Measuring the Thermal Accommodation Coefficient while Aerobraking Magellan

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Abstract

The Magellan spacecraft was inserted into an elliptical orbit ($e = 0.392$) around the planet Venus on August 10, 1990 and went on to map more than 97% of the surface using a Synthetic Aperture Radar during the first three 243 day "Cycles". High resolution gravity data was collected in a band near the equator for a full 360 degrees of longitude in Cycle 4. Significantly better gravity science is currently being taken from a nearly circular orbit, which was reached by aerobraking during a 70 day phase that began on May 25, 1993 (late in the extended mission). A small aerodynamic force was applied to the spacecraft for 730 consecutive orbits to lower the apoapsis of the orbit from 8500 km to 541 km. Atmospheric drag removed a maximum of 2 m/sec per orbit from the velocity at periapsis for a total AV of 1200 m/sec. This paper will discuss the thermal accommodation coefficient which was inferred from one of the four solar panel temperature measurements from the aerobraking pass through the atmosphere.

1. Introduction

Knowledge of the thermal accommodation is required to properly design a thermal control system for vehicles which plan to use aerobraking. The thermal accommodation coefficient represents the percentage of the kinetic energy of the atmospheric molecules which is turned into heat upon impact with the spacecraft. An accurate understanding of the thermal accommodation is essential for designing the correct thermal control system for future aerobraking missions. Characterizing the particle surface interactions will enable future missions to measure the properties of the upper atmosphere by observing the effects of atmospheric interactions on the spacecraft.

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2. Magellan Aerobraking Data Collection

During the Magellan aerobraking phase [1-5], each pass through the atmosphere was made in a "tail-first" attitude where the 3.7 m high gain antenna trailed the spacecraft to create an aerodynamically stable geometry (Figure 1). The back (side-A) of the solar panels *were* face-on to the flow to maximize the exposed surface area while protecting the solar cells on the front of the panel from erosion by atomic oxygen. Two thermocouples mounted on each of the two solar panels provided the only useful temperature measurements from the surface of the spacecraft, since most of the other external thermocouples had failed prior to the start of aerobraking due to thermal cycling. The thermocouples were mounted on the inside surface of the front side of the solar panel, so interpretation of the measurements had to account for the time lag required for the heat to soak through the solar panel from the aerodynamically heated back side to the front side. Since the aerobraking attitude precluded real time communication with the Earth, selected telemetry channels were recorded in the Command and Data System computer memory for playback later in the orbit when the High Gain Antenna could be pointed at the Earth.

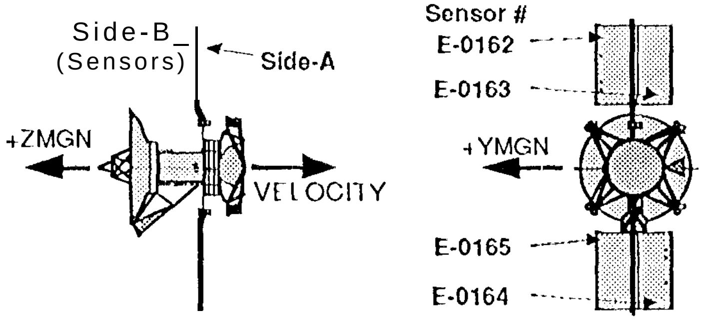

Figure 1: The Magellan Spacecraft Aerobraking Configuration.

3. A Simple Model

Although a complicated finite-element model of the entire spacecraft was used during flight, the project did not have sufficient funding to allocate money for a major data reconstruction using the complicated model. Thus, a simple thermal model from [5] was used to illustrate the sensitivity of the temperature measurement to both aerodynamic (side-A) and non-aerodynamic heating inputs for both sides of the "flat-plate" model of a Magellan solar panel. The model includes thermal mass ($C_A = 2038$, $C_B = 1506$ J/(m^2 'K)), thermal conductivity ($\kappa = 59.5$ W/(m^2 'K)), solar absorptivity ($\alpha_A = 0.20$, $\alpha_B = 0.58$), and emissivity ($\varepsilon = 0.83$). The heat input from the planet is approximated by a time varying background temperature, while shading and reflected heat inputs from other body components are missing completely,

The simple model integrates the following pair of equations (1):

$$\dot{T}_A = \frac{\dot{q}_A - \varepsilon\sigma(T_A^4 - T_0^4) - \kappa(T_A - T_B)}{C_A}$$

$$\dot{T}_B = \frac{\dot{q}_B - \varepsilon\sigma(T_B^4 - T_0^4) - \kappa(T_B - T_A)}{C_B} \qquad (1)$$

The heating input for side-A is the sum of the aerodynamic heating (a function of thermal accommodation, speed, and atmospheric density) and the Solar heating (a function of absorptivity, solar constant, solar incidence angle). The solar heating occurs on either side-A or side-B (determined by testing $\cos(\beta)\geq 0$ for side-A otherwise side-B).

$$\dot{q}_A = \dot{q}_{in} + \alpha_A H\cos(\beta)\,(\cos(\beta)\geq 0)$$

$$\dot{q}_B = -\alpha_B H\cos(\beta)\,(\cos(\beta)<0)$$

where

$$\dot{q}_{in} = \frac{1}{2}\rho V^3 A_c \quad \frac{W}{m^2} \quad \text{Aerodynamic Heat Input}$$

ρ = Scaled Venus International Reference Atmosphere to agree with Nav estimate of density at periapsis.

V = Velocity from conic based on navigation reconstruction of the orbital elements at periapsis [4].

A_c = Thermal Accomodation Coefficient , $A_c = 1$ implies molecules "Stick", $A_c < 1$ implies "Bounce"

H = *2664.6* $\frac{W}{m^2}$ (Solar Flux at Venus)

β = Angle between Sun Vector and Panel Normal (β = 0 means Full Sun on side-A, No Sun on side-B.)

σ = 0.5673 E-7 $\frac{W}{m^2\,{}^\circ K^4}$ is the Stefan-Boltzmann Constant

An average "Background" temperature, To , for the radiation term is assumed to account for the unmodelled albedo effects, the cold temperature of space, the warm temperature of the planet, and the warm parts of the spacecraft which are radiatively coupled to the solar panels. A time varying value for To was computed from:

$$T_0 = T_{0Venus}\, T_0Frac(t) + T_{0Space}\,(1 - T_0Frac(t))$$

where

$$T_0Frac = \sin^2\left(0.5 \arcsin\left(\frac{\text{Radius-to-Upper-Atmosphere}}{\text{Radius-to-Spacecraft}}\right)\right)$$

is the fraction of the sky occupied by the planet and varies between 20% and 44% for the most eccentric orbit during the data collection period. Since the solar panels are edge-on to Venus while in the aerobraking attitude, both sides see the same fraction of Venus and space except that the High Gain Antenna blocks part of the view of space from side-El.

The above model has been used as follows to reconstruct measured temperatures during aerobraking. The initial temperatures of the two sides are set equal to the initial temperature measurement. To is fitted to the data by adjusting the values of T_{venus} and T_{space} such that integrating equations (1) results in a "best fit" of the measured temperature as a function of time prior to the start of atmospheric heating. This "best-fit" approach should absorb some of the unmodelled effects, although the results suggest otherwise. The thermal response during the aerodynamic heat pulse is computed for several values of the thermal accommodation coefficient A_c by integrating all the way through the aerodynamic heating pulse. The best fit thermal accommodation value is estimated from the data near the maximum temperature which occurs as the spacecraft exits the atmosphere.

3.1 Results from the Simple Model

Figure 2 shows a typical plot generated by the simple model for orbit 7926. The vertical scale depends on the quantity being plotted, while the horizontal scale is "seconds since periapsis". The time of periapsis is from the best navigation reconstruction of the orbit. The broad parabolic shape which reaches a maximum near time = O is the average background temperature, To, divided by the maximum value listed in Table 1, column "To Max". The curve which has a sudden spike at periapsis is the net heat flux, $\dot{q}_A + \dot{q}_B$. The spike is due to the aerodynamic heating by the atmosphere (for $A_c = 1$), while the more linearly decreasing and increasing values are due to the direct Sun on first the low-α side-A of the solar panel (the side exposed to the aerodynamic heating), and then on the "front", high-u. side-B. The

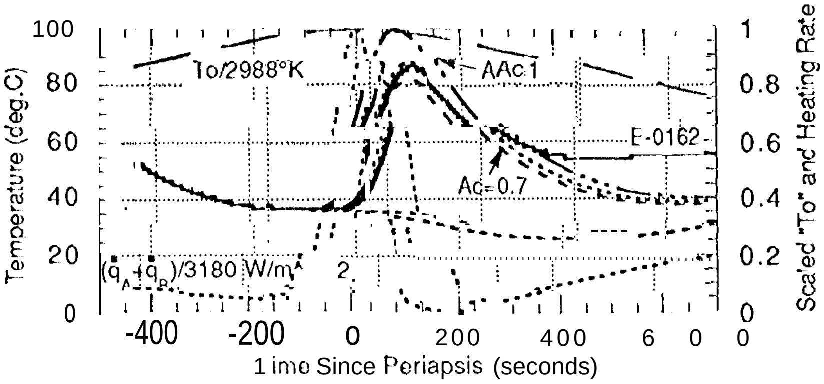

Figure 2: Typical Output from the Simple Model Software.

jagged curve is the data from one of the four thermocouples (E-1062). The remaining 4 curves are integrated values from the model using Ac = 1.0, 0.8, 0.7, and 0.0. The highest peak corresponds to Ac = 1.0, and occurs about 80 seconds after the peak aerodynamic heating due to the time delay required for the heat to soak from the aerodynamically heated side-A to the measurement side-B through the the finite thermal mass.

The initial fit of the model to the data is guaranteed by choosing the background temperature parameters which result in the best fit. The aerodynamic heating is also modelled very well by choosing the best fit for the thermal accommodation. The example for Figure 2 was chosen because the model diverges significantly from the data for times greater than about 300 seconds after periapsis. The reason for this divergence is understood, and is due to the attitude oscillations within the wide (± 10°) attitude control dead-band during the tail-first pass through the atmosphere. Including the actual attitude from the flight data in the simple model, rather than using the ideal "tail-first" attitude, usually improved the agreement between the model and the post-periapsis temperature measurements, however, the best fit value of A_c changed little (less than 5% in the five examples studied so far - column A_{cR}).

Table 1. Summary of Cases Studied using the Simple Model

Date	Orbit	LST	Ac	ΔT °C	Peak-T °C	T_{os} °K	T_{ov} °K	T_{omax} °K	A_{cR} attitude	%Δ
5/31	7667	11.1	.64	42	64	30	670	309		
6/1	7680	11.3	.67	48	68	30	670	309	.70	+5 %
6/5	7712	11.7	.66	43	60	27	666	306		
6/15	7794	12.7	.76	50	83	82	580	299	.78	+3 %
6/16	7800	12.8	.75	44	81	100	562	302		
6/18	7821	13.1	.75	45	78	93	562	298		
6/19	7831	13.2	.75	50	82	80	589	302		
6/20	7834	13.2	.75	50	82	80	589	302		
6/28	7914	14.1	.74	46	84	80	590	303	.78	+5 %
6/29	7926	14.2	.78	50	87	68	590	296	.78	0 %
6/30	7930	14.3	.75	52	87	70	595	300		
7/20	8160	16.4	.80	47	62	40	582	278		
7/20	8161	16.4	.84	63	77	150	419	268		
7/21	8174	16.5	.78	44	64	100	492	272		
7/27	8252	17.1	.83	27	37	134	420	259		
7/27	8253	17.1	.89	36	46	200	320	252	.88	-1 %
8/2	8346	17.8	.90	40	30	200	280	235		

Figure 3 plots the inferred accommodation coefficients listed in Table 1, columns Ac & AcR. The box-tics are for cases which model the ± 10° attitude oscillation, while the circle-tics connected with a line are for cases assuming no oscillation. "Ac" is computed by linear interpolation of the peak values, varies between 0.64 and 0.90, and seems to be correlated to Local Solar Time (LST), which increases from orbit to orbit. One explanation for this apparent correlation is that the unmodelled heat and albedo of the planet is not being correctly accounted for by estimating the best fit values for the To_{Venus} and To_{Space} parameters, which would mean that the inferred thermal accommodation is wrong. An alternative explanation is that the thermal accommodation coefficient is actually increasing due to "weathering" as more and more molecules interact with the exposed surface.

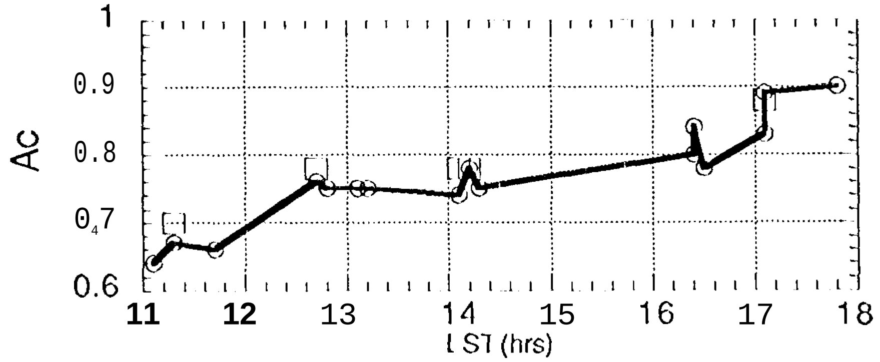

Figure 3: Best-Fit Thermal Accommodation Coefficient.

Figure 4 shows a plot of the best fit parameters and the peak value of the computed maximum value for To, which is smooth and gradually decreases as local solar time moves away from noon. The large differences between To_{Venus} and To_{Space} near noon where the orbit was very eccentric imply that the average background temperature had to be significantly hotter near periapsis in order to correctly model the measured temperatures. The nearly equal parameters near the evening terminator (18:00 hrs LST) where the orbit was nearly circular, imply a much more uniform average background temperature. Since the effects of solar missmodelling are smallest near the end of the aerobraking phase where the panels are nearly edge-on to the Sun and reflections from the planet are small, the estimated value of Ac = 0.90 near 18:00 hrs LST may be more accurate than the value of Ac = 0.66 near noon.

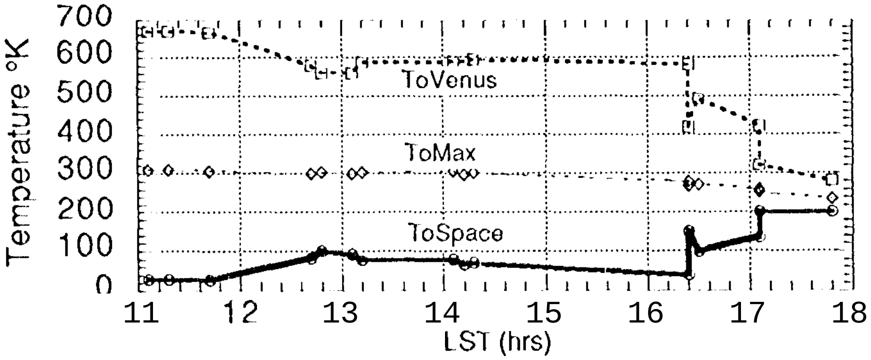

Figure 4: Background Temperature Parameters for the Best-Fit.

5. Conclusions

Although the initial philosophy was to use a simple thermal model to reconstruct the thermal accommodation coefficient, the simple model became more sophisticated as more cases were analyzed. A single atmospheric scale height good for orbits near noon was not good for orbits near the terminator, so the full atmospheric model as a function of altitude and local solar time was scaled to agree with the navigation reconstruction of the density at periapsis. The aerodynamic heating rate is very well known because it is derived from the observed changes to the orbit, which depend on the integrated effects of dynamic pressure. A constant background temperature did not adequately model the measured temperatures prior to the onset of atmospheric heating, so a time varying background temperature was developed, The perfectly "tail-first" attitude was used for most of the data presented in this paper, however, the model was modified to include the actual attitude in order to show that the attitude oscillations changed the inferred value of the thermal accommodation by less than 5%.

Even though the simple model became more sophisticated to separate the effects of thermal accommodation from other thermal effects, the simple model produced a “best-fit” value for the thermal accommodation which still had an unexpected and unexplained increase in the thermal accommodation coefficient (0.64 to 0.90). Is the increase due to improperly modelled solar or planetary heating or does the thermal accommodation actually increase due to a weathering effect from the previous particle impacts? Further study is needed to answer this question.

To further cloud our understanding of the effects of the particle surface interactions, the best fit value of thermal accommodation from the complicated model that is used during operations to model entire orbits is only 0,63. Is the simple model too simple or is the complicated model biased because it must model the entire orbit and not just the effects near periapsis?

6. References

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