vector of each entry adjusted as well, the SCET times of the polynomial vectors would change as well. In this way, the SCLK truncation of fractional seconds could be almost reduced to zero. This would almost eliminate the timing error in this important observation. Table 3 reflects the updated timing adjustment.

Table 3. Extract of adjusted RSS Inertial Vector Definition table

| Time:     | '2014-297T02:30:00.400' |
| Position: | -0.4790898733 -0.8401887398 0.2540782850 |
| Time:     | '2014-297T02:30:01.400' |
| Position: | -0.4786979697 -0.8401887398 0.2540782850 |
| Time:     | '2014-297T02:30:02.400' |
| Position: | -0.4783048656 -0.8401887398 0.2540782850 |

Figure 2. Pointing error from a test of an early T106 command sequence
This change was made in a subsequent delivery of the pointing sequence. The final command sequence was tested again in the Cassini hardware Integrated Test Laboratory and it was verified that the large pointing error was corrected (Fig. 3). The corrected sequence was uplinked and the actual T106 radio science activity was successful. The reconstructed pointing based on flight telemetry showed very good agreement with the laboratory results.

V. Conclusion

The process of building a command sequence that meets the pointing needs of all the science instrument teams involved in Cassini is greatly helped by the pointing paradigm called Inertial Vector Propagation. This is a powerful and versatile capability built into the Cassini attitude control flight software. To populate and manage the onboard IVP with vectors necessary to achieve the desired pointing requires an equally capable and robust ground component – the IVP tool. The IVP tool is embedded in the pointing design tool that is used by all science teams to build their observations. All science designs are integrated into a sequence and passed to the attitude control team. The attitude control team is responsible for running the IVP tool that generates the actual vector commands. All vector commands are then merged with the rest of the sequence to form the uplinkable products.

Experience has shown that this process works extremely well, but in certain cases, particularly to suit the strict pointing needs of radar and radio science, some lessons learned and workarounds have evolved. The Cassini hardware Integrated Test Laboratory has been a vital resource throughout the life of the Cassini project. Flight sequences containing radar and radio science designs are routinely run through the hardware laboratory and comparisons of the simulated telemetry with the original pointing design are made. A few tests have produced results that required workarounds to deal with small but significant pointing errors. In particular, the ground command translation system can introduce a small timing shift due to spacecraft clock truncation of fractional seconds. The attitude control operations team has successfully worked around these difficulties. Tools, testing, updated procedures, and documented corporate memory play a key role in contributing to the continuing success of the Cassini mission at Saturn.
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References