TOPOGRAPHIC MAPPING OF TITAN: COMPLETION OF A GLOBAL RADARGRAMMETRIC CONTROL NETWORK OPENS THE FLOODGATES FOR STEREO DTM PRODUCTION. R.L. Kirk[1], E. Howington-Kraus[1], B. Redding[1], O. Aharonson[2], B.G. Bills[3], A.G. Hayes[4], L. Iess[5], R.M.C. Lopes[3], R.D. Lorenz[6], A. Lucas[2], J.I. Lunine[4], R. Meriggiola[5], K.L. Mitchell[3], C.D. Neish[7], J. Radebaugh[8], B.W. Stiles[3], E.R. Stofan[9], S.D. Wall[3], C.A. Wood[10]. [1]Astrogeology Science Center, USGS, 2255 N. Gemini Dr., Flagstaff AZ 86001 (rkirk@usgs.gov), [2]Caltech, Pasadena, CA 91125, [3]Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, [4]Cornell Univ., Ithaca, NY 14853, [5]DIMA, Univ. La Sapienza, Roma, Italy, [6]Johns Hopkins Univ. Applied Physics Lab, Laurel, MD 20723, [7]NASA Goddard Space Flight Center, Greenbelt, MD, 20771, [8]Brigham Young Univ., Provo, UT 84602, [9]Proxemy Research, Gaithersburg, MD 20882, [10]Wheeling Jesuit Univ., Wheeling, WV 26003.

Introduction: This abstract is one in a series of reports on our efforts to map the topography of Saturn's satellite Titan at resolutions as high as a few kilometres [1–4], based on radargrammetric analysis of stereo image pairs from the Cassini RADAR [5]. This instrument uses microwaves with 2.2-cm λ to form synthetic aperture (SAR) images with 350-1400 m resolution, as well as obtaining radiometric, scatterometric, and altimetric data. To date, the instrument has obtained full resolution SAR swaths useful for stereomapping on 33 Titan flybys between Ta and T77. These images form 110 possible stereopairs, covering a combined area greater than 2% of Titan.

In this abstract, we report on substantial recent progress in controlling the majority of the available SAR images and provide a first look at the most recent digital topographic models (DTMs), which are being produced rapidly now that the control is complete.

Technical approach: To perform stereo analysis of Cassini SAR data, we use the software package SOCET SET (® BAE Systems) [6] for controlling sets of images so topographic results are consistent with one another and with *priori* data such as SAR topography elevations; creation of DTMs with powerful, highly adjustable image matching algorithms; and manual editing or even creation of DTMs. To apply these functions to Cassini data, we used the SOCET Developer's Toolkit to implement "sensor model" software that computes the transformations between pixel coordinates and ground coordinates by rigorous modeling of the physical process of SAR image formation [7]. The USGS in-house cartographic software package ISIS [8] is used to prepare the images and metadata for ingestion into SOCET SET.

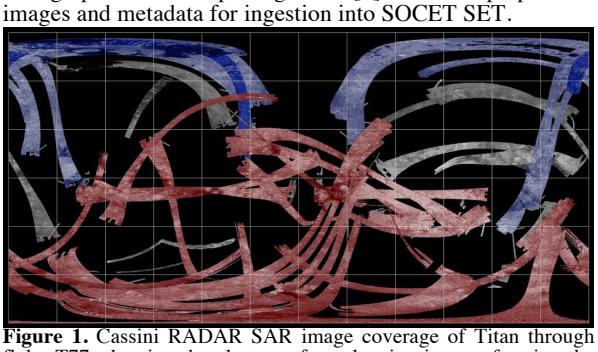

Figure 1. Cassini RADAR SAR image coverage of Titan through flyby T77, showing the clusters of overlapping images forming the northern (blue) and southern (red) control networks. A few images (gray) have yet to be connected to either network. Simple Cylindrical projection with north at top, centered on 180°W, with 30° grid.

Geodetic Control: Our first Titan DTM [2] was uncontrolled, i.e., the spacecraft trajectory as reconstructed by the Cassini mission was used. Trajectory errors propagate into both horizontal and vertical errors in DTM coordinates. Later DTMs [3] were individually controlled by bundle adjustment based on image-to-image tiepoint measurement and ground control points with elevations constrained by SARTopo data [9]. The control process can be extended to more than two images at a time. In [10], we performed a joint bundle adjustment of all 6 images in the north polar area of lakes and seas (shown in light blue in Figure 1), based on 166 tiepoints (66 with ground control). A total of 14 controlled DTMs of the circumpolar area (and one at the southern end of T25-28) were collected from the adjusted images and found to be consistent at a level suggesting that the precision of matching the images is about 1.4 pixel or 250 m. This yields vertical precisions in the range from 50 m for DTMs with opposite-side stereo geometry to ~300 m for same-side imaging.

Over the last two years, we have produced a few DTMs from individually controlled stereopairs and have added the T64 image (Fig. 1, dark blue) to the north polar control network [4] but our primary effort has been the construction of a similar network covering the southern hemisphere and mid latitudes to about 30°N (Fig. 1, red). This network includes images from 25 flybys between T7 and T71. The control solution, incorporating 632 tiepoints (376 with ground control), had a RMS residual of 270 m, almost identical to that for the northern network.

At present, the northern and southern networks are independent. Our goal is to add the few unattached images (Fig. 1, gray) to one or both networks and attempt a global solution. The next few flybys (T82–86) will greatly strengthen the connection between the northern and southern clusters once their processing is finalized.

Titan rotation modeling: Tiepoints between images are the basic input for modeling of Titan's rotation, as well as for controlling DTMs. Past studies have relied on points measured by comparing images side-by-side and have concluded [11] that the random measurement errors are ~1 km at best and often significantly worse. In addition, the most recent analyses include data only through T61 [12]. Our control points described above extend to T71 and achieve <300 m random error as a result of the superior measurement tools available in SOCET SET and the use of the control adjustment process to "weed out" erroneous measures. These measurements are being incorporated in the modeling [13] with the expectation that they will improve our knowledge of precession, libration, nutation, and possible nonsynchronous rotation, and thereby shed light on Titan's interior structure. A better rotation model, valid over the whole Cassini mission, could also be used to improve the georeferencing of the SAR images. If this comes to pass, our control network calculations would have to be repeated, but the controlled DTMs would not have to be regenerated because SOCET SET provides effective tools for transforming DTM data between coordinate systems.

Exploring Titan's "Antarctic": With the images now controlled, DTMs can be produced in as little as a few days; we have generated ~20 in November-December 2012. Our recent mapping has focused largely on the south polar region, which was imaged extensively during Cassini's Equinox mission. Figure 2 shows color-coded topography from 9 new DTMs collected in November 2012 (plus the three-image DTM of Ontario Lacus from [10]). Though only a subset of the pairs in this area has been mapped so far, DTM coverage is approaching that for the north pole. Some initial results are as follows:

- Several radar-dark, ovoid areas, interpreted as dry (with the exception of Ontario Lacus) sea basins [14] are confirmed to be topographic depressions with depths of hundreds of meters or more. Channels and steep shoreline features are observed near several of these basins.
- An especially deep depression near 75°S, 270°W is not radar-dark and therefore not prominent in the images.

SARTopo shows a comparable depression (or a southward extension of this one) at around 84°S.

- Bright, "lacy" terrain north of the dark basin at 65°S, 345–360°W, initially interpreted as a possible swamp, consists of steep outcrops of bright material up to 1000 m high, many with basal debris aprons. This material seems to form the boundary between two of the dark basins.
- As in the northern hemisphere, the region of smaller, steep-sided depressions (some of which contained transient lakes [15]) near 90°W is elevated hundreds of meters above the major basins.
- Steep-sided depressions near 80°S, 240°W resemble some northern-hemisphere lakes in planform, but their rims are elevated and in places heavily eroded, and their floors are comparable in elevation to the surrounding plains. It therefore appears the surface was raised by deposition or upwarp before the depressions formed.

Mid-Latitude Results and Prospects: Stereo overlaps in the southern network cover diverse terrains. We have produced the first stereo DTM of a highly modified impact crater (Soi, 78 km diameter), confirming a preliminary depth estimate from SARTopo [16] but with substantially reduced uncertainty. Stereo coverage is in hand for two other likely craters (68-km Guabonito and a 35-km circular structure in Shikoku Facula) and a 139-km ring is covered by T84, which is awaiting final processing. Other targets of interest include multiple samples of the equatorial dune fields, isolated mountain ranges, Xanadu, and numerous areas for which cryovolcanic activity has been suggested.

As we investigate these targets, it may be worthwhile in a few cases to remake past DTMs. As noted above, tools exist to transform older DTMs so they are consistent with the new control network, but a few of our earlier DTMs were unrealistically "tilted." The hypothesis [4] that this resulted from using a mixture of "early" (Ta-T30) and "late" (T39 on) images processed in two different coordinate systems has been confirmed now that the early images have been reprocessed in the latter system. What is more, our experiments show that the artificial tilt interfered with stereo matching and that substantially more detailed DTMs, e.g., resolving individual mountains within Xanadu, can now be made.

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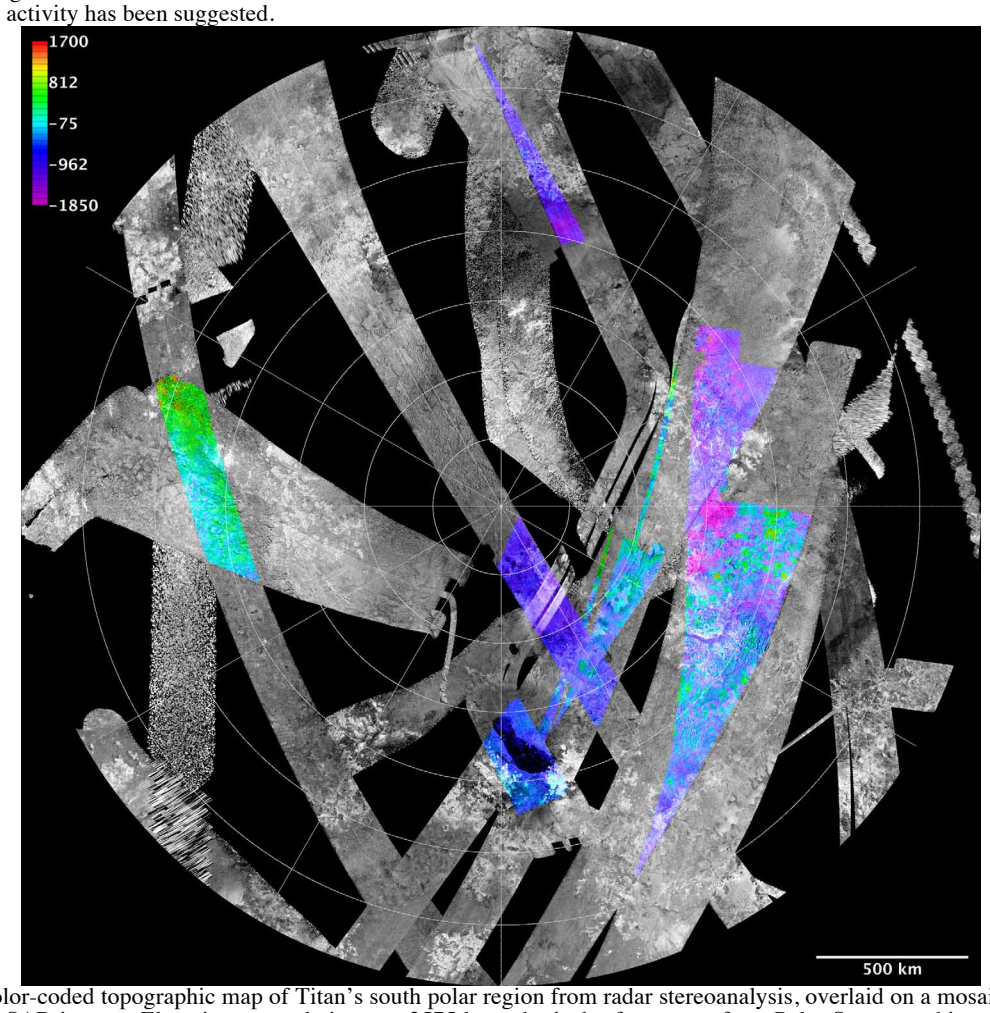

Figure 2. Color-coded topographic map of Titan's south polar region from radar stereoanalysis, overlaid on a mosaic of SAR and high altitude SAR images. Elevations are relative to a 2575 km spherical reference surface. Polar Stereographic projection, -90° to -60° latitude, 0° longitude at top, with 5° latitude by 30° longitude grid.