Mimas and Enceladus: Formation and interior structure from astrometric reduction of Cassini images.

R. Tajeddine, V. Lainey, N. Rambaux, N. Cooper, S. Charnoz, C.D. Murray
Center of Mass / Center of figure

- The center of figure is the same as the center of mass when a body is homogeneous or symmetrically differentiated.

- If the body contains a mass anomaly, the center of mass is shifted in the direction of this anomaly.
Water emission from Enceladus’ south pole
Existing models

Nimmo & Pappalardo 2006:

- Global ocean, with subsurface ice melting localized in a specific region of the equator, caused by the tidal effects (?).
- Formation of a low density ice diapir resulting in a reorientation of the satellite’s anomaly to the south pole.
- Because of this low density anomaly, the center of mass is shifted northward.
Existing models

Collins & Goodman 2007

- No Global ocean, only a localized south polar sea.
- The density in this area is higher than it is in the rest of the ice shell.
- The center of mass is shifted southward.
Existing models

Charnoz et al. 2011

• The satellites core is formed by accretion of large silicate chunks (size 10-100 Km).
• This model could cause a shift in center of mass
Objective

• Astrometric reduction of the ISS-Cassini NAC images.
• Compare the satellite’s observed center of figure position obtained from Astrometry to its center of mass position predicted by the ephemerides (sat317 and sat351).
• Discriminate between different models.
Astrometry

Algorithm used to convert a position from (RA,DEC) in radians to (sample, line) in pixels:

\[
\begin{align*}
\rho : & \text{ Scale factor (arcsec/pixels)} \\
\end{align*}
\]
Astrometry

Scale factor = $1.2354 \pm 10^{-4}$ arcsec/pixel
(based on 100 observations of stars clusters with 225 star per image)
Finding the center of figure
Finding the center of figure

- Fit the cartesian equation parameters of an ellipse:
  \( f(x,y) = Ax^2+Bxy+Cy^2+Dx+Ey+F = 0 \)
  to the bright part of the satellite, to finally obtain the ellipse parameters
  \( (X_c,Y_c, a, b, \theta) \).

- In this work, \( a \) and \( b \) were fixed using the projection of the satellite’s shape given by Thomas (2010). Thus, only three parameters are fitted at every limb fitting.

- UCAC2 catalogue was used for pointing correction.
## Residuals Mimas: (1006 images)

<table>
<thead>
<tr>
<th></th>
<th>SAT317</th>
<th>SAT351</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt;O-C&gt;)_{\text{sample}} )</td>
<td>$2.69 \times 10^{-2}$</td>
<td>$-5.34 \times 10^{-2}$</td>
</tr>
<tr>
<td>(\sigma_{&lt;O-C&gt;\text{sample}})</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>(&lt;O-C&gt;)_{\text{line}} )</td>
<td>$2.10 \times 10^{-2}$</td>
<td>$6.16 \times 10^{-2}$</td>
</tr>
<tr>
<td>(\sigma_{&lt;O-C&gt;\text{line}})</td>
<td>0.94</td>
<td>1.01</td>
</tr>
</tbody>
</table>
Residuals Enceladus: (1141 images)

<table>
<thead>
<tr>
<th></th>
<th>SAT317</th>
<th>SAT351</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle O-C \rangle_{\text{sample}}$</td>
<td>$2.71 \times 10^{-2}$</td>
<td>$-2.69 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\sigma_{\langle O-C \rangle_{\text{sample}}}$</td>
<td>$0.83$</td>
<td>$0.73$</td>
</tr>
<tr>
<td>$\langle O-C \rangle_{\text{line}}$</td>
<td>$6.72 \times 10^{-2}$</td>
<td>$4.69 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\sigma_{\langle O-C \rangle_{\text{line}}}$</td>
<td>$0.85$</td>
<td>$0.84$</td>
</tr>
</tbody>
</table>
Coverage (Mimas)
Coverage (Enceladus)
COM/COF shift

**Mimas:**

Center of mass shift with SAT317 ephemeris:

\[ X = 858 \text{ m} \pm 165 \text{ m} \]
\[ Y = -580 \text{ m} \pm 207 \text{ m} \]
\[ Z = 976 \text{ m} \pm 139 \text{ m} \]

Center of mass shift with SAT351 ephemeris:

\[ X = 734 \text{ m} \pm 163 \text{ m} \]
\[ Y = -535 \text{ m} \pm 210 \text{ m} \]
\[ Z = 925 \text{ m} \pm 134 \text{ m} \]
**COM/COF shift**

**Mimas:**

Center of mass shift with SAT317 ephemeris:

\[
\begin{align*}
X &= 858 \text{ m} \pm 165 \text{ m} \\
Y &= -580 \text{ m} \pm 207 \text{ m} \\
Z &= 976 \text{ m} \pm 139 \text{ m}
\end{align*}
\]

Center of mass shift with SAT351 ephemeris:

\[
\begin{align*}
X &= 734 \text{ m} \pm 163 \text{ m} \\
Y &= -535 \text{ m} \pm 210 \text{ m} \\
Z &= 925 \text{ m} \pm 134 \text{ m}
\end{align*}
\]

Charnoz et al. 2011
What are we expecting to observe on Enceladus?

A more important shift?

Northward?

Southward?

![Silicate fraction vs Distance graph]

![Diagram of Enceladus's interior structure]

The arguments for a convective interior and thinning of the lithosphere required, which will be less likely to yield unique solutions. The presence of question marks indicates the uncertainty of many of the inferences made. The arguments for a convective interior and thinning of the lithosphere required, which will be less likely to yield unique solutions. The presence of question marks indicates the uncertainty of many of the inferences made.
**Enceladus:**

Center of mass shift with SAT317 ephemeris:

\[
\begin{align*}
X &= -73 \text{ m} \pm 159 \text{ m} \\
Y &= -120 \text{ m} \pm 171 \text{ m} \\
Z &= -5 \text{ m} \pm 132 \text{ m}
\end{align*}
\]

Center of mass shift with SAT351 ephemeris:

\[
\begin{align*}
X &= -345 \text{ m} \pm 155 \text{ m} \\
Y &= -276 \text{ m} \pm 170 \text{ m} \\
Z &= -136 \text{ m} \pm 133 \text{ m}
\end{align*}
\]
Enceladus:

Center of mass shift with SAT317 ephemeris:

\[ X = -73 \text{ m} \pm 159 \text{ m} \]
\[ Y = -120 \text{ m} \pm 171 \text{ m} \]
\[ Z = -5 \text{ m} \pm 132 \text{ m} \]

Center of mass shift with SAT351 ephemeris:

\[ X = -345 \text{ m} \pm 155 \text{ m} \]
\[ Y = -276 \text{ m} \pm 170 \text{ m} \]
\[ Z = -136 \text{ m} \pm 133 \text{ m} \]
Don’t be..

- Collins and Goodman (2007) explained the observed south polar depression by Isostasy.
- Isostasy causes mass compensation within Enceladus’ interior.
- Center of Mass is back again at the center of figure and no shift is observed.
Why Isostasy did not take effect on Mimas?

Since tidal heating is way more important on Enceladus than on Mimas.
\[ t_{\text{relax}}(\text{Enceladus}) < t_{\text{relax}}(\text{Mimas}) \]

And since Enceladus is older than Mimas. This latter, did not have enough time to relax and Isostasy did take effect on Mimas.
Summary

- We used astrometry to study the internal structure of Mimas and Enceladus.
- On Mimas we have detected a shift of the center of mass of about 800 meters in positive (X,Z) direction. Possible asymmetry in Mimas’ core (closer to Charnoz et al. model).
- No shift in center of mass has been detected on Enceladus. Strong dissipation on Enceladus causes isostasy in its interior, therefore mass compensation.
- Next step: Fit NOE dynamical model to these observations adding the center of mass shift in the model.