Preparation for Cassini Grand Finale – Validation of Saturn Ring Heating in TSS

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Thermal analysis of spacecraft at Saturn have previously been restricted to three environmental heat fluxes: solar, Saturn planet IR, and Saturn planet albedo. Heat flux from Saturn's rings were not available in any commercially available thermal analysis tools. While preparing for the Cassini Grand Finale, during which Cassini will travel extremely close to the rings of Saturn, it was determined the existing thermal model required updating to accurately predict heat fluxes from the rings. This is particularly important for Cassini's Visual and Infrared Mapping Spectrometer infrared spectrometer (VIMS-IR) (Ref 1.), as it is cooled by a passive radiator which operates below the temperature of Saturn's rings. This paper discusses the validation of the heat flux from solar, Saturn, and Saturn's rings in Spacedesign's Thermal Synthesizer System (TSS). The incorporation of heating from Saturn's rings also led to the use of SPICE geometry to ensure accurate spacecraft positioning and pointing. Thermal model results are compared against historical heating events as well as predictive Grand Finale sequences.

Nomenclature

CIRS	=	Composite Infrared Spectrometer
CK	=	Camera-matrix Kernel
FPA	=	Focal Plane Assembly
FRPO	=	F-Ring Proximal Orbits
SOI	=	Saturn Orbit Insertion
SPK	=	Spacecraft Planet Kernel
TSS	=	Thermal Synthesizer System
VIMS-IR	=	Visual and Infrared Mapping Spectrometer infrared spectrometer

I. Summary

THIS paper details the results of the most recent VIMS-IR thermal modeling effort. A review of historical data indicated the existing thermal model was a poor predictor of focal plane assembly (FPA) temperatures when the VIMS-IR instrument had a view of Saturn's rings. This effort successfully integrated the heating caused by the rings of Saturn into a commercially available thermal analysis software package. This effort also developed a procedure to accurately feed spacecraft position and pointing data into the same thermal analysis software. This paper contains the comparisons of the thermal model to seven historical sequences as well as two predictive F-Ring Proximal Orbits (FRPO) events.

II. History

The Cassini-Huygens spacecraft was launched from Kennedy Space Center on October 15, 1997, arriving at Saturn on July 1, 2004. After completing its primary mission in 2008, the program was extended to June 2010 to allow for observations during the equinox season of Saturn. After successful completion of this extension, the program was continued a second time to 2017. This second extension is allowing for observations of Saturn's summer solstice in the northern hemisphere. This extension also called for a series of FRPO and for the disposal of the spacecraft[2].

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The Cassini spacecraft is home to twelve unique instruments, not including those on the Huygens probe, which provide valuable insight into the composition of Saturn and its many satellite moons. One of the instruments located on Cassini is the Visual and Infrared Mapping Spectrometer (VIMS). This instrument consists of two imaging spectrometers, one for the infrared region, and one for the visible. The infrared spectrometer, VIMS-IR, was built by the Jet Propulsion Laboratory (JPL). The FPA on VIMS-IR is cooled to operational temperatures (~60 K) through the use of a passive cooler on the exterior of the spacecraft.

Over the course of its mission, Cassini has completed several sequences which have significantly raised the temperature of the FPA. These rises are typically caused by external heating sources, which can be from any combination of solar, planetary or satellite moons. Since the successful operation of the FPA is highly dependent on temperature, the Cassini program tagged large rises in the FPA temperature as a programmatic consumable in order to limit the number of thermal cycles on the FPA. The program allows for a maximum of 40 consumable events, marked by a rise greater than 2 K in the temperature of the FPA. Because the VIMS-IR instrument is passively controlled, the time constant for the focal plane to return to nominal temperatures is on the order of hours to days, depending on the maximum temperature reached. Therefore, accurate predictions of the heating of the FPA are critical in mission planning to identify consumable events. This knowledge becomes even more imperative with the future FRPO planning as the spacecraft will be closer to one of its heating sources than ever before.

During the FRPO mission phase, the spacecraft will pass just outside of Saturn's F-Ring for 20 orbits then fly between the inner-most ring and Saturn's cloud tops for another 22 orbits. As the spacecraft passes through closest approach, it will rotate about its axes so as to allow the various instruments on board to observe Saturn and its rings, exposing the VIMS Radiator to heat flux from both Saturn and rings.

Once the spacecraft team started designing these observations, it was realized that the original VIMS Thermal model was inadequate when the spacecraft was so close to Saturn and its rings. A better model was needed, quickly.

III. Updates to Thermal Model

Before the Cassini spacecraft was launched in 1997, a thermal model of the VIMS passive cooler, integrated on the Cassini spacecraft, was generated. The VIMS thermal model consisted of three main components: sunshield, top rim, and radiator patch. No internal component detail was captured in this thermal model as the focal plane temperature can be easily determined by calculating the heat flux on the radiator patch and using this flux in conjunction with the known capacitance of the focal plane.

However, the original version of the model was only able to account for heat fluxes from the Sun and Saturn's planetary IR and albedo. Prior to the launch of Cassini, little was known about Saturn's rings. Saturn had only been visited three times before, Pioneer 11 in 1979[3], Voyager 1 in 1980, and Voyager 2 in 1981[4]. All three of these missions were fly-by missions, each spending a very short period of time at Saturn and none dedicated to determining the composition and temperature of Saturn's rings. Therefore, knowledge of Saturn's rings has been obtained over the past decade during Cassini's residence at Saturn.

As previously mentioned, FRPO planning began in 2013, at which time the existing thermal model was evaluated for the feasibility in accurately predicting the focal plane temperature during closest approach. Comparison of model results to historical FPA temperatures indicated significant underprediction of the FPA when Saturn's rings were expected to be in the field of view of the radiator. A review of scholarly articles published using data from Cassini observations revealed that although the rings are typically colder than Saturn[5], they are warmer than the steady state temperature of the passive cooler. Since this particular heat source was expected to be one of the primary heating sources for VIMS during the FPRO orbits, it became apparent that heating from Saturn's rings needed to be incorporated into the thermal model.

None of the commercially available thermal tools included Saturn's rings as a source of external heating, meaning a simple conversion of the existing model to another software package was not an option. Spacedesign, the company behind TSS, agreed to work with JPL in incorporating the heating from Saturn's rings into their software package. Discussions with Spacedesign began in 2014 and continued through October 2015.

Although the initial focus of this effort was to incorporate the heating from Saturn, it was quickly determined accurate positioning and pointing of the Cassini spacecraft were just as important. TSS is somewhat limited with respect to inputting orbital parameters, as TSS requires orbits to be defined by the orbital parameters at a single point in time. For example, the majority of Cassini's orbits thus far can be simplified to reflect a basic Keplerian orbit over a short period of time. However, the parameters for the actual, as flown, orbit can vary widely from hour to hour. In addition, Cassini has many complex rotation maneuvers, which enable communication with DSN, instrument data collection events or to reduce/prevent direct solar loading on the passive cooler. Each of these rotations or movements can have a significant impact on the amount of heating observed on the VIMS-IR cooler.

The timing of these maneuvers is also critical, as an offset as small as 5-10 minutes in pointing can result in direct solar loading versus only albedo from the planet on the radiator surface.

All spacecraft attitude information, whether historical or predictive, is stored in a series of files in SPICE format[6]. The two files of most interest to this effort were identified as the SPK and CK. SPK files contain information on spacecraft position relative to another object. For the VIMS modeling, it was decided SPK files would be generated for the Cassini spacecraft relative to Saturn. CK files indicate the orientation of the spacecraft relative to a reference frame. For ease of incorporation into TSS, it was chosen to report the orientation, or pointing, of Cassini relative to the Sun.

Although it would be ideal for TSS to directly read SPK and CK files to determine the position and pointing of the spacecraft, TSS currently does not have the capability to do so. This complication coupled with the need for accurate pointing led the team to develop a procedure utilizing a series of pre-existing scripts and programs coupled with new MATLAB routines to format the SPK and CK files for direct input to TSS. Due to the widespread use of SPICE files across the aerospace industry worldwide, this capability will likely be added to TSS in the future.

In addition to incorporating and validating ring heating in TSS, an additional tool was also developed. Since it is not practical for mission planners to run a full thermal analysis for each potential sequence, a quick validation tool was needed. An existing mathematical tool for the CIRS instrument developed by Stuart Pilorz of SETI, was modified for use by the VIMS instrument. This tool, known as VIMS Light, was developed in parallel with the TSS thermal model work. Results from each tool were used to check against one another, in addition with comparison with historical results. Mission planners will utilize VIMS Light to run quick analyses during the iterative planning phase, while the TSS model will be utilized to validate final sequence temperatures prior to execution. The results from VIMS Light are shown in conjunction with TSS temperature predicts and historical data, where available.

IV. Model Correlation Results

As the thermal model was developed and validated, the various heat loads were isolated, when possible. This isolation was possible due to TSS having the ability to break down heat fluxes into five distinct sources: Solar, Saturn IR, Saturn albedo, Saturn ring IR, and Saturn ring albedo. By isolating the individual heat flux sources, it was possible to ensure accurate pointing, and to a lesser extent, the position, of the spacecraft in TSS. VIMS Light has the capability to directly read in the SPK and CK files, therefore comparing the VIMS Light and TSS model heat flux values ensured the complex TSS import tools were executed correctly. This was especially true for solar loading, however was somewhat limited for Saturn, as VIMS Light summed together the individual components of Saturn and Saturn ring loading before reporting the total heat flux as “Saturn”. Therefore, when individual heat fluxes are shown below, they are reported from TSS, not VIMS Light. VIMS Light heat fluxes are shown for comparison only in the second figure for each sequence analyzed and consist of a summation of both solar and Saturn loading. TSS heat flux results are also summed in the second figure for each sequence.

It is also important to note the focal plane has two modes of operation, active and sleep. During many of the analyzed sequences, the focal plane changes its operating state, thus changing the amount of internal heating on the focal plane. The TSS thermal model correctly models the FPA active/sleep states, whereas the VIMS Light model was run with the focal plane in active mode for all cases. This often resulted in the absolute temperature of the focal plane starting too high at the beginning of the sequence or a slight change in the profile when the focal plane returned to standby. Cases where the VIMS Light results were impacted by leaving the focal plane in active mode are discussed in the individual sequences.

A. Solar Only Sequences

As the thermal models were developed and validated, the various heat loads were isolated, when possible. Therefore, the first two historical sequences analyzed contained external heating exclusively from the Sun.

Both of the solar only sequences were unique, as Sequence 5 (S05) included a Titan fly-by and Sequence 7 (S07) featured the release of the Huygens probe. These cases were used to validate the spacecraft pointing methodology in TSS as well as the ability of the models to accurately predict solar loading.

Sequence 05

The first sequence analyzed was S05. As seen in Figure 1, the only heating as observed by the VIMS cooler during the period of interest came from the Sun. Figure 2 shows both VIMS Light and TSS predict the heating occurs at the same time, with nearly identical heat flux values, thus indicating correct pointing of the spacecraft. The difference in heat flux values is believed to be caused by one of two modeling differences. One difference is the VIMS Light program has a slightly simplified VIMS Light model, which is only represented by a series of five

plates, while the TSS model is much closer to the actual configuration (Figure 3). The additional surface detail in the TSS model is likely leading to additional bounces and solar entrapment, leading to a higher heat flux on the cooler for the TSS model. The slight heat flux discrepancy may also be caused by a slight difference in the way the solar flux is modeled. TSS utilizes a single fixed heat flux, whereas VIMS Light utilizes the ephemeris to determine the distance from the Sun and calculates the appropriate solar flux value.

The astute reader may notice the VIMS FPA absolute temperature predicted by the offset VIMS Light model is higher than the TSS model prediction, even though the heat flux from the VIMS Light is lower. It is believed this is partially due to the fact the temperature was offset as opposed to calculated at the correct starting point, resulting in a lower capacitance being used. In addition, VIMS Light does not decay as quickly as the historical data. This is due to the VIMS Light model being run with the FPA in active mode only, while the historical and TSS temperatures reflect the actual active/standby modes.

The TSS model shows excellent agreement with the historical data, predicting temperatures within 2 K of the actual observed data. Potential reasons for this difference are described at the end of S07.

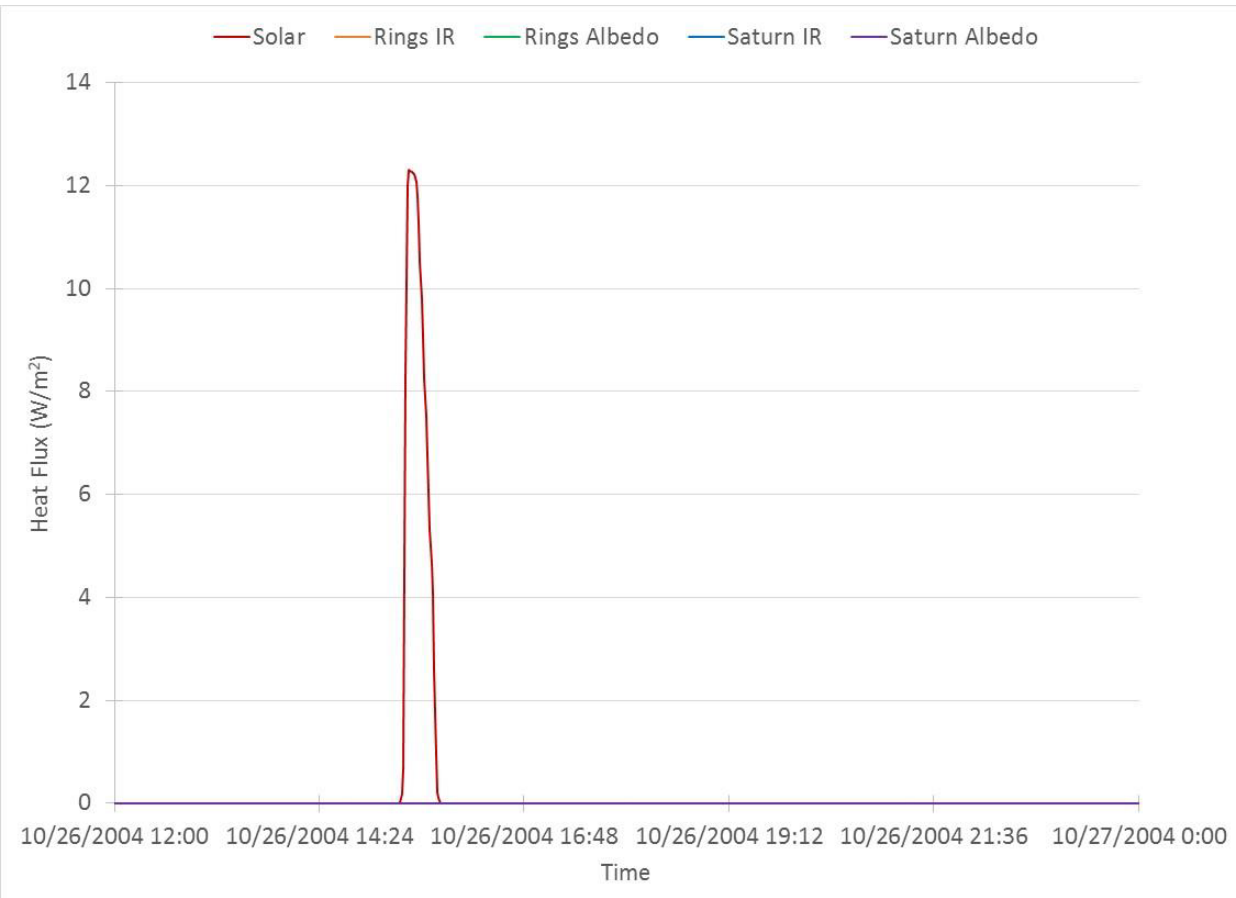

Figure 1. S05 TSS Heat Flux Sources

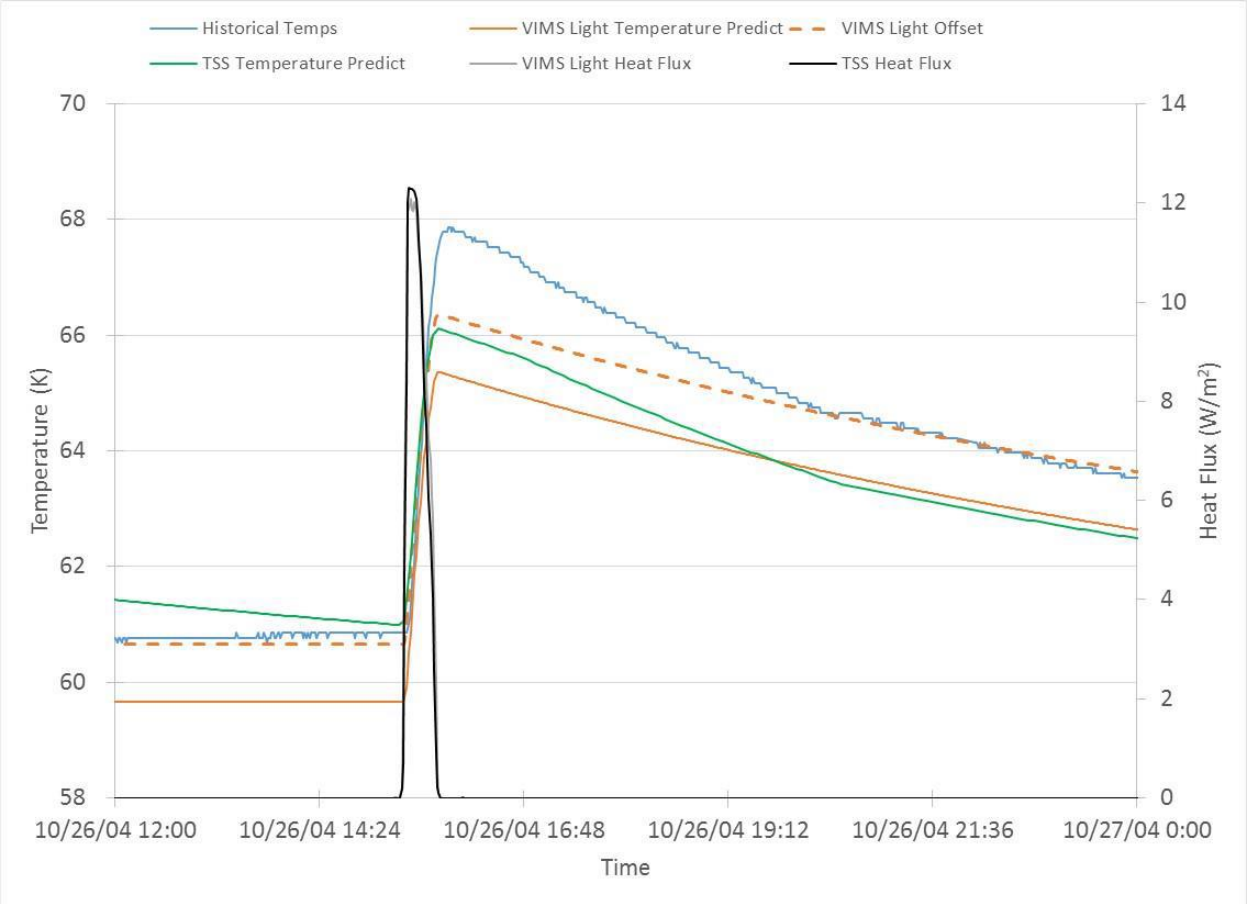

Figure 2. S05 Heat Flux and FPA Temperature Predictions

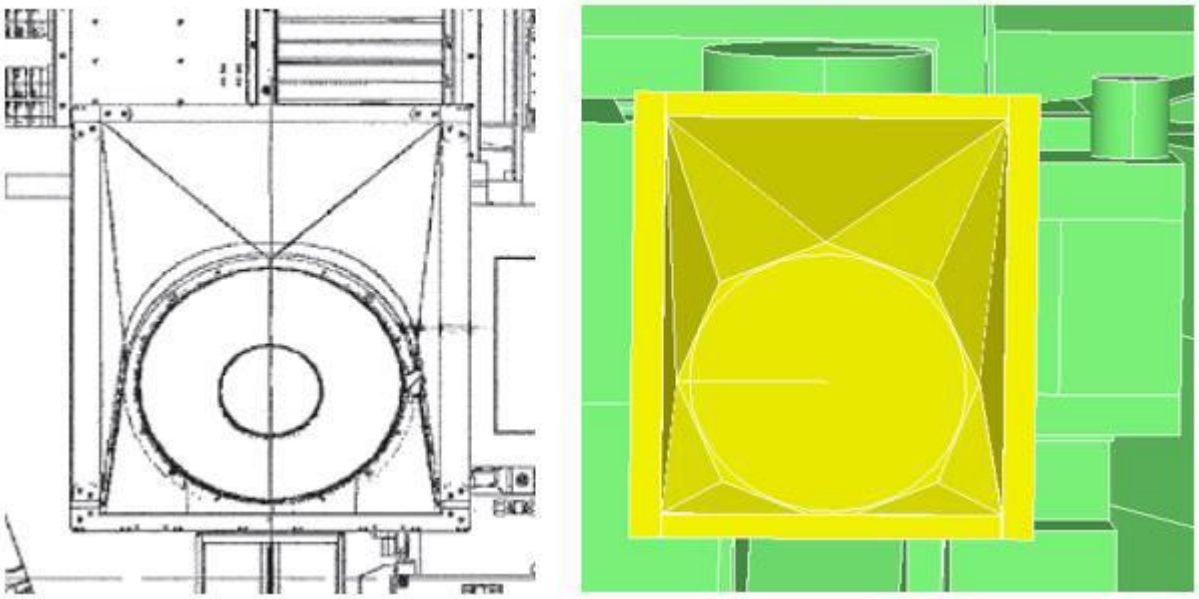

Figure 3. VIMS-IR Radiator Drawing (Left), VIMS-IR TSS Thermal Model Radiator (Yellow, Right)

Sequence 07

The second sequence, S07, was also a solar-only case. For this sequence, the VIMS instrument experienced a short period of direct solar loading, lasting approximately 30 minutes (Figure 4). Figure 5 confirms VIMS Light and TSS appear to have good agreement for heat flux start and stop times. Starting at approximately 01:50 on 12/25/04, the TSS model predicts a higher heat flux than the VIMS Light model, which is believed to be caused by the same issues identified during S05. Otherwise, the TSS temperature profile shows good agreement (within 3 K) with the historical data.

Both of the solar-only sequences underpredict the temperature and delta-T rise in the FPA temperature. As will be observed in later sections, these two solar loading cases result in the largest discrepancies between historical and modeling results. The team believes this is caused by the nature of the two sequences that were analyzed. S05 included a Titan fly-by, however Titan is not included in the thermal analysis. Therefore, it is possible additional thermal loading on the VIMS-IR cooler was caused by the presence of Titan. S07 was also irregular, as this sequence involved the release of the Huygens probe. The SPK and CK files were reconstructed from this event, so it is possible the pointing of the spacecraft is slightly misaligned.

A second, but unlikely, cause of the difference could be due to an incorrect assumption of the solar loading on the VIMS cooler. Although the VIMS-IR TSS model is fairly close to the actual geometry of the radiator and sunshield, it is possible slight inaccuracies in the modeling caused a lower flux to hit the radiator surface than that observed on the flight cooler. Therefore, a higher solar flux would potentially be required to account for this difference.

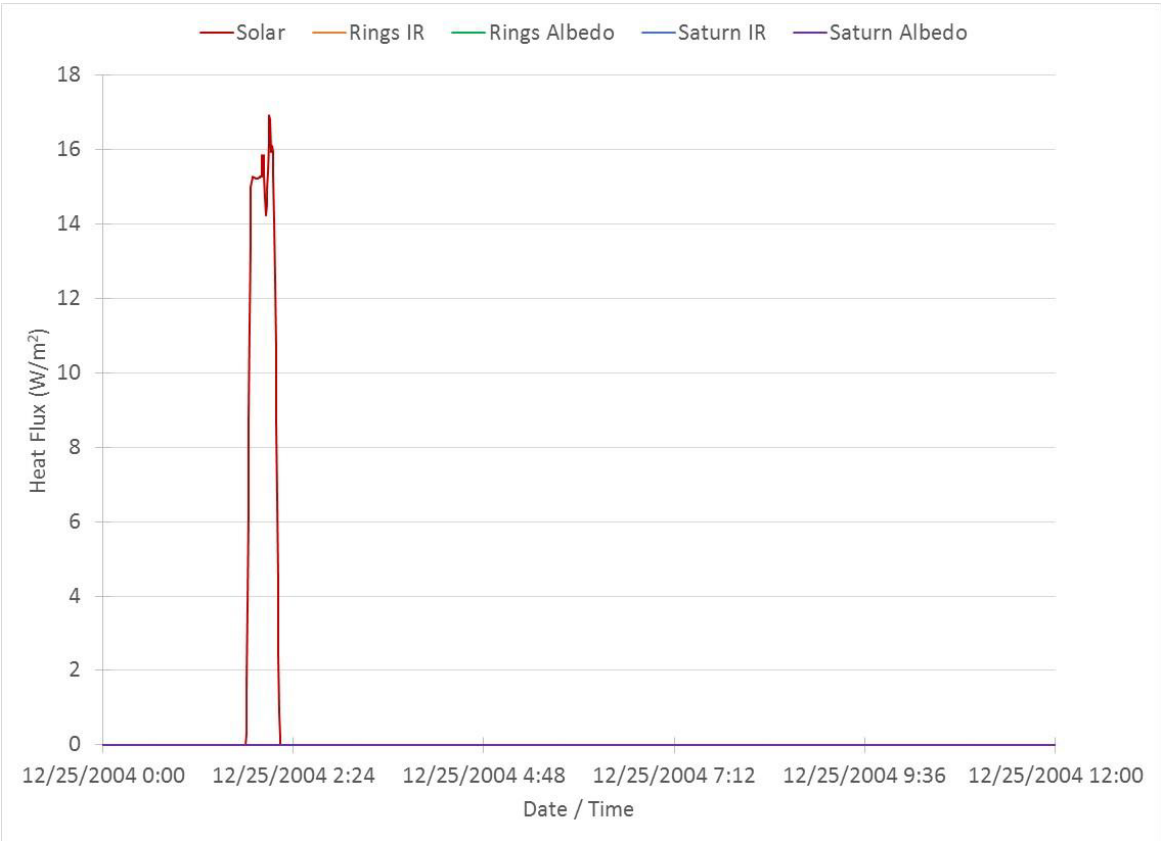

Figure 4. S07 TSS Heat Flux Sources

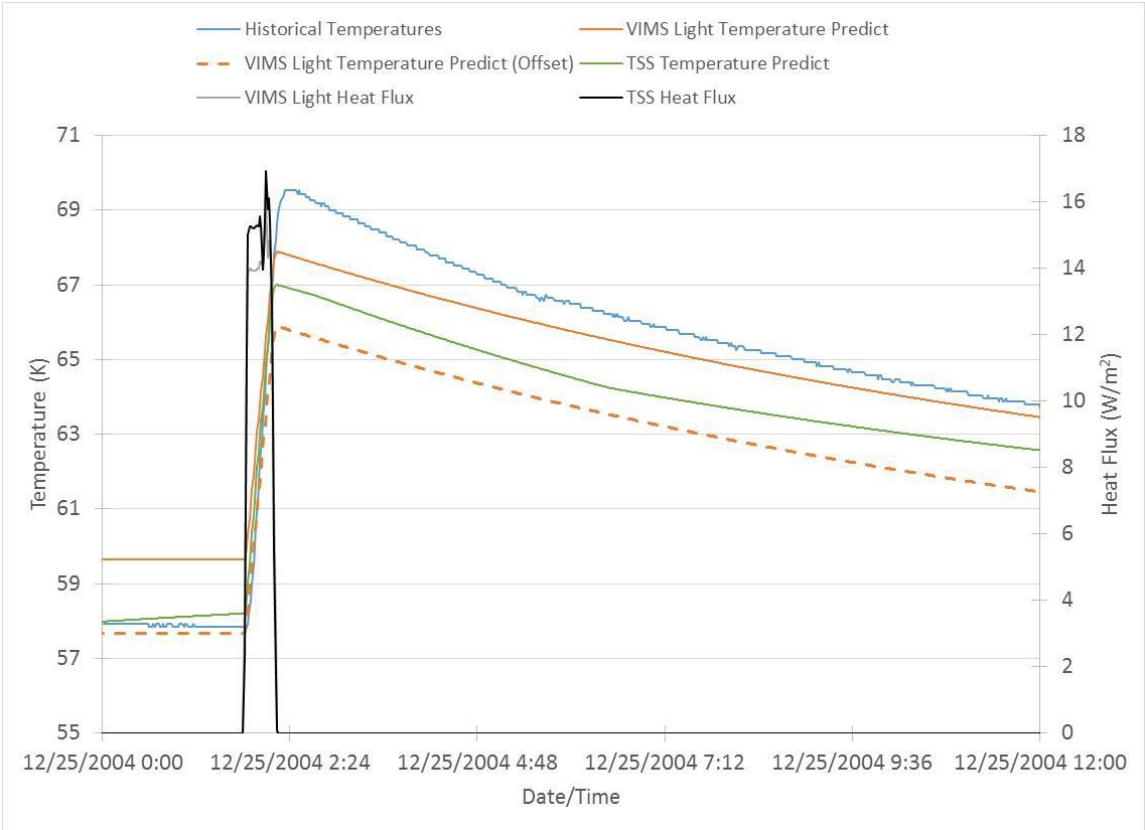

Figure 5. S07 Heat Flux and FPA Temperature Predictions

B. Saturn Planet Loading

One sequence featured heating exclusively from Saturn's surface, no solar or ring heating was observed. This is due to the nature of the fly-by, as this sequence is very nearly in the same plane as Saturn's rings (Figure 6), therefore no loading is observed from them. This case allowed for validation of Saturn's thermal parameters, such as albedo and planet temperature.

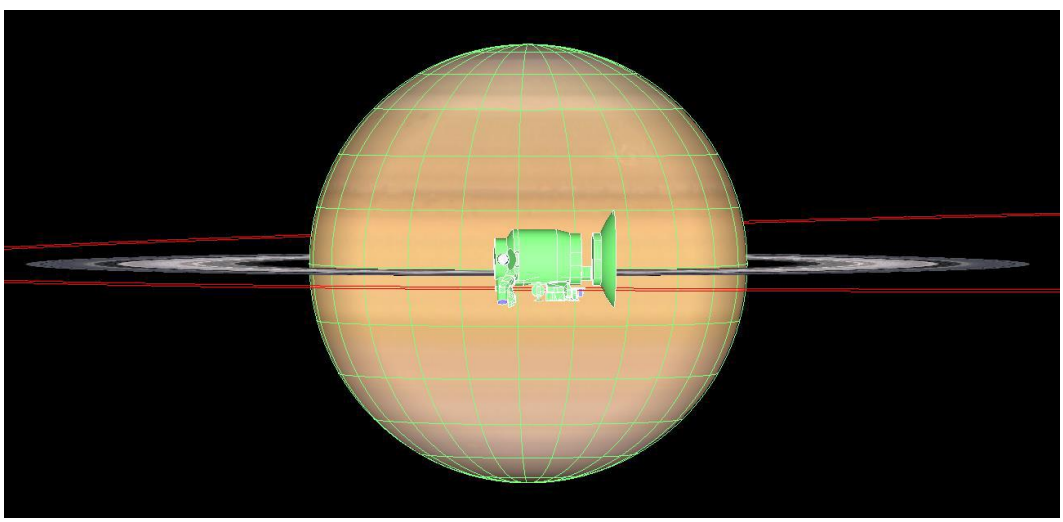

Figure 6. Cassini in Orbit Plane, Sequence 54

Sequence 54

As verified in Figure 7, S54 featured heating exclusively from Saturn; no heat flux was observed on the VIMS cooler from Saturn's rings. This single heating event occurred from 11/2/2009 07:00 to 08:00. Comparing the TSS and VIMS Light heat flux shows the major heating event occurred at the same time, indicating the spacecraft is pointing in the same direction. The VIMS Light heat flux is again slightly lower than what was predicted by TSS, however the overall profile is identical. A sharp temperature decline is seen at the beginning of the period of interest (Figure 8), which was caused by a series of active/sleep cycles.

The temperature prediction from TSS matches the historical data to within 0.6 K at the peak temperature. Both VIMS Light and TSS have nearly identical temperature delta predictions, even though the VIMS Light absolute temperature is higher at the start of the period of interest than the TSS and historical temperatures. This higher absolute temperature was caused by the VIMS Light model being run with the FPA in active mode for the entire duration, therefore the internal heating of the FPA resulted in a higher steady state temperature.

It is not clear why the steady state temperature after the heating event is much higher than seen in previous sequences. The additional heat source is seen as far back as 10/30/2009, and warms the instrument by an additional 0.75 K. However, since the delta-T is within 0.6 K of the historical data, this slight anomaly was not investigated further.

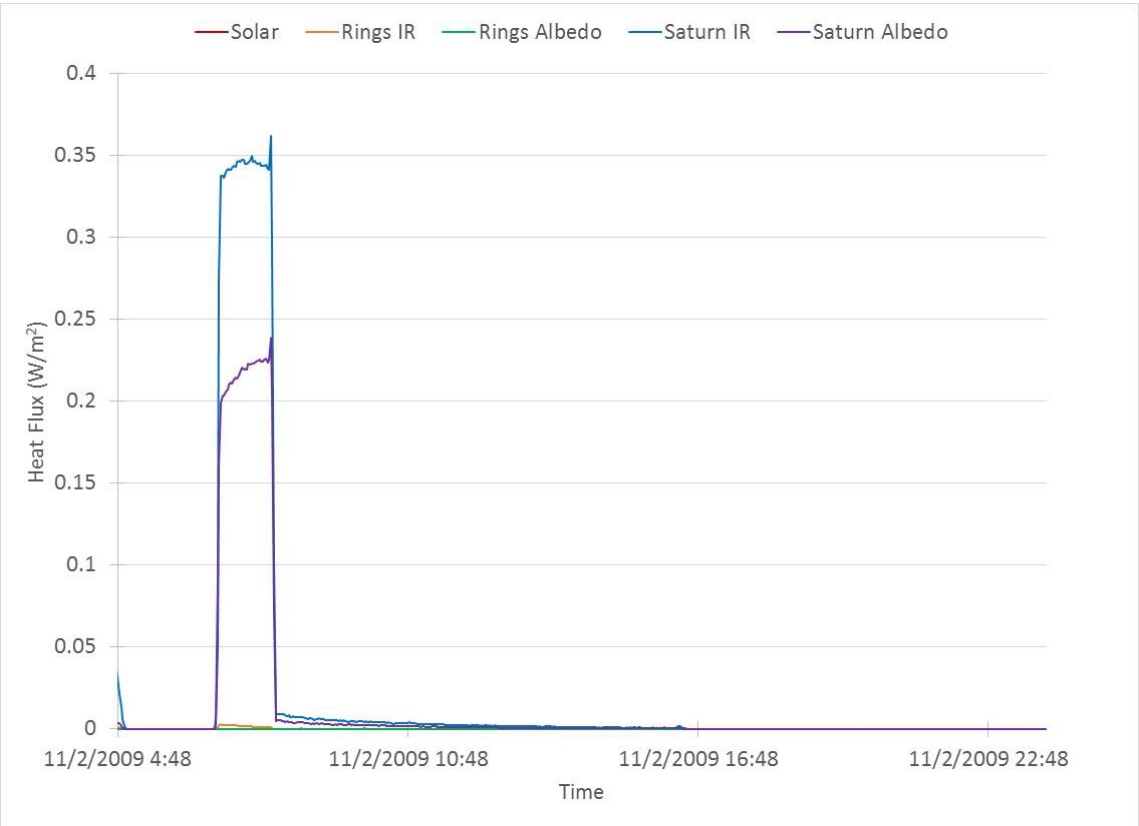

Figure 7. S54 TSS Heat Flux Sources

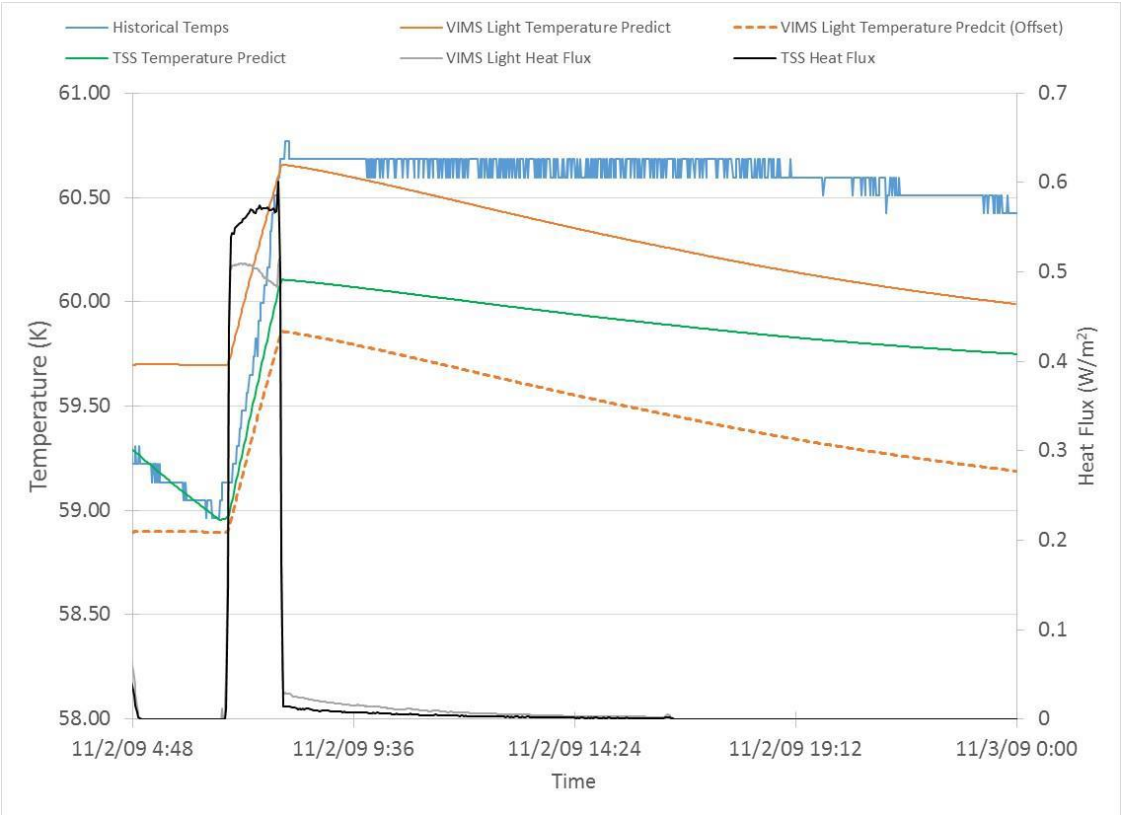

Figure 8. S54 Heat Flux and FPA Temperature Predictions

C. All Heating Sources

Once solar and Saturn planet heating sources were validated, Saturn's rings were integrated. The remainder of the historical cases were a combination of all sources, none of these cases featured heating exclusively from Saturn's rings. However, since there is a high level of confidence in the model's ability to accurately predict solar and Saturn planet heat fluxes, the team was confident any issues with ring heat fluxes could easily be identified.

Saturn Orbit Insertion (SOI/Sequence 2)

SOI (S02) or the Saturn insertion sequence, was the first case analyzed with the rings playing a role. During this sequence, two main heating events occurred (Figure 9), with the first being mainly driven by the IR from Saturn from 7/1/2004 01:00 to 03:10. The second event occurred from 7/1/2004 03:54 to 04:18. This second event included albedo and IR from the rings in addition to planet IR. Comparing the TSS temperature to flight data shows the heating events are at the correct times. Although the predicted FPA temperature is slightly lower than the historical data (<0.5 K), the focal plane continues to rise after the external heat sources are removed. This is due to the internal heating caused by the focal plane being in active mode. The FPA thus continued to rise until it reached its steady state temperature.

Comparing heat fluxes calculated by TSS and VIMS Light show slight differences in the total heat flux values. The first portion of the heating event (7/1/04 01:00 – 03:07) shows TSS slightly underpredicts the heat flux. Examining Figure 9, all of the heating comes from planet IR. Interestingly, during this same period, the temperature predictions for this TSS heat flux (Figure 10) are nearly identical to the historical temperature data, suggesting a slight error in the VIMS Light model possibly caused by the difference in geometry between the two models. From 03:17 to 04:18, Saturn's rings play an important role, although IR from Saturn remains the dominant heating source. During this period, TSS has a slightly higher hat flux than VIMS Light. The largest difference in heat flux occurs during this heating event, where TSS predicts a maximum heat flux of 1.6 W/m2, whereas VIMS Light only predicts a maximum of 1.35 W/m2. During this period, the TSS model temperature continues to closely mirror the historical temperature profile. After 04:18, the temperature predicted by TSS is within 0.5 K of the historical temperature.

The temperature predictions for the VIMS Light model appear to be significantly offset as compared to the historical data. This is attributed to the VIMS Light model being run with the FPA in active mode throughout the entire run, causing a higher starting focal plane temperature. Due to this modeling simplification, the temperature profile for the VIMS Light model was shifted downward to match the historical data starting temperature. The FPA temperature appears to drop after the second heating event, whereas the TSS model increases in temperature. This is simply due to the difference in temperature at the end of the second heating event. Both models are heading toward their steady state temperature of 59.6 K, thus the different temperature direction.

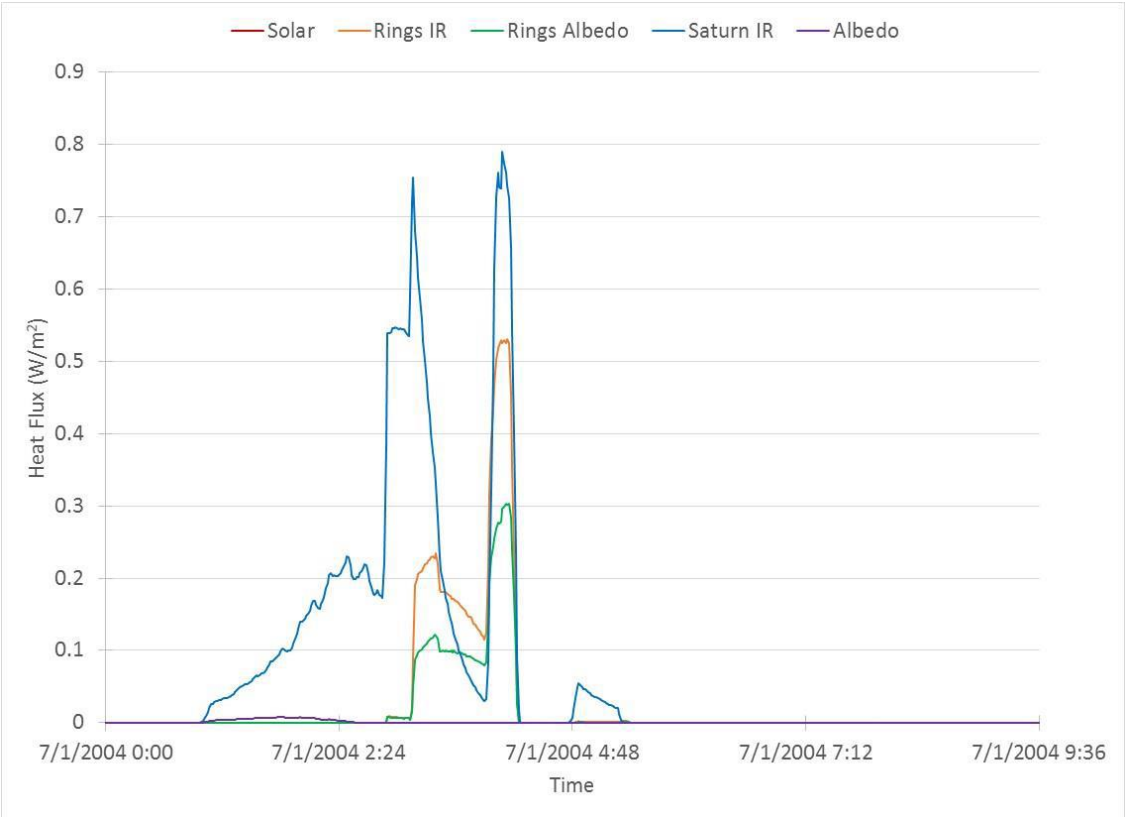

Figure 9. SOI (S02) TSS Heat Flux Sources

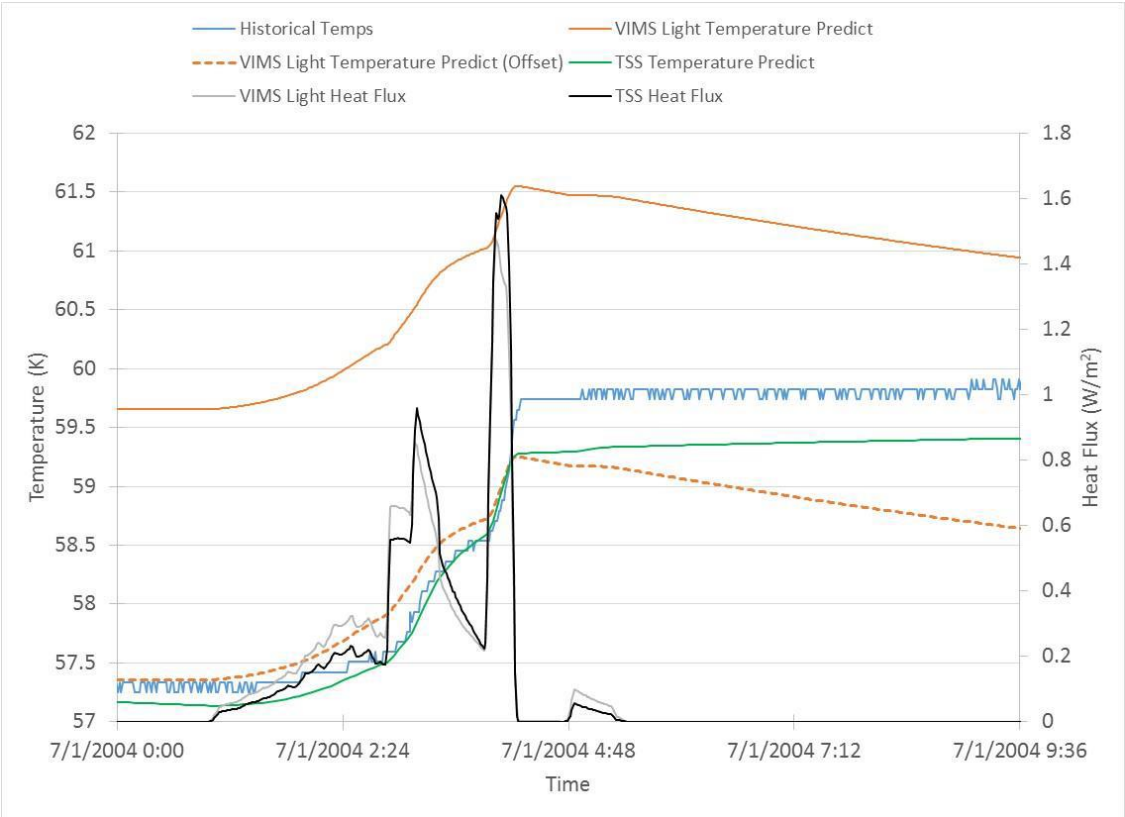

Figure 10. SOI (S02) Heat Flux and FPA Temperature Predictions

Sequence 26

S26 was the only historical sequence to feature the largest heat flux component from Saturn's rings. This sequence featured a series of complex pointing maneuvers before crossing the ring plane. No changes in the FPA operational state occurred during the period of interest, therefore all of the temperature changes are caused by external factors.

VIMS Light and TSS produce very similar heat fluxes, with TSS heat fluxes typically slightly higher than those predicted by VIMS Light. When heat flux deviations do occur between the two models, they are much smaller than 0.05 W/m^2.

Temperature predictions for both models very closely follow the historical temperature profile, with the largest temperature delta less than 0.5 K. This is significantly lower than the success criteria of temperature differences less than 2 K.

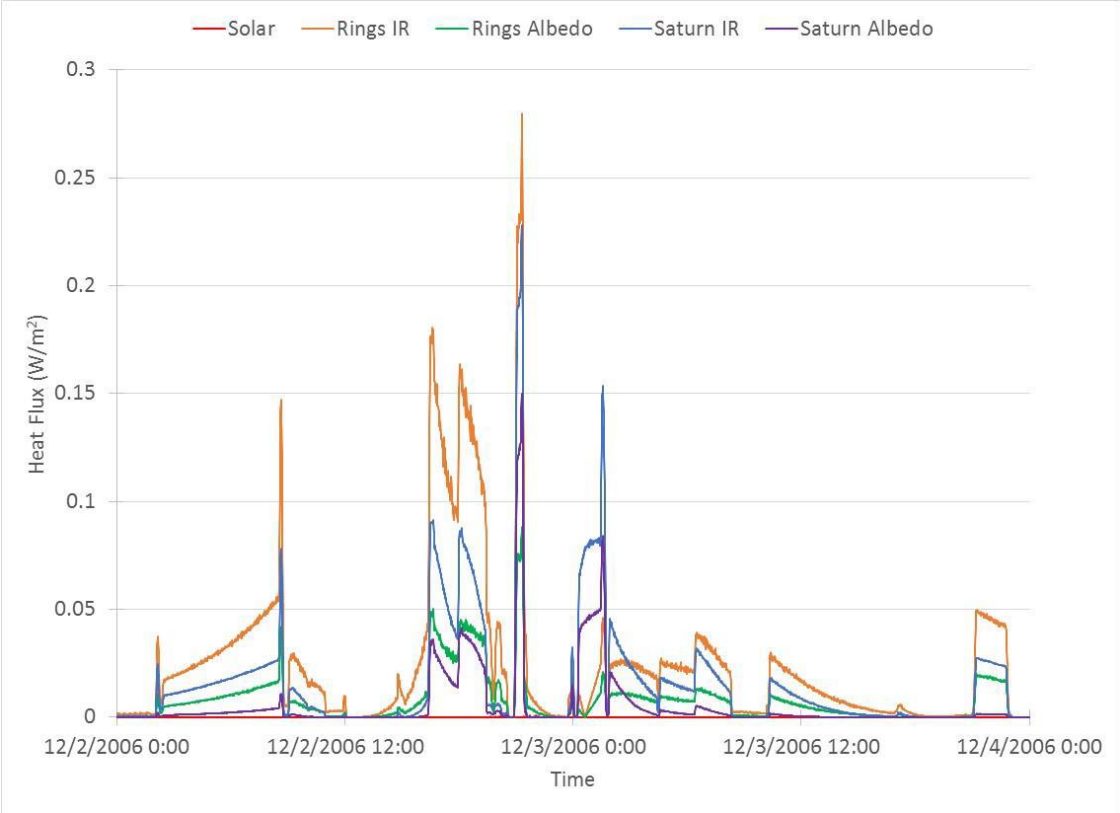

Figure 11. S26 TSS Heat Flux Sources

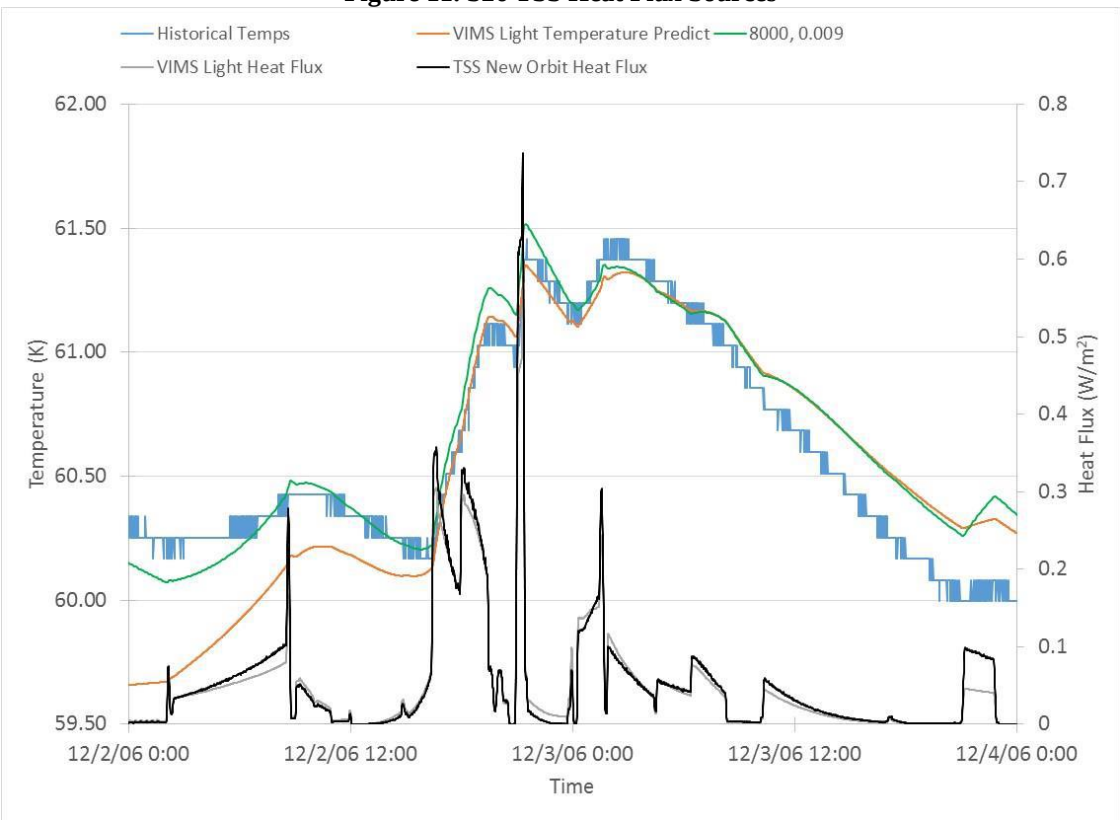

Figure 12. S26 Heat Flux and FPA Temperature Predictions

Sequence 60

S60 is particularly interesting as all of the heating sources play a role during the period of interest. Three major heating events occurred during this time frame. The first event (6/3/2010 02:30 through 03:00) was nearly exclusively a solar event. A second event (6/3/2010 06:00 to 07:30) was similar to the first event as it was nearly exclusively Saturn IR. The third heating event (6/3/2010 09:00 to 13:00) was a combination of Saturn albedo and IR, with a small impact from Saturn ring IR. TSS consistently underpredicted the heat flux, when compared to the VIMS Light model. With the exception of the solar heating event, the heat fluxes in both models followed each other within 0.1 W/m^2, suggesting good overall agreement.

The TSS temperature predict closely follows the historical data in value and profile, never deviating more than 1 K from historical values. As mentioned previously, the VIMS Light model used a starting temperature of 59.6 K, which is the source of the temperature offset. The VIMS Light model also shows good temperature agreement, even with the initial temperature offset.

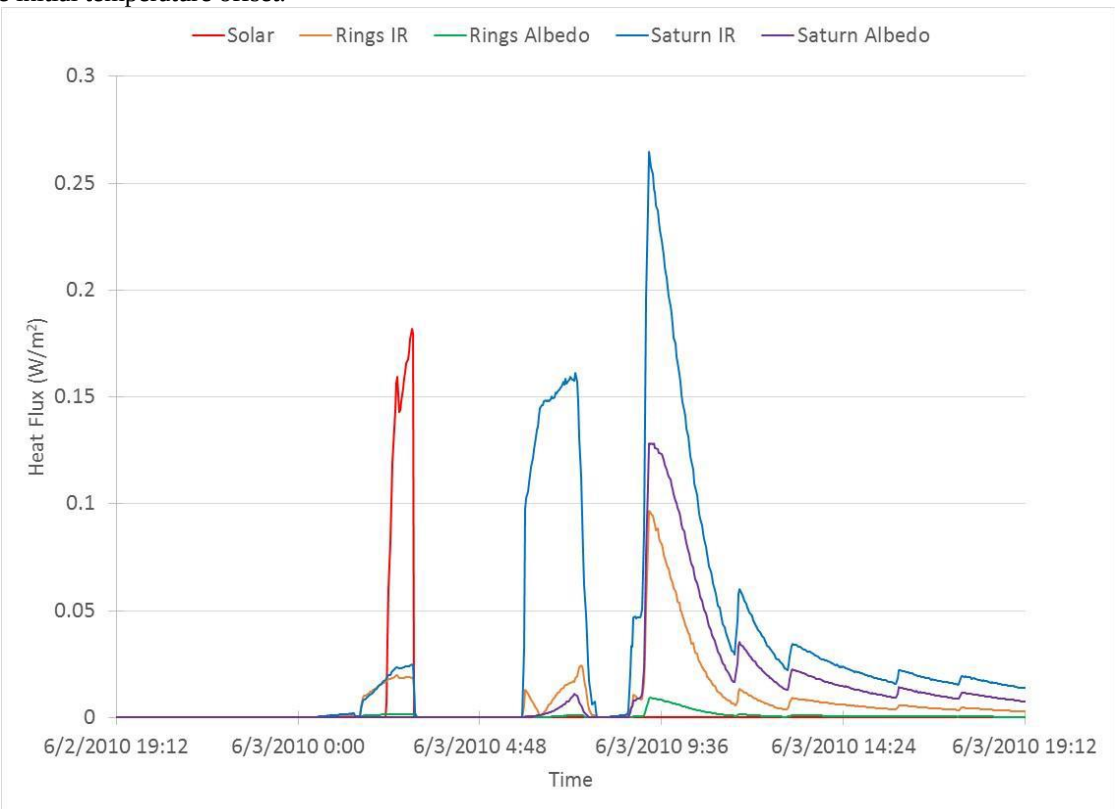

Figure 13. S60 TSS Heat Flux Sources

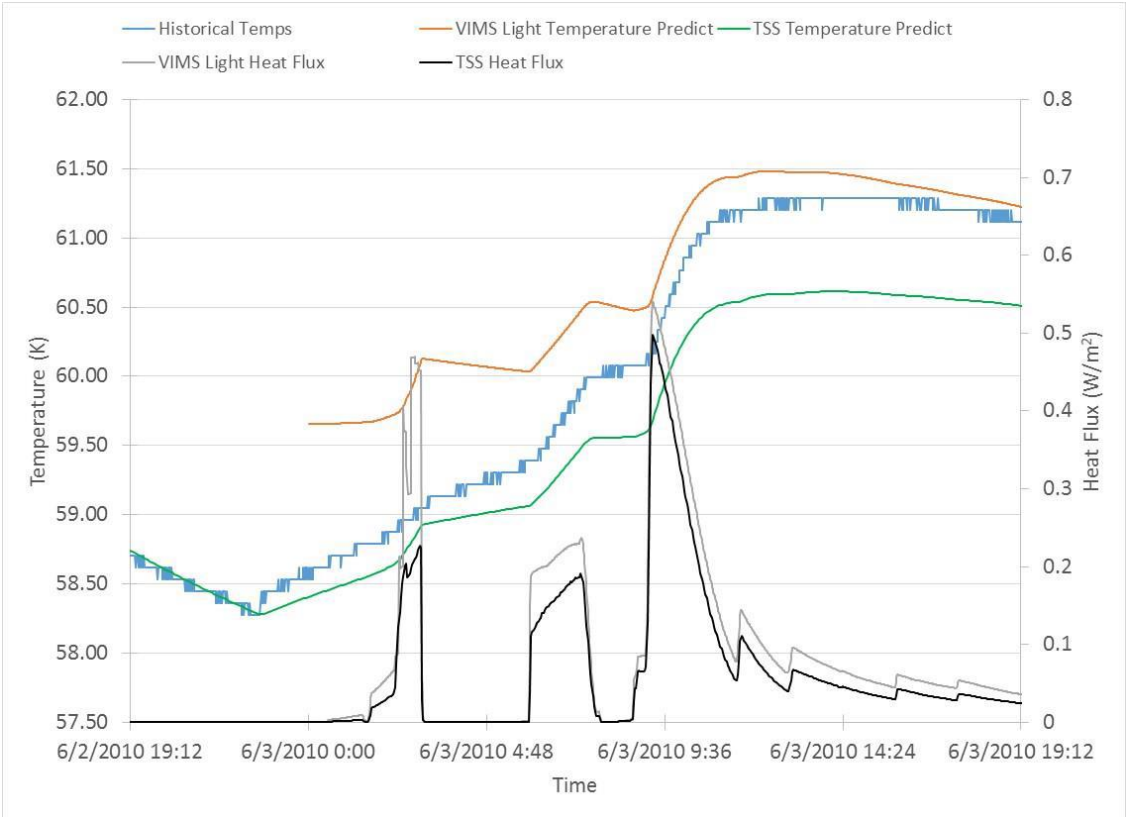

Figure 14. S60 Heat Flux and FPA Temperature Predictions

Sequence 42

Although it appears benign, S42 produced the greatest discrepancy between the VIMS Light and TSS models. As seen in Figure 15, the main source of heat flux for S42 is from ring IR. A quick comparison of the heat fluxes in Figure 16 shows the TSS model predicts a heat rate nearly double that of VIMS Light at the peak. Since the heat fluxes occur at the same times, it is not believed this difference can be attributed to incorrect pointing of the spacecraft.

Due to the increased heat flux value, the TSS model greatly overpredicts the heating on the VIMS-IR FPA. At the peak, the TSS model exceeds the historical temperatures by 2.3 K. Once the external heating is removed from the instrument, the TSS temperature prediction quickly drops off and closely matches the historical data starting at approximately 7/22/08 18:00.

Again, since VIMS Light does not break down the individual heat fluxes from Saturn, it is difficult to determine which of the heat fluxes are causing the TSS prediction to greatly exceed those predicted by VIMS Light. Since the Cassini spacecraft passed under the ring plane during the period of highest flux, it was hypothesized the TSS model was incorrectly selecting the lit temperature for the rings visible by the VIMS-IR radiator as opposed to the unlit temperature. A second run was made, fixing all of the ring temperatures to their unlit values. As seen in Figure 17, this did reduce the total heat flux by approximately 0.2 W/m^2, however this is still an overprediction as compared to VIMS Light by 0.3 W/m^2. Since this was the only case with a severe discrepancy and only a slightly larger than desired temperature difference between TSS and historical temperatures, the team decided to accept the model as-is.

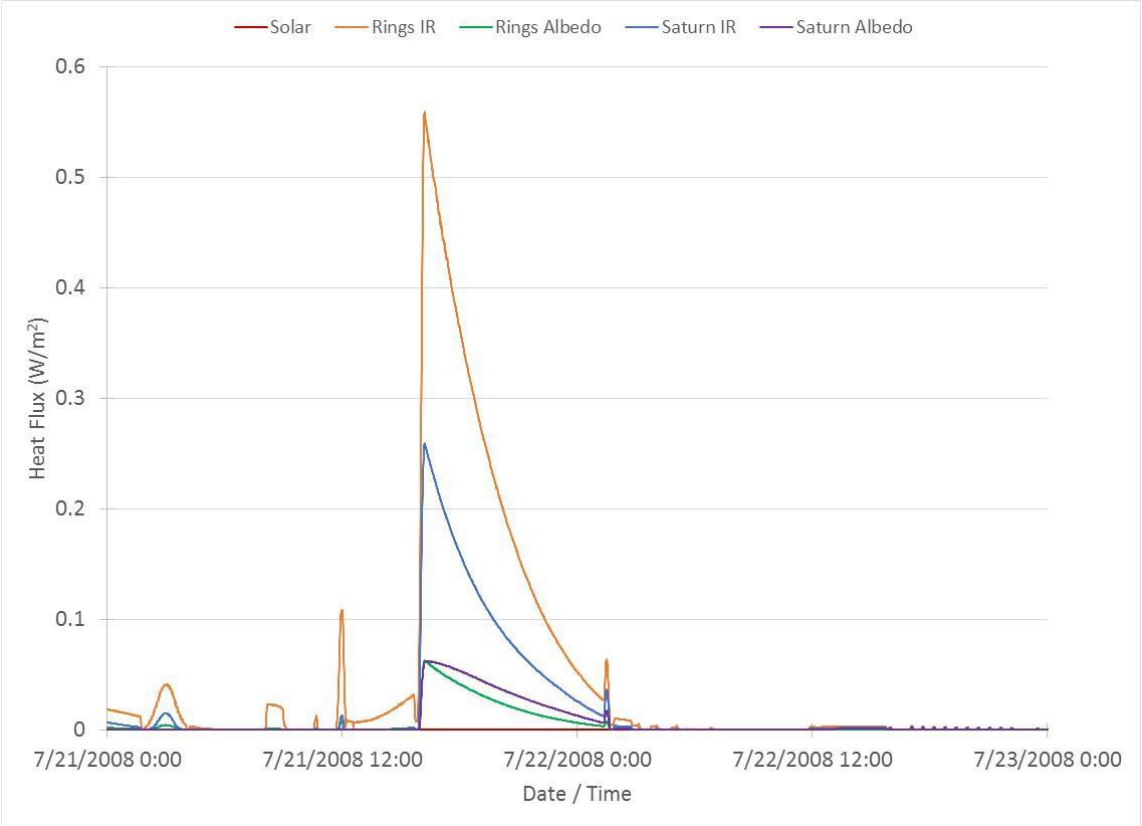

Figure 15. S42 Heat Flux Sources

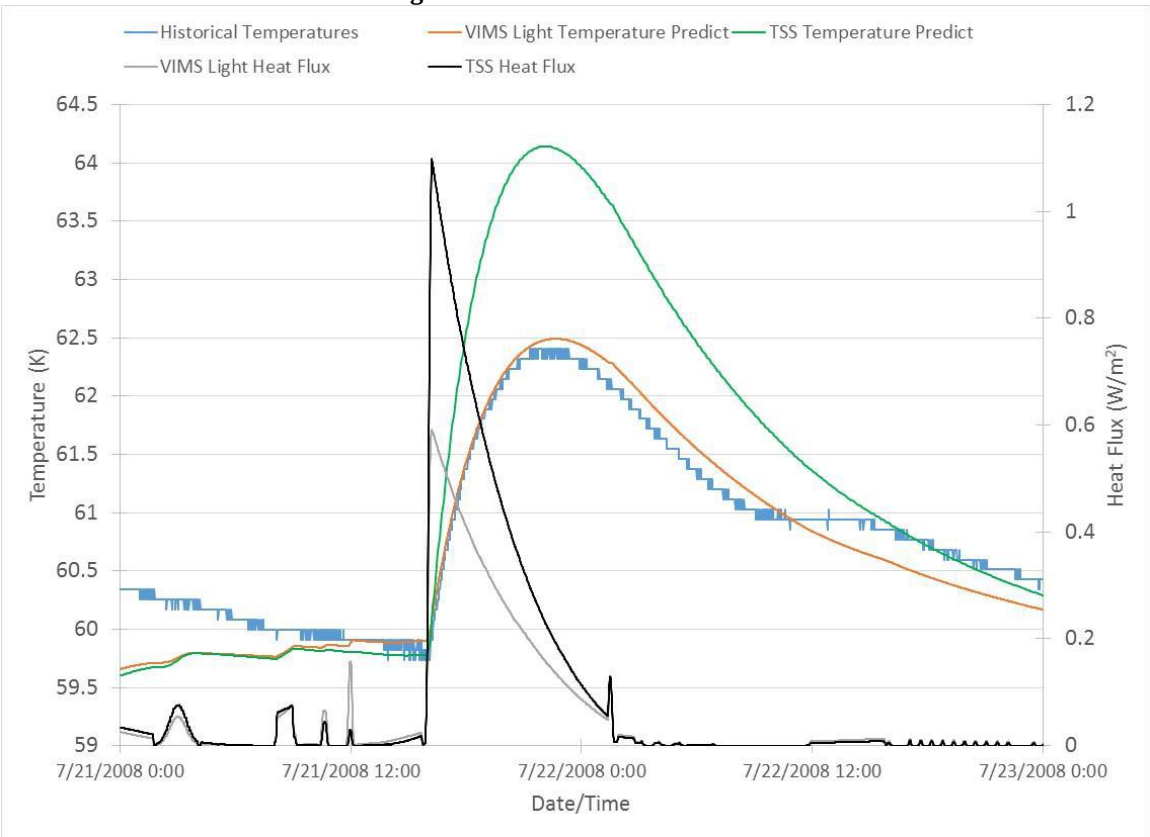

Figure 16. S42 Heat Flux and FPA Temperature Predictions

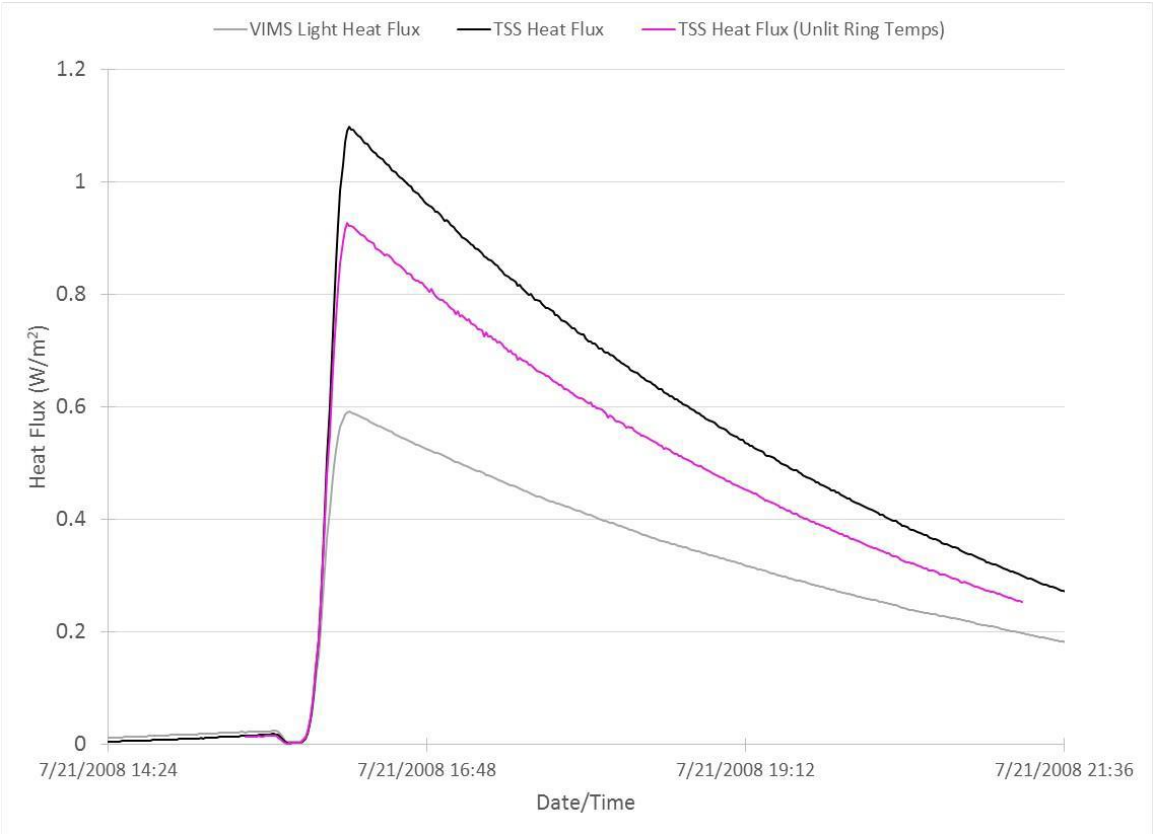

Figure 17. S42 Heat Flux with Unlit Ring Temperatures

D. Predictive Cases

Two predictive cases, current as of 7/28/2015, were analyzed to validate both models produced similar results without the availability of historical data. Both S286 and S289 are proximal sequences, where the Cassini spacecraft passes between the inner D-ring and the planet atmosphere. Figure 18 shows a sample orbital path, with the red line indicating a potential path of travel. Since no historical data exists for this particular flight path, it is imperative both the TSS and VIMS models are in good agreement to allow for accurate mission planning.

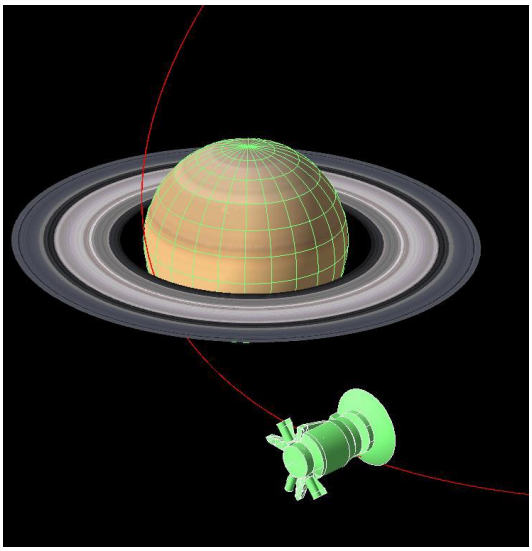

Figure 18. Sample Sequence Orbital Path, Proximal Orbit

Sequence 286

S286 is a good compilation of all possible heating sources. As seen in Figure 19, the largest heating event occurs just before crossing the ring plane. The Cassini spacecraft is rotated so the VIMS radiator is pointed slightly toward Saturn, which causes the spike in heating fluxes from Saturn IR and albedo. There is also a slight ring view during this period. After Cassini crosses through the ring plane, all heat loads drop to zero, at approximately 06:18 on 8/1/2017. Solar loading is observed immediately before the crossing due to the rotation of Cassini for the transit between the rings and the planet. After completing the crossing, Cassini then rotates back toward the planet, and once again sees loading from Saturn.

Figure 20 indicates good agreement between TSS and VIMS Light heat flux predictions, with very small variances. The temperature predictions are also very close, varying by no more than 0.25 K. Therefore, the team is confident both models are accurately predicting the heating event with what is currently known about the Saturn heating environment.

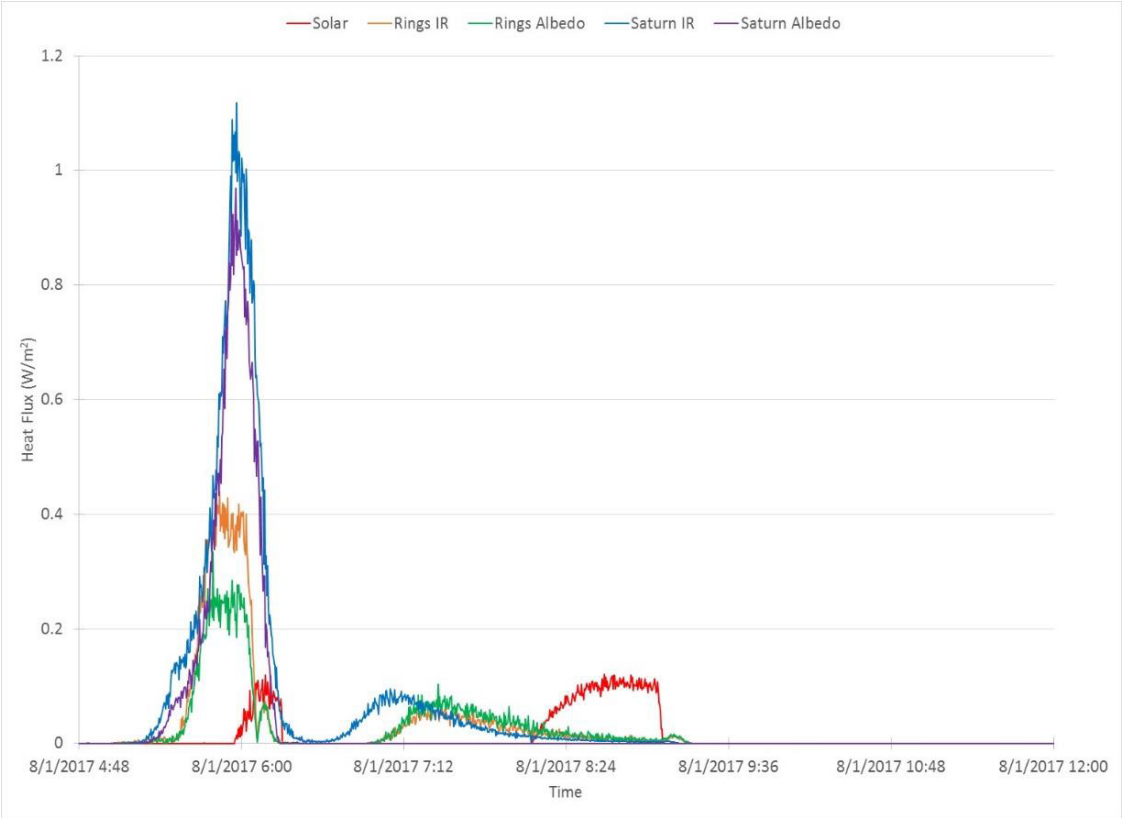

Figure 19. S286 TSS Heat Flux Sources

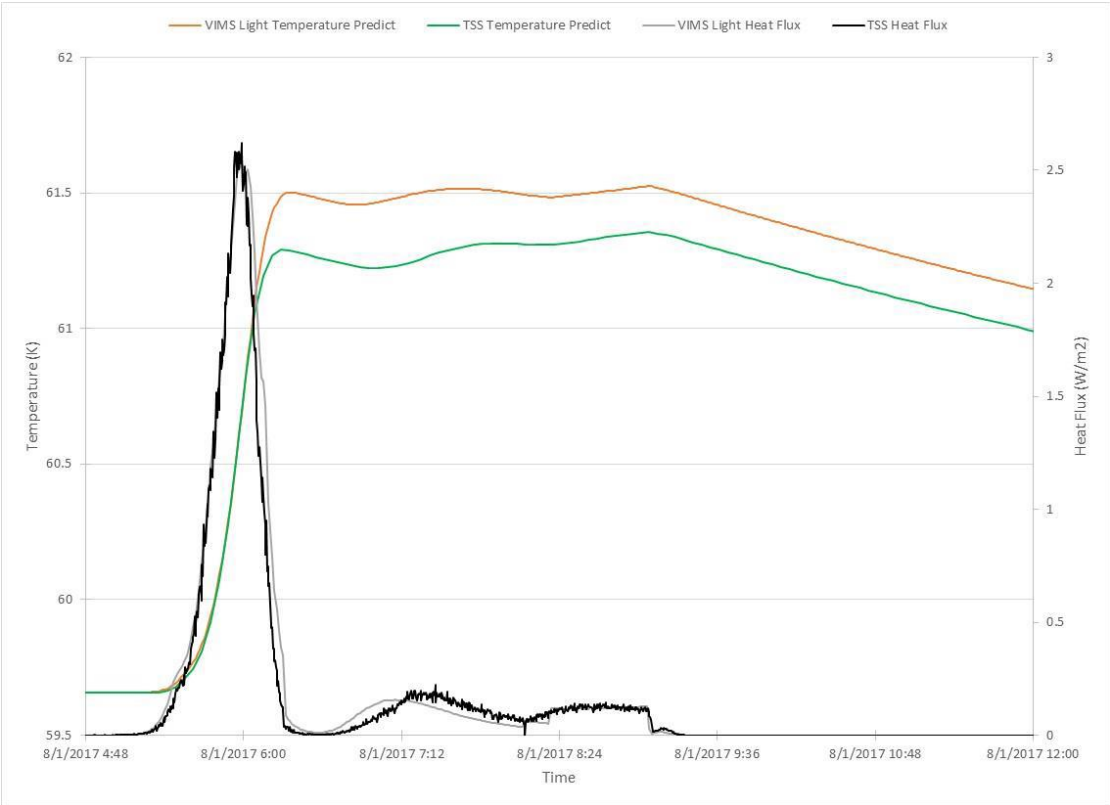

Figure 20. S286 Heat Flux and FPA Temperature Predictions

Sequence 289

Similar to S286, S289 experiences the greatest loading from the planet IR, closely followed by planet albedo. Once again, this is caused by the rotation of Cassini immediately before and after the ring crossing. Crossing the ring plane is a little more definitive in S289, as the IR and albedo heat flux from the rings quickly drops to zero and returns, at approximately 15:23 on 8/20/17, as shown in Figure 21. Comparing VIMS Light and TSS heat flux results show a much larger variation in the VIMS Light heat fluxes. Since VIMS Light does not break down the individual sources coming from Saturn, it is unknown what is driving these spikes.

Although the heat fluxes vary slightly during the ring plane crossing between the two models, the temperature predictions are nearly identical, varying by no more than 0.3 K (Figure 22). Since this is much lower than the goal of 2 K, the team has a good level of confidence in the temperature predictions of the two models.

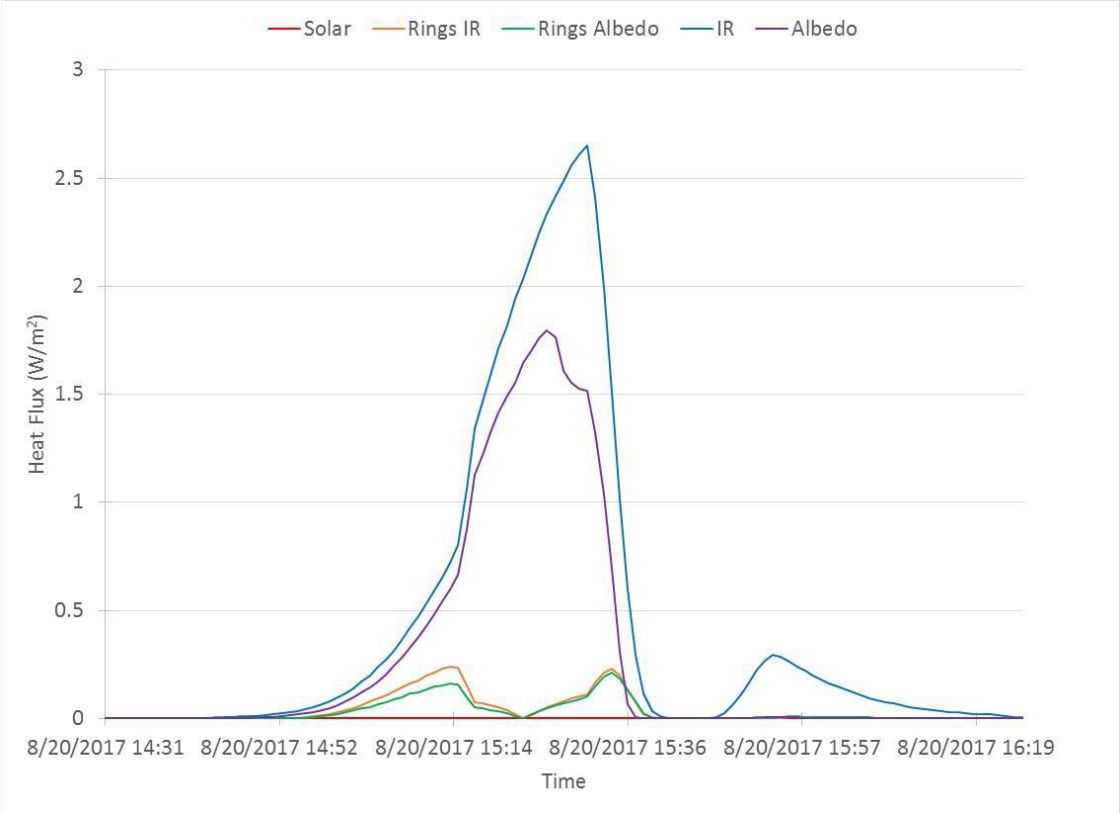

Figure 21. S289 TSS Heat Flux Sources

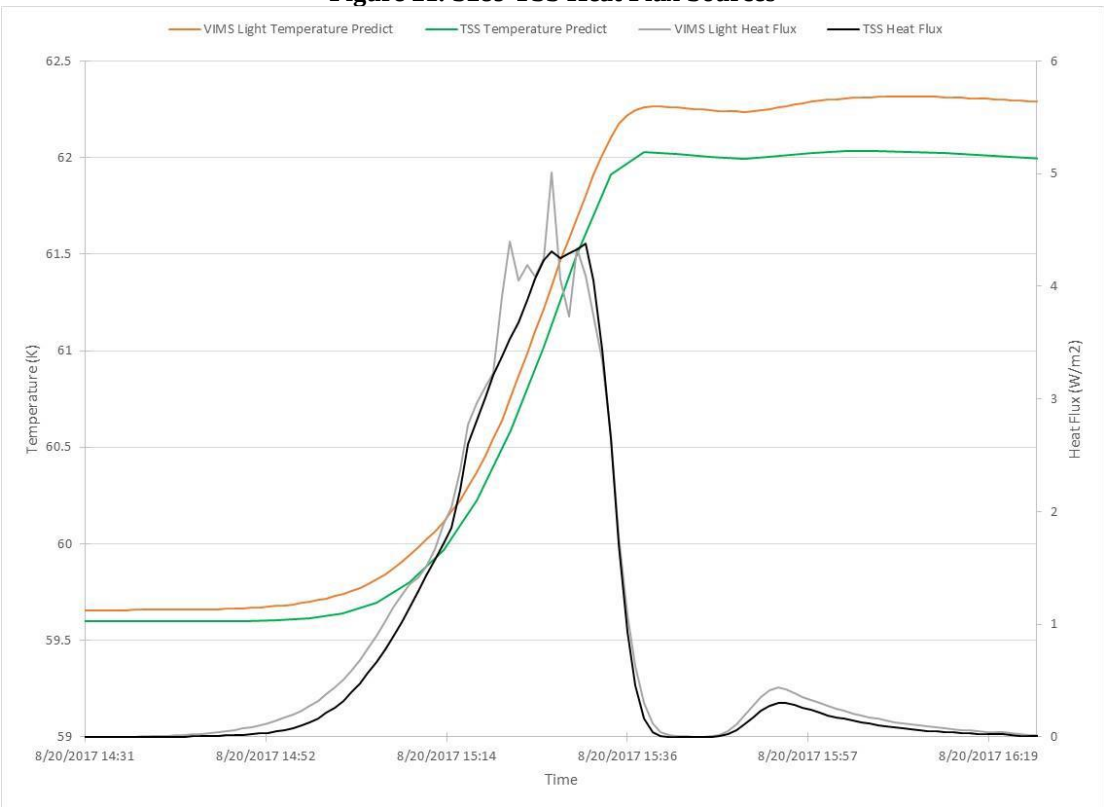

Figure 22. S289 Heat Flux and FPA Temperature Predictions

V. Conclusion

Through the thorough analysis of seven historical sequences, the TSS software has proven the capability to correctly determine the heat flux impinged on the Cassini VIMS-IR radiator from solar, Saturn planetary, and Saturn ring sources. With the exception on one historical case, temperature differences between the TSS model and historical data are within 2 K. With this level of accuracy, the Cassini team is confident that the results produced by the TSS model are correlated, validated with historical data, and the model is ready for use in predictive FRPO cases and future Saturn mission planning.

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