RADAR REVEALS TITAN TOPOGRAPHY. R. L. Kirk[1], P. Callahan[2], R. Seu[3], R. D. Lorenz[4], F. Paganelli[2], R. Lopes[2], C. Elachi[2], and the Cassini RADAR Science Team. [1] U. S. Geological Survey, Flagstaff, AZ 86001, U.S.A. (rkirk@usgs.gov), [2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109. U.S.A., [3] Universitá La Sapienza, 00184 Rome, Italy, [4] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, U.S.A.

Introduction: The Cassini Titan RADAR Mapper [1] is a K_u-band (13.78 GHz,λ= 2.17 cm) linear polarized RADAR instrument capable of operating in synthetic aperture (SAR), scatterometer, altimeter and radiometer modes. During the first targeted flyby of Titan on 26 October, 2004 (referred to as Ta) observations were made in all modes [2,3]. Evidence for topographic relief based on the Ta altimetry and SAR data are presented here. Additional SAR and altimetry observations are planned for the T3 encounter on 15 February, 2005, but have not been carried out at this writing. Results from the T3 encounter relevant to topography will be included in our presentation.

Data obtained in the Ta encounter include a SAR image swath extending from 133° W, 32° N through a closest approach of 1174 km to 12° W, 29° N (~100° of arc or ~4500 km), followed by a ~10° (~400 km) long altimetry profile extending from 10° W, 28° N to 1° W, 22° N. These datasets cover 1.1% and 0.015% of Titan's area, respectively. The SAR image reveals a surface of surprising geologic complexity [4], with several distinct classes of features that may be cryovolcanic in origin [5], and dark regions that have been interpreted as "ponds" of (liquid or solid) organic material [6]. The diversity and unfamiliarity of the features seen are such that even qualitative topography can be of aid in their interpretation. Quantitative topographic information will ultimately be needed to address such questions as the rheology and hence composition of cryovolcanic flows. Unfortunately, the Ta SAR and altimetry footprints do not overlap one another, and neither overlaps the currently available, high-resolution images from the Cassini ISS and VIMS instruments.

The T3 SAR strip will extend from 5° N, 125° W to 5° N, 10° W, and thus will cover a substantially larger area than the Ta image. Altimetry profiles will be obtained both before and after SAR imaging. Both datasets lie in areas currently illuminated by the Sun, and high-resolution optical images of parts of both the SAR and altimetry tracks will be obtained during the flyby. In addition, the SAR image will cover part of the 4000-km wide bright region known as Xanadu. Interpretations of this feature, which is visible in Earthbased and HST telescopic images (e.g., [7]) range from a highstanding "continent" to a large impact crater [8]. Topographic data could thus constrain the range of viable interpretations significantly. The SAR swath will also cross areas known to be optically dark.

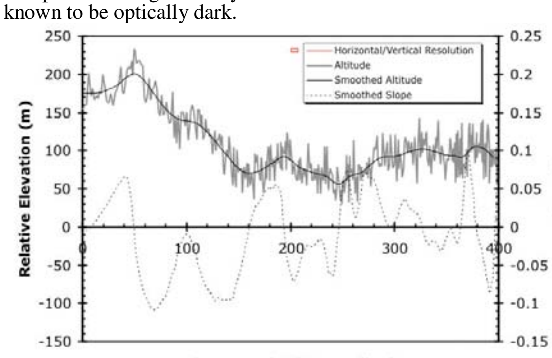

Figure 1. Ta altimetry profile. Raw elevations relative to a 2575-km sphere (gray) have been smoothed (solid black line) by convolution with a Gaussian function with standard deviation 7 points (~7 km). Bidirectional slopes (dotted line) are computed from smoothed elevations. Horizontal resolution is limited to ~25 km and vertical precision of smoothed curve to ~4 m, as shown by small red rectangle.

Altimetry: The Ta altimetry dataset contains, on average, one measurement per km along track, with horizontal resolution limited by the diameter of the beam footprint, which increased from 25 to 40 km during the observation. The nominal vertical precision is 35 m but absolute accuracy is likely to be poorer. Figure 1 shows the elevations (relative to a reference sphere of radius 2575 km) obtained by using a simple thresholding algorithm to detect the echos. The RMS point-to-point variation is ~20 m. The figure also includes a version of the elevation profile smoothed to suppress these variations, and along-track bidirectional slopes computed from the smoothed profile.

Cassini RADAR scatterometry data from the Ta encounter indicate the presence of a radar-dark spot to the northeast of the altimetry track [5, Fig. 1], but neither the scatterometry data nor the low-resolution optical images currently available suggest that the track crosses a major terrain boundary. Until high resolution images of this area are obtained, the significance of the altimetry results can only be discussed in generic terms. The total relief along the ~400-km ground track is only 150 m, and the surface lies within 200 m of the 2575 ± 0.5 km mean radius of Titan estimated from Voyager occultation results [9]. These comparisons should not be over-interpreted because of the small area sampled by the profile, but they suggest that both relative and absolute relief are limited to a few hundred meters. Slopes along track are in the range ±0.1° with a RMS of 0.05°. These values are comparable to regional slopes on the terrestrial planets: Earth, Mars, and Venus all have modal slopes of ~0.05° over 100-km baselines [10]. Large icy satellites undoubtedly constitute a more appropriate population with which to compare Titan, but their regional topography has not been well characterized. Limb profiles indicate that (positive) regional relief of more than a few hundred meters is rare [11], but graben ~1000 m deep and at least 100 km wide are known to be present on Ganymede [12]. Large craters (diameter >30 km and therefore resolvable by the altimeter if they were present on Titan) have depths on the order of 1000 m on Ganymede and Callisto and ~200 m on Europa [13]. No such features are seen in the Ta profile, but the scarcity of even candidate impact craters in the SAR image [14] makes the absence of significant depressions in the much smaller altimetric coverage unsurprising. More localized topographic features with heights from 200 to 1000 m are ubiquitous on Ganymede [15], Europa [16], and Triton [17] but the majority of these features have lateral dimensions of 5 to 20 km so that comparable features on Titan would not be resolved. At least some plateaux on Europa [18] and km-thick putative flows on Ariel [19] are broader than the altimetry beam so that they could have been detected on Titan. Thus, the extremes of relief known on other icy satellites have not been detected on Titan, but there is no reason, given the resolution and limited coverage of the Ta altimetry, to conclude that Titan is significantly smoother than these bodies.

SAR Shape-from-shading: The SAR image potentially provides additional information about topographic relief at much higher resolution and with a direct connection to specific geologic features, though without the geometric rigor of the altimetry. Only a small subset of the features seen exhibit the close pairing of bright and dark areas along a profile in range that is characteristic of topographic shading, rather than (or in addition to) the regional brightness differences that result from non-topographic effects such as textural and compositional variations. Radarclinometry (radar shape-from-shading) can be used to assess the plausibility that such features are truly exhibiting topographic shading, and to estimate their dimensions if so. The results reported here have been derived by a simple, one-dimensional profiling technique in which backscatter values on a profile across a feature are interpreted as slopes toward or away from the spacecraft and are integrated to yield an elevation profile (cf. [20] for a similar approach to analysis of visible images). The features of interest are geometrically simple so that clinometry approaches that yield a topographic model over a two-dimensional region [21] are not essential. The analysis requires a model scattering law. A law of the form $\sigma_0 \propto 1/\sin(i)$ was used, which closely fits the backscatter of uniform plains in the SAR image over a range of incidence angles $5° \le i \le 45°$. The constant of proportionality (i.e., σ_0 at a specific incidence angle i) was chosen independently to give an overall level surface for each feature modeled.

The features having the strongest qualitative appearance of topographic relief are a set of small (5-10 km wide) apparent hills at the extreme eastern end of the SAR strip (Figure 2). Several tens of these features exist, all with bright-dark pairing in the range direction, making it unlikely that these are accidental associations of dark and bright surface spots. This region was imaged at lower incidence angle than the majority of the strip (6°–12° incidence angle, compared to 12°–45°), resulting in greater topographic modulation of the backscatter signal for given slope. Despite the significant backscatter modulation across these features, approaching a factor of 7 between bright and dark sides, the estimated relief is only about 100 m. The inferred slopes are also low and are somewhat asymmetric, reaching 5° on the dark faces but only 3° on the bright sides. This asymmetry could be explained by some combination of intrinsic reflectivity variations, modest departures from the assumed scattering law, the finite resolution (~2 km) of the image in this region, or the slight deviation of the illumination direction from the direction of the profile. Even allowing for these effects, the relief is unlikely to be much more than 100 meters and slopes do not approach the incidence angle, so that the features are not severely distorted by layover.

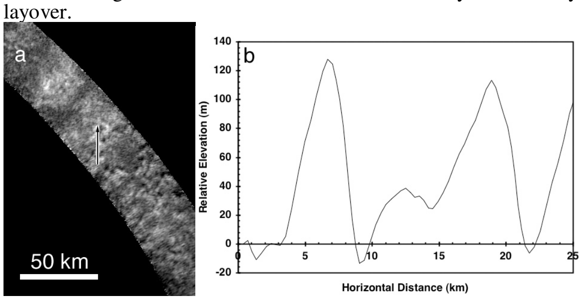

Figure 2. (a) Apparent hills near 11.5°W 31°–35°N. North is approximately to top. (b) Radarclinometric profile at location indicated by arrow in (a).

A more subtle feature that also appears to have positive relief is the 80-km long apparent flow emanating from a 10-km circular feature at 38.5°–41° W, 47° N (Figure 3). This flow has a relatively bright near edge and dark downrange edge, both close to the limit of the image resolution. A topographic profile across the flow indicates that it is 200–300 m high with maximum slopes on the order of 7° on both edges. As reconstructed, the top surface of the flow is relatively flat but tilted ~2°. A more likely interpretation is that the top surface of the flow simply has slightly enhanced backscatter at given incidence angle compared to the sides.

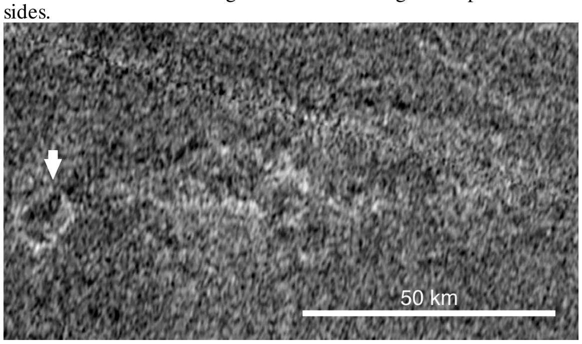

Figure 3. Bright-rimmed circular feature near 41° W, 47° N (arrow) interpreted as caldera, with possible flow extending to east. North at top. Flow thickness from radarclinometry is 200–300 m.

A bright lobate feature extending from 50° W, 52° N to 44° W 47° N that has been interpreted as a cryovolcanic flow (see Fig. 2 of [5]) is a somewhat less secure candidate for radarclinometric modeling. A profile across the easternmost lobe of this feature shows that the backscatter (corrected to constant incidence angle) varies almost linearly from 3 times the brightness of the background plains at the near edge to the background brightness at the far edge. This pattern could plausibly be interpreted as the result of a gradient in composition or texture across the flow, but it could also be interpreted as topographic shading. If the feature is topographic, it is roughly parabolic in cross-section with maximum slopes of ±4° and the height of its 70-km wide eastern extension is 1000 m. This is substantially greater than any other relief identified on Titan, and comparable to the thick flows on Ariel [19].

Other features appear to display topographic shading, but this shading is partially masked by what are clearly intrinsic variations in backscatter properties, making the estimation of relief by radarclinometry impossible. The most intriguing example is a large, quasi-circular feature 180 km in diameter, centered near 50° N, 87° W. This feature resembles steep-sided volcanic domes on Venus in several respects, and has been tentatively interpreted as a cryovolcanic dome or shield [5, Fig. 1]. The margins of the feature are radar-bright, but the brightening is most pronounced on the illuminated side, consistent with the shading that would be seen on a positive relief feature with steep sides and a relatively flat top. As with the lobate flow discussed above, however, we cannot rule out the possibility that the apparent "shading" is merely the result of variations in scattering properties. Alternative explanations for the feature, e.g., that it is a highly modified impact crater, must therefore continue to be entertained.

SAR Geologic Evidence: Some circumstantial evidence of a large-scale slope (downhill to the East) is given by the consistent direction of the flows just discussed and the bright fan features at numerous locations in the eastern half of the SAR strip [22]. All of these features appear to flow in an east to southeast direction, which is the same direction indicated as downhill in the first 100 km of the altimeter track. On the other hand, the interpretation of dark areas as hydrocarbon deposits [6] indicates local topographic depressions but no regional slopes in some areas. If the brighter spots that mottle some of these dark features are islands, relief of at least some tens of meters over a distance of a few kilometers is implied, because the low microwave absorbtivity of candidate infilling materials such as liquid and solid hydrocarbons would make them invisible to the RADAR unless they are this thick.

Comparison with Optical Remote Sensing: Cassini VIMS data appear to show a series of parallel ridges transverse to the direction of solar illumination near 8° N, 144° W [23]. They are >50 km long, with separations of 10–12 km. Photoclinometric modeling yields an amplitude of topography of 600–800 m. Thus these features are slightly larger than those described here, but not surprisingly so given that they occur in a different region of Titan.

Future Prospects: Future Titan flybys, starting with T3, will yield additional altimetric profiles and SAR images that are likely to contain additional examples of topographic shading. If complex features with uniform scattering properties are imaged, their shapes will be reconstructed by two-dimensional radarclinometry [21]. The acquisition of overlapping observations of various types in the future will provide even more interesting possibilities for topographic analysis. Beginning in 2007, the RADAR instrument will acquire SAR images that overlap previously obtained swaths. We are adapting the radarstereogrammetric techniques and software previously developed for the Magellan mission [24] and will use them to map the SAR overlaps. Overlapping SAR images will also provide information to separate topographic shading from intrinsic variations in backscatter. SAR and optical images, including those to be obtained in the T3 flyby, will also be obtained with effective stereo convergence and can in principle be analyzed with the same software. The key question—to be answered in the immediate future—is whether any common features will be identifiable in the two very disparate types of images. Finally, both SAR and optical images will provide much-needed geologic context for interpreting the altimetric profiles.

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