IMPROVING THE RAND-USGS CONTROL NETWORK FOR IO.

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Introduction: We present here our current results from photogrammetric triangulation solutions for a control network and reference surface for Jupiter's moon Io. It is compared to previous such solutions by us and others, and on-going work to further improve these results is described.

Significance: A good determination of a control network and shape model for Io is desirable for a number of reasons, including the practical one that it is needed in order to project spacecraft imagery in order to derive controlled mosaics of the surface of Io. In addition, such a network and shape model can be used to assist with current and future spacecraft operations in the vicinity of Io, and also serves to constrain various models on the internal structure of Io as well as its evolution.

Previous Results: There have been a number of solutions, obtained via various techniques, for the mean radius and semi-axis lengths for Io over the past several years. These include the results of photogrammetric solutions using both Voyager and Galileo SSI image measurements, both by RAND-USGS and the DLR [1], solutions by Thomas et al. [2] obtained via absolute limb measurements from Galileo imagery, and a solution by Schubert et al. [3] derived entirely from Galileo spacecraft tracking data during four encounters with Io. There appeared to be good agreement between the latter results when a best-fit equilibrium shape is assumed. For example the limb fitting results [2], giving semi-axis length determinations of a=1829.6±0.6 km, b=1819.2±0.5 km, and c=1815.8±0.4 km, compare favorably with the dynamical tracking results [3] where a=1830.0±0.5 km, b=1819.2±0.5 km, and c=1815.6±0.5km. From geometrical arguments one could also argue that the limb fitting results should be quite accurate, perhaps more so than from a photogrammetric solution. Figure 1 shows a plot of solution semi-axis lengths vs. b and c semi-axis lengths for various solutions, including a) for reference purposes, the most recent solution by Thomas et al. and the Schubert et al. solution, and b) our two current solutions, to be discussed below. The Thomas et al. result did not have uncertainties associated with them, so they appear here without error bars. It can be seen they are nearly the same as the Schubert et al. results within the uncertainty (error bars) of the latter.

However, the earlier photogrammetric results from RAND-USGS and DLR [1] (not shown in figure 1) appeared to be significantly different, giving (assuming an equilibrium fit) a=1826.5 km, b=1815.7 km, and c=1812.2 km. More recent RAND-USGS solutions, incorporating additional measurements of Galileo SSI images, gave semi-axis lengths (also not shown here) that were different from the other types of determinations by even larger values. This situation implied that there might be some fundamental problem in mixing the measurements from both Voyager and Galileo in the same solution.

The 2000 RAND-USGS Galileo solution: In 2000, a new photogrammetric solution was derived, this time using only measurements from Galileo imagery [4, 5]. This became possible at that time because only recently had additional images of Io been obtained, extending longitude coverage of that body. The new solution included 2148 measurements of 432 control points from 116 Galileo SSI images. Although the imagery provides for good longitudinal coverage of Io, there is a lack of control points in the region of 320º to 20º (east) longitude. See Figure 2 for the locations of the control points. Solved-for parameters include the control point positions (latitude and longitude), spacecraft camera angles (3 per image), and the 3 best fitting semi-axes for Io. The camera focal length and orbits were assumed known, and other constants were held at the IAU 1994 [6] values. The *a posteriori* mean measurement error of the solution was 7.7 micrometers (in the Galileo SSI camera image plane). This solution yielded a best-fit ellipsoid of a=1828.8±1.0 km, b=1820.8±0.5 km, and c=1816.9±1.3 km. The mean radius derived from these values is r=1822±1.3 km. These results were in line with those obtained by the other methods. However, this left the mystery unresolved as to why the solutions including Voyager measurements give such different results.

Comparison of solutions: There is no obvious reason why there would be a problem with the Voyager imagery of Io in particular. No similar problems were seen with RAND-USGS control solutions for the other Galilean satellites [1], which included both Voyager and Galileo SSI imagery. However, there are a number of reasons why problems may result in the case of Io as opposed to the other satellites. First, the appearance of Io can vary dramatically between images of different colors or different phase angles, making the selection or at least measurement of control points difficult. The best fitting regular shape for Io is a triaxial ellipsoid, as opposed to a rotational ellipsoid or even a sphere in the case of the other moons. Io is also essentially unique in the solar system in that many features have changed between the Voyager and Galileo missions and even between individual encounters by Galileo, due to the ongoing resurfacing by volcanic processes – so the control points themselves can come and go – or worse, even move between images. Finally, the image coverage from all three spacecraft (Galileo and particularly Voyager 1 and 2) of the sub-Jovian area of Io (at 0º degrees longitude) is rather poor. In order to try to determine which control points or (presumably) Voyager imagery is causing the discrepant results, a solution was done using all the data, but with the semi-axis lengths fixed at their Galileo SSI-derived values. Differencing the control point positions from their previously determined positions showed a number of large positional changes (up to 14 km), but only over a specific region of Io, i.e. near and to the west of the sub-Jovian point. A further solution was done with all the data holding everything fixed to the previous solution's values, except for control point radii. The radii themselves showed only the differences between the original and newly determined ellipsoidal surfaces, but their standard deviations again showed a number of extreme values (up to 58 km) in the same area where the large horizontal changes occurred. In conclusion, it appears that there were problems with a number of control point measurements from the Voyager images covering this area. This was partially confirmed by examining some of these images, and finding that the coverage of this area of Io by the two Voyager spacecraft was indeed rather poor, with most of the control points here occurring near the limb (i.e. at high emission angles) on the Voyager imagery. There are also some indications that these images and their measurements (apparently done circa 1980 - by matching pin-pricked points on prints of the images) are of lower quality than for other areas of Io.

Remeasurement: Given this situation, it was decided to remeasure positions of a number of control points, which appeared problematic. Five classes of measurements were rechecked: a) measurements where the control points showed large horizontal position changes in the differenced solutions described above; b) points whose latitude solution sigmas were greater than 0.01º; c) points whose longitude solution sigmas were greater than 0.3º; d) points with measurements having residuals (in x or y) of more than 0.04 mm; and e) control points with radii uncertainties of greater than 10 km. These classes contained about 21, 9, 8, 11, and 10 control points respectively (with some overlap). It was realized of course that remeasuring points would not improve control point position uncertainties (since they are dependent only on the measurement geometry), but these values were checked in any case to assure there were no large measurement errors or blunders masked by these large uncertainties. Given these classes, an initial list of 650 measurements of 53 control points was prepared, and remeasurements were made using the ISIS [7] "qmatch" software.

In the process of making these measurements, several problems were found and corrected. Essentially all of the Voyager image measurements were slightly off, e.g. usually a few pixels, and often several pixels. The centers of calderas were often used as control points, but upon visual inspection of these measurements, many of the Voyager measures did not appear to be well centered and in some cases were even outside the obvious calderas. As already noted, these measurements may simply have appeared poor due to the differences in the measurement technology between now and circa 1980, when these measurements were originally collected. The current digital display and measurement of these images would be expected to give somewhat better results. In addition, as explained above, these measurements were selected as likely the worst of the Voyager measurements so perhaps such problems should be expected. In addition to this general problem, a few control point-specific problems were noted. At least a few points had one measurement made on the wrong feature and these were all corrected (except in one case where the correct feature was past the limb, i.e. not even on the image in question). For several points, it was also found that the measurements spanned images covering such a range of resolution that the same point could not be reliably measured in all the images. For example in the highest resolution image (~0.5 km/pixel) the measured point would be a feature at the center of a caldera, while there would also be measurements of this point in images with resolutions as low as 50 km/pixel at the same area, and the caldera itself could not be clearly visible on such a small full disk image. It was still possible to solve for the location of these points in the photogrammetric solution, but these points clearly tended to have higher residuals (e.g. 3-5 pixels) than others. In these cases the control points were "broken up" into two or more separate control points, so their positions could be solved separately.

There were also similar cases where a point would fall near the limb (i.e. with a high emission angle) on high-resolution images, and near the center of the disk (with a low emission angle) on other images.

These points had some of the highest residuals in the photogrammetric solutions until they were "broken up" into two separate control points. The reason for this problem is not clear, although it could be due to poor spacecraft positions or unmodeled camera distortions, neither of which can be corrected for in these photogrammetric solutions. P. Schenk (personal communication) has also reported similar problems in photogrammetric solutions he has done with image measurements of the Galilean and Saturnian moons so this problem is apparently not unique to Io or the methods/software being used by RAND-USGS. In any case the final photogrammetric solutions showed order 1º -2º positional differences for the locations of the ("broken up") control points of these supposedly identical features. If these differences are due to orbit errors, then the positions of the control points that have lower emission angle data are likely the more accurate. For this same reason, when making mosaics of Io (and possibly the other Galilean or Saturnian moons imaged by the Voyager spacecraft) it may be necessary to trim the higher emission angle portions of the images in order to assure the best fit between images.

New Solutions: The process of checking these existing measurements and collecting new measurements (where necessary) continued, with new photogrammetric solutions being performed at intermediate steps. In this way a few new measurements were identified as poor by their large residual errors and in turn corrected. In addition, once the new measurements were incorporated into the solutions, other measurements also began showing higher residuals. So in an iterative fashion, the measurements for additional control points were also added to the list of those to be checked and remeasured. At the end of this process, a total of 970 measurements of 70 control points were checked.

The final maximum residual sizes were (in Voyager-sized pixels, i.e. 1 mm = 84.8 pixels) 3.4 for all of the data (from Voyager and Galileo images) and 2.8 from solutions with only Galileo data. The all data solution gave semi-axis lengths of a=1824.0±0.3 km, b=1819.0±0.2 km, and c=1816.5±0.2 km, while the Galileo data only solution gave a=1828.7±1.0 km, b=1820.6±0.5 km, and c=1817.1±0.5 km. Solution *a posteriori* mean measurement errors were 8.8 (0.75) and 7.9 (0.67) micrometers (Voyager pixels) respectively. From these results it appeared that checking and remeasurement of the data did result in improved (larger) values for the size of Io in the all-data solution. Still, values appeared somewhat low. For the Galileo data only solution, the semi-axis lengths also increased from their previous values, but only slightly, still agreeing generally with the limb fitting solution values.

Having reached this stage where likely problem measurements had been carefully checked and remeasured as necessary, solutions still appeared not to be giving quite the "correct" (or at least the same) values for semi-axis lengths. We began to suspect that the poor coverage of Voyager images near the sub-Jovian (0º longitude) area, and lack of measurements of control points in this area on Galileo images may still be the source of some problems. To determine if the solution could be improved we next planned to add additional measurements of Galileo images covering this area as well as new Galileo images of Io that were not available until recently.

The 3-second difference: After the remeasurement and solution process just described was completed, preparations were made to handle new *a priori* spacecraft position and camera angle (i.e. NAIF SPICE, see http://pds.jpl.nasa.gov/naif.html and [8]) data, as output from the new "level" versions of the ISIS software. This would allow us to process measurements from any new Galileo images. As part of this process, the position and angle data for all existing Galileo images were regenerated from current JPL SPICE data. At this step, it was found that the time (in ephemeris Julian days) for many of the early Galileo images did not match the existing times we had assumed for those images, with a difference of 3 seconds. A check showed that this 3-second difference had been due to a bug in the previous ISIS software used for formatting this data (the predicted number of leap seconds from the fundamental epoch of J2000.0 to the time of the Galileo images had been applied in order to compute the *ephemeris* time, when it should not have been). This problem had been noted a few years ago and fixed, but for some reason corrected data had not been supplied for processing. (We have confirmed that the image times were corrected as necessary in solutions for the other Galilean moons.) In any case, the image times, positions, and angles were all now updated and new solutions undertaken. Note that there were slight differences between the old *a priori* position and angle values as well, presumably due to the reprocessing of tracking data and improvements in Galileo orbit determination methods at JPL.

After these changes, the semi-axis lengths increased significantly in both the "all data" and "Galileo data only" solutions. The new (and current) results are that the all data solution gave semi-axis lengths of a=1825.1±0.2 km, b=1819.0±0.2 km, and c=1816.6±0.2 km, while the Galileo only solution gave a=1831.0±0.9 km, b=1819.6±0.5 km, and c=1817.4±0.5 km. The solution *a posteriori* mean measurement errors decreased slightly, from 8.8 to 8.7 micrometers, and 7.9 to 7.6 micrometers for these respective solutions, showing that the changed orbit information and image times did in fact improve the solutions. The maximum residuals are now (again in Voyager-sized pixels) 3.3 and 2.4 for these solutions.

As can be seen in comparison to the reference limb fitting and dynamical solution results, this means the all-data solution is now showing semi-axis lengths that are larger are closer to what they should be, while the "Galileo-data-only" solution is showing semi-axis lengths that have also increased, but now (e.g. for the a and c axes) to slightly more (by ~1 km) than what they likely should be.

Continuing work: Currently we have what we believe are improved solutions, one using all of the available Voyager and Galileo image measurements, and the other using just the Galileo measurements. However, the semi-axis lengths derived from all the data still do not match well with their expected values and the axes lengths from the Galileo-data-only solution appear slightly larger than they perhaps should be. One possible reason for both of these problems still not addressed is the image coverage of the sub-Jovian area of Io by all three spacecraft may not be very good, with either poor coverage and high emission angles (by the Voyager spacecraft), or very few images by Galileo. In addition measured control points in this region are still lacking on the Galileo images, existing only on the edges of these images, far from this area.

We plan to make additional control point measurements on these Galileo images for which other measurements are already included in our solution, in order to check that the ties across this region are adequate and to make measurements more uniform over the entire surface. We also plan to incorporate additional newer (1999-2000) Galileo images of Io into these networks, some of which cover this sub-Jovian area of Io (and some of which will simply be useful as well in building the image mosaics).

In order to complete the planned image mosaics in the near-term (months) our work on deriving an improvement network for Io will probably cease after these new measurements have successfully been incorporated into the solution(s). If we still are not successful in obtaining what we feel are reasonable values for the size of Io, we may have to select some 'best' semi-axis length values as determined by one of the other methods or some combination of the values determined by those methods and the results from the Galileo data only solution. We would then solve for the control point coordinates and camera angles using those fixed values. These control networks and the associated camera angle information will then be used to project imagery to make at least two controlled mosaics, one with Galileo, and the other with Voyager images, so that the surface changes during the ~18 year period between these missions can be examined. This is as described in more detail by Becker et al. [9].

Whatever the outcome of these solutions, possible future work on improving them could still be done by re-adjusting the Voyager spacecraft orbits and camera angles. It is our understanding that this has not been done since the time of these missions, and it seems likely that given modeling and software improvements that have occurred in the last 20 years (including better gravity fields for Jupiter and the Galilean moons) that the spacecraft position information could be improved, which would result in improved control network solutions where the Voyager imaging data is used.

Finally, given the quality of the Voyager image measurements and the apparent quality of the Voyager spacecraft orbits, similar control network problems may currently be hidden in the RAND solutions for the Saturnian moons, developed in the late 1970's to early 1980's. It would be advisable to revisit and check this data and the solutions, before this information is relied upon during the Cassini mission in 2004 and beyond.

Summary: New photogrammetric triangulation solutions for Io have been performed, using improved and corrected Voyager and Galileo SSI image measurements, and Galileo SPICE data. For a solution with all the available data and a solution with only the Galileo image measurements, Io triaxial ellipsoid semi-axis estimates are still not quite consistent with estimates made by limb fitting and spacecraft tracking dynamical solutions. However, we plan to use additional measurements of current and new Galileo images to improve these solutions. The "best" available estimates of the semi-axis lengths will be used to complete these adjustments; upon which controlled USGS Voyager and Galileo image mosaics of Io will be based.

References: [1] Davies et al. (1998), *Icarus*, 135, 372-376. [2] Thomas et al. (1998), *Icarus*, 135, 175-180. [3] Schubert et al. (2000), DPS2000 abstract. [4] Archinal, et al. (2001), AGU, EOS, 81, no. 48, F317. [5] Archinal, et al. (2001), LPSC, XXXII, no. 1746. [6] Davies et al. (1996), *Cel. Mech. & Dyn. Ast.*, 63, 127-148. [7] Torson J. and Becker K. J. (1997), LPSC XXVIII, 1443-1444. [8] Acton, et al. (2001), this workshop. [9] Becker, T. et al. (2001), LPSC, XXXII, no. 2009.

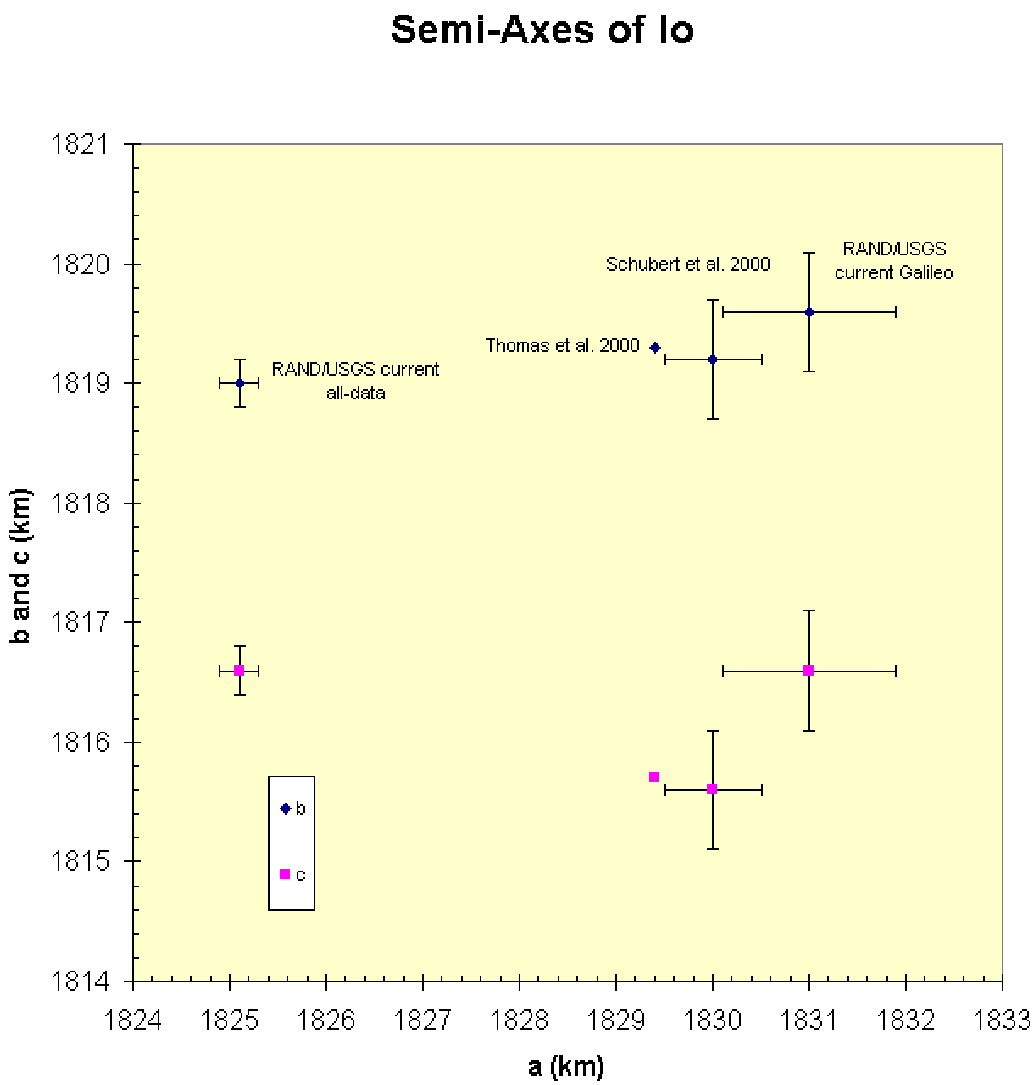

Figure 1: Io semi-axis length solutions, shown as **a** semi-axis vs. **b** semi-axis (diamond symbols – with and without error bars - in the upper part of the plot) and **a** semi-axis vs. **c** semi-axis (square symbols – with and without error bars - in the lower part of the plot) in km. Solutions are as discussed in text. Note that only the **a** vs. **b** axis solutions are labeled. The corresponding **a** vs. **c** axis solutions fall immediately below the **a** vs. **b** solutions.

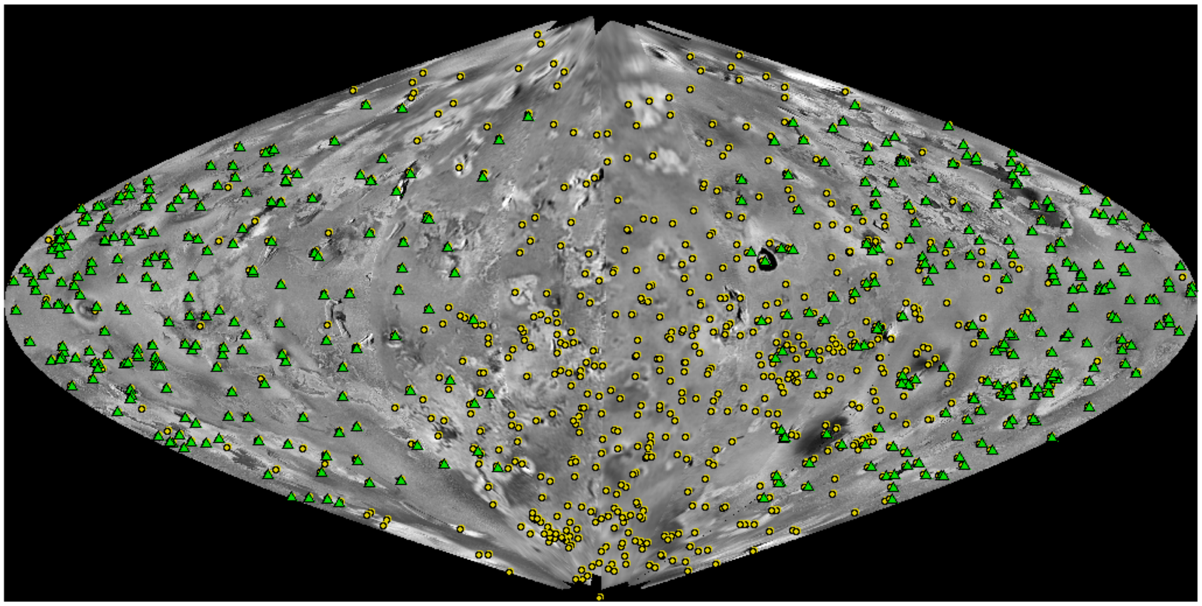

Figure 2: Io Control Network. Triangles indicate control points for which there are measurements on Galileo SSI images (used in both the "all data" and "Galileo data only" solutions). Circles indicate additional control points for which there are Voyager image measurements (also used in the "all data" solution). The background image is a sinusoidal projection of a preliminary uncontrolled USGS mosaic of Io. The sub-Jovian point (and the 0^{o} longitude meridian) lies at the center, 180^{o} longitude is at the right and left edges, and north is up. The lack of Galileo image control point measurements in the center of the sub-Jovian hemisphere is obvious.