GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L24S02, doi:10.1029/2007GL030865, 2007

Structure of Titan's mid-range magnetic tail: Cassini magnetometer observations during the T9 flyby

C. Bertucci,[1] F. M. Neubauer,[2] K. Szego,[3] J.-E. Wahlund,[4] A. J. Coates,[5] M. K. Dougherty,[1] D. T. Young,[6] and W. S. Kurth[7]

Received 7 June 2007; revised 20 August 2007; accepted 24 September 2007; published 6 November 2007.

[1] We analyze the magnetic structure of Titan's mid-range magnetic tail (5–6 Titan radii downstream from the moon) during Cassini's T9 flyby. Cassini magnetometer (MAG) measurements reveal a well-defined, induced magnetic tail consisting of two lobes and a distinct central current sheet. MAG observations also indicate that Saturn's background magnetic field is close to the moon's orbital plane and that the magnetospheric flow has a significant component in the Saturn-Titan direction. The analysis of MAG data in a coordinate system based on the orientation of the background magnetic field and an estimation of the incoming flow direction suggests that Titan's magnetic tail is extremely asymmetric. An important source of these asymmetries is the connection of the inbound tail lobe and the outbound tail lobe to the dayside and nightside hemispheres of Titan, respectively. Another source could be the perturbations generated by changes in the upstream conditions. **Citation:** Bertucci, C., F. M. Neubauer, K. Szego, J.-E. Wahlund, A. J. Coates, M. K. Dougherty, D. T. Young, and W. S. Kurth (2007), Structure of Titan's mid-range magnetic tail: Cassini magnetometer observations during the T9 flyby, *Geophys. Res. Lett.*, *34*, L24S02, doi:10.1029/2007GL030865.

1. Introduction

[2] Since the arrival of Voyager 1 at the Kronian system in 1980, in situ magnetometer measurements suggested that if there is an internal field at Titan, it is not sufficient to generate an intrinsic magnetosphere [*Neubauer et al.*, 1984]. As Voyager's plasma measurements revealed, the structure of Titan's magnetosphere resembles an 'induced' magnetosphere generated by the pile up and draping of the external magnetic field [*Ness et al.*, 1982] around a conducting obstacle represented by its ionosphere and the mass loading by ions of exospheric origin [*Hartle et al.*, 1982]. The simplest description of such a magnetosphere dates back to *Alfvén* [1957] who explained the formation of comet plasma tails in terms of the draping of interplanetary magnetic field lines around the comet's coma. As a consequence of the currents driven in the upper ionosphere by the modified Kronian convection electric field and the combination of massloading by pick-up ions and the effects of elastic collisions with exospheric particles, the magnetic field lines pile up in front of Titan and stretch along the direction of the incoming flow leading to an 'induced' magnetic tail. This tail consists of two lobes of opposite polarity (parallel and anti-parallel to the incoming flow) which are separated by a current sheet with tangential discontinuity properties. This picture was confirmed by Cassini magnetometer [*Dougherty et al.*, 2004] measurements from the first flyby [*Backes et al.*, 2005; *Neubauer et al.*, 2006].

[3] T9 is Cassini's only encounter with Titan's mid-range magnetic tail thus far. It took place on December 26, 2005, in the pre-dawn sector (0306 hours of Saturn Local Time, SLT) of Saturn's magnetosphere. At the time of the encounter, the spacecraft was on the outbound leg of the Rev 19 orbit, with an inclination of 0.12° (i.e., northwards) with respect to Titan's orbital plane. Cassini's closest approach occurred at 1858:57 at an altitude of 10409.6 km (4.04 R_T; R_T = Titan radius = 2575 km) while the spacecraft was still south (108.7 km) of Titan's orbital plane. Because of the geometry of the encounter, Cassini explores the magnetic tail sector corresponding to Titan's dayside hemisphere on the flyby's inbound leg, whereas the tail sector downstream from the nightside hemisphere is crossed on the outbound leg.

[4] This flyby is extremely important because it provides constraints on Titan's magnetic tail size and shape, as previous Cassini flybys occurred at altitudes below 1.4 R_T. At unmagnetized objects, the outer edge of the magnetic tail - the magnetic tail boundary or magnetic pileup boundary [e.g., *Bertucci et al.*, 2005] - encloses the region where most of the transfer of linear momentum from the incoming flow to the planetary ions occurs [*Saunders and Russell*, 1986; *Dubinin et al.*, 2006]. Thus, determining the spatial extent of Titan's magnetic tail is essential in order to measure the escaping flux of plasma.

[5] In this article, we analyze the structure and variability of Titan's magnetic tail during the T9 flyby from Cassini MAG data and supported by Cassini Radio and Plasma Wave Science Langmuir Probe (RPWS/LP), and Cassini's Electron Spectrometer (CAPS/ELS) data [*Gurnett et al.*, 2004; *Young et al.*, 2004]. We will begin by studying the magnetosphere's orientation and structure assuming steady state conditions for the external plasma and will then move

[1]Space and Atmospheric Physics Group, Imperial College London, London, UK.
[2]Institute of Geophysics and Meteorology, University of Cologne, Cologne, Germany.
[3]Research Institute for Particle and Nuclear Physics, Central Research Institute for Physics, Hungarian Academy of Sciences, Budapest, Hungary.
[4]Swedish Institute of Space Physics, Uppsala, Sweden.
[5]Mullard Space Science Laboratory, University College London, Dorking, UK.
[6]Southwest Research Institute, San Antonio, Texas, USA.
[7]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA.

0094-8276/07/2007GL030865

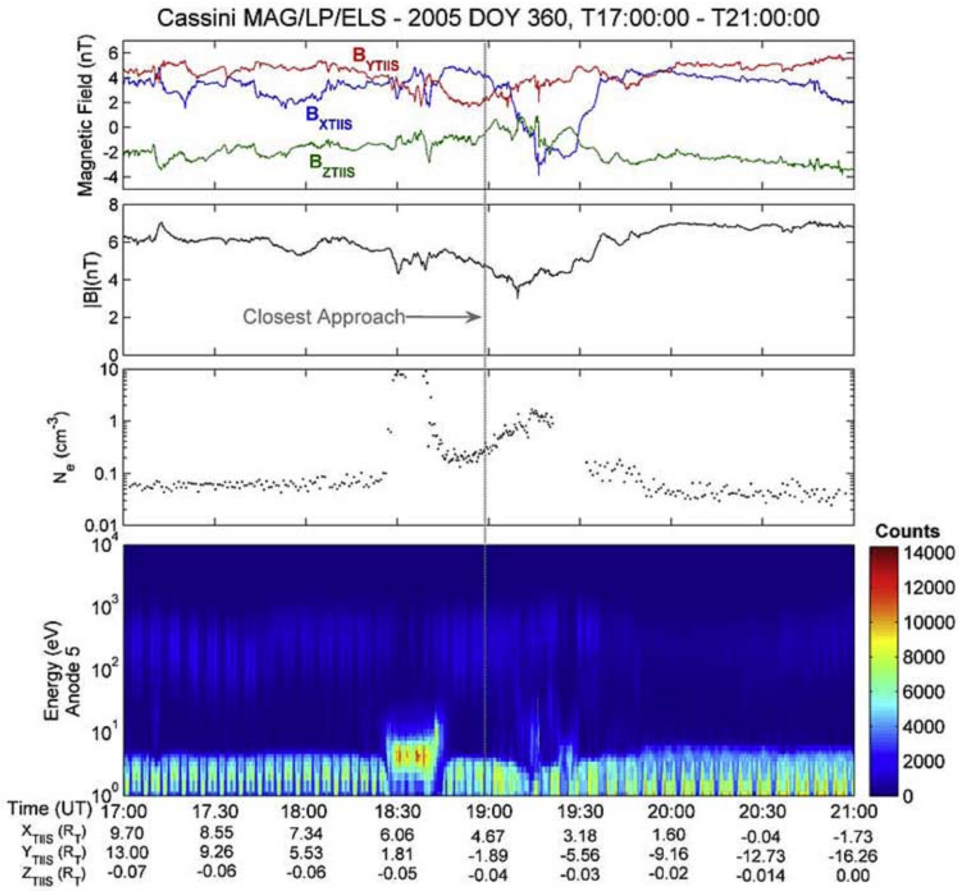

Figure 1. From the top: Magnetic field vector in TIIS coordinates and magnitude (Cassini MAG), electron density from RPWS/LP, electron counts (anode 5) for energies between 1eV and 10 keV from CAPS/ELS, and spacecraft position during the T9 flyby (December 26, 2005) for distances below ~16 R_T from Titan. Closest approach time is indicated with a grey line. Please note that there is no RPWS/LP data for the intervals 1832–1838 and 1921–1932 UT due to a change of mode of the instrument.

on to discuss the validity of this approximation and explore other interpretations.

2. Observations and Results

[6] Figure 1 shows the magnetic field vector data in Titan ionospheric interaction (TIIS) coordinates, the magnetic field magnitude, the electron density (from RPWS/LP) and the electron energy spectrum (from CAPS/ELS) for energies between 1 eV and 1 keV, between 1700:00 and 2100:00 (within ~16 R_T from Titan). In the TIIS coordinate system the x axis points along the nominal corotation direction, the y axis points towards Saturn, and the z axis completes the right-hand triad.

[7] In the hours leading to the encounter, $B_{XTIIS} > 0$ and $B_{YTIIS} > 0$, indicating that, as occurred in most of the encounters so far, Titan is located below Saturn's magnetodisk [*Arridge et al.*, 2007; C. Bertucci et al., manuscript in preparation, 2007]. At 1830, B_{XTIIS} becomes the dominant component. This signature, typical of draping, is accompanied by the entry into a region dominated by dense (up to 10 cm^{-3}), cold, and heavy (16–19 and 28–40 amu ions [*Szego et al.*, 2007]) plasma from ionospheric origin, as ELS detects ~20 eV photoelectrons [*Coates et al.*, 2007]. At 1840, CAPS and LP data suggest that Cassini exited this region, whereas MAG data clearly reveals tail lobe fields. A few minutes after closest approach (around 1906) B_{XTIIS} displays a sudden and strong change compatible with the crossing of the tail's polarity reversal layer. This signature is immediately followed by a minimum in the magnetic field magnitude (3 nT at 1909:31). Then, B_{XTIIS} remains negative until ~1935. During that interval, CAPS and LP data reveal a second region populated with cold plasma from Titan but with a different composition (1–2 amu ions according to *Szego et al.* [2007]).

[8] In order to identify the region where Saturn's magnetic field is perturbed by the presence of Titan, we analyzed MAG measurements in a coordinate system that takes into account the natural symmetries of an induced magnetosphere. In the ideal scenario of a steady external plasma flow with velocity **V** carrying a field **B** perpendicular to it, and assuming an ionosphere-atmosphere system symmetric with respect to **V**, the three-dimensional magnetic field structure resulting from the magnetic field line draping will be symmetrical with respect to the plane generated by the vectors **V** and **V** × **B**. Thus, a natural coordinate system to describe this structure will be that formed by the unit vectors: **b**, **b** × **v**, and **v**, where **b** = **B**/|**B**|

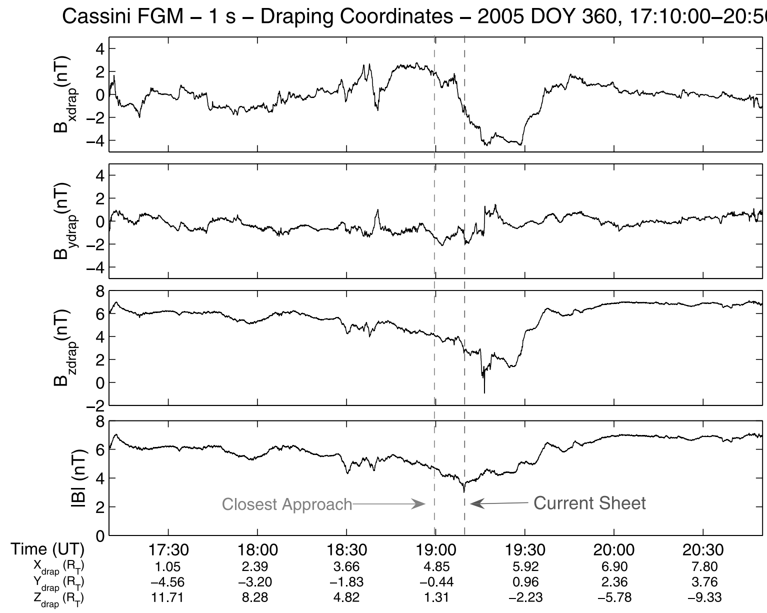

Figure 2. Magnetic field and spacecraft position in draping coordinates (see text for details). Light grey and grey dash lines indicate the time of closest approach and the time of crossing of Titan's current sheet (this is based in assumptions described in the text).

and $\mathbf{v} = \mathbf{V}/|\mathbf{V}|$. From now on, this system will be referred to as the 'draping' coordinate system and represented by the subscript "DRAP".

[9] The background magnetic field **B** = (3.68, 4.69, −2.36) nT was estimated from the average of the fields in two regions with stable values near the encounter (1644:22–1754:54 and 1941:51–2050:07). In absence of accurate measurements of **V**, an estimation of its direction can be found approximately by assuming that Cassini crossed the center of Titan's tail when the magnetic field was at its lowest value. The location of the spacecraft in TIIS coordinates is (4.21, −3.06, −0.04) R_T, which gives a unit vector **v** = (0.81, −0.59, −0.01). This indicates that the apparent central axis of the tail points 36.05° away from the ideal corotation towards Saturn, on the (X_{TIIS}, Y_{TIIS}) plane. Interestingly, the angle that this direction makes with respect to the mean field is 87.94°, favoring the use of the draping coordinate system. With these estimations, the draping coordinate system is then defined by the following unit vectors: Z_{DRAP} = **b** = (0.57, 0.73, −0.37), Y_{DRAP} = **b** × **v** = (−0.22, −0.29, −0.93), and X_{DRAP} = (**b** × **v**) × **b** = (0.79, −0.62, 0.01). Here, we use (**b** × **v**) × **b** instead of **v** since the latter is not exactly perpendicular to **b**.

[10] Figure 2 shows MAG data in DRAP coordinates. In this system, the change in the sign of B_{XDRAP} indicating the crossing of the magnetic tail now coincides with the minimum in |**B**|. We performed a minimum variance analysis [*Sonnerup and Scheible*, 1998] across this signature in order to find the normal vector to the tail's current sheet. For the interval 1906–1915, we obtain a well defined (λ_2/λ_3 = 10.1) normal vector (0.57, 0.73, −0.37) that lies very close to the local mean magnetic field (8.3° ± 2.7°) and close to the background magnetic field (~29°). However, in opposition to the idea that this boundary is a tangential discontinuity, the normal component of the magnetic field is comparable to the mean magnetic field ($|B_n|/|\mathbf{B}|$ = 0.99).

[11] Another important piece of information is the extent of the magnetic tail along the trajectory. On the inbound leg, the entry into the induced magnetosphere seems to occur a few minutes before 1830 where B_{XDRAP} becomes positive. This signature is close to the cooling of the electron fluxes observed by CAPS/ELS around ~1825 [*Szego et al.*, 2007]. The distance to the X_{DRAP} axis is 5.5 R_T. On the outbound leg, the outer edge of the magnetic tail is likely crossed around 1936. This signature coincides with the cooling of electrons detected by ELS around 1930. The distance to the X_{DRAP} axis is 3.19 R_T. The location of the magnetic tail boundary crossings on the Y_{DRAP}, Z_{DRAP} plane make angles with respect to the Z_{DRAP} axis which are very similar (20.7° for the inbound leg and 22.5° for the outbound leg).

3. Discussion and Conclusions

[12] The observations by Cassini MAG during T9 suggest the crossing of Titan's magnetic tail. Assuming a steady state regime and that Cassini crosses the center of Titan's tail when the magnetic field displays a minimum, the orientation of the tail is compatible with magnetodisk-type of field with a flow velocity that has a non-zero component along the Saturn-Titan direction. This is supported by the detection of a well-defined current sheet, whose normal is close to the background magnetic field. At both sides of this discontinuity, signatures compatible with the crossing of the two tail lobes are also quite clear in the data.

[13] The magnetic field observations show quite different properties during the inbound and outbound legs. First, the increase in the draping of the magnetic field – indicative of the entry into the tail lobes – is sharper on the outbound leg of the flyby. Second, the inbound lobe seems to be broader and displays more pileup than the outbound one. It is reasonable to postulate that these asymmetries are in part generated by the location of the subsolar point with respect

to the direction of the incoming flow. The angle between the subsolar direction and the flow as deduced from MAG measurements is 80.8°. The extrapolation of the magnetic field in the inbound lobe intersects Titan's ionosphere [*Wei et al.*, 2007], suggesting that the ionospheric plasma detected between 1830 and 1840 is actually escaping along field lines which have penetrated the ionosphere of Titan. The field line penetration seems to be quite efficient as the direction of the flow (deduced from MAG) almost coincides with the terminator, where the ionosphere is not well developed. On the dayside hemisphere, a more efficient massloading could account for the observed extent of the lobe and the more pronounced pileup in the inbound leg. On the other hand, the highly draped fields in the outbound lobe are probably less massloaded and connected to deeper layers in Titan's nightside atmosphere (no photoelectron signature is observed).

[14] The comparison between MAG, LP and ELS data however yields some unresolved issues. The first such issue is the detection of cold plasma from Titan in only a few intervals (from 1827 to 1842, and around 1914 and 1920) inside Titan's magnetotail. A second point is the presence of magnetospheric (∼100 eV–1 keV) electrons throughout the interaction region (although fewer counts are observed in the intervals 1827–1840 and 1922–1930, where cold plasma from Titan is detected). These observations indicate that there is either a complex steady state situation where the asymmetries in the photo-production may lead to a magnetotail with a heavy ion wake and a light ion wake [see *Modolo et al.*, 2007a, 2007b], or, a more unlikely scenario, a transient situation due to the variability in Titan's plasma environment (C. Bertucci et al., manuscript in preparation, 2007). With regards to the latter possibility, however, it is important to mention that CAPS data reveal significant changes in the direction of the magnetospheric flow during the encounter [*Szego et al.*, 2007]. These changes may have caused the re-orientation of the induced magnetosphere in such a way that Cassini may even have left Titan's tail during the flyby. Although MAG data do not show evidence of such excursions (magnetic field variations around but outside the induced magnetosphere of Titan are only moderate), the variability of the plasma parameters near Titan could have changed significantly during the T9 flyby.

[15] In summary, Cassini plasma measurements during T9 revealed that Titan's induced magnetosphere is a complex system in which both the difference between the EUV flux and the incoming flow direction and the variability of Saturn's magnetosphere play important roles. Unfortunately, Cassini will not perform any additional mid-range tail flybys during the remaining primary mission. Hopefully, as the mission progresses, we will be able to characterize the variability in the properties of the incident plasma as a function of Saturn Local Time and its impact on the structure of Titan's induced magnetosphere.

[16] **Acknowledgments.** CB was supported by a STFC Postdoctoral Fellowship at Imperial College London. MKD was supported by a STFC Senior Research Fellowship at Imperial College London. KSz acknowledges the support of OTKA grant K-62617.

References

Alfvén, H. (1957), On the theory of comet tails, *Tellus*, *9*, 92–103.

Arridge, C. S., C. T. Russell, K. K. Khurana, N. Achilleos, N. André, A. M. Rymer, M. K. Dougherty, and A. J. Coates (2007), Mass of Saturn's magnetodisc: Cassini observations, *Geophys. Res. Lett.*, *34*, L09108, doi:10.1029/2006GL028921.

Backes, H., et al. (2005), Titan's magnetic field signature during the first Cassini encounter, *Science*, *308*(5724), 992–995.

Bertucci, C., C. Mazelle, M. H. Acuña, C. T. Russell, and J. A. Slavin (2005), Structure of the magnetic pileup boundary at Mars and Venus, *J. Geophys. Res.*, *110*, A01209, doi:10.1029/2004JA010592.

Coates, A. J., F. J. Crary, D. T. Young, K. Szego, C. S. Arridge, Z. Bebesi, E. C. Sittler Jr., R. E. Hartle, and T. W. Hill (2007), Ionospheric electrons in Titan's tail: Plasma structure during the Cassini T9 encounter, *Geophys. Res. Lett.*, *34*, L24S05, doi:10.1029/2007GL030919.

Dougherty, M. K., et al. (2004), The Cassini magnetic field investigation, *Space Sci. Rev.*, *114*(1–4), 331–383.

Dubinin, E., M. Fränz, J. Woch, E. Roussos, S. Barabash, R. Lundin, J. D. Winningham, R. A. Frahm, and M. Acuña (2006), Plasma morphology at Mars: Aspera-3 observations, *Space Sci. Rev.*, *126*(1–4), 209–238, doi:10.1007/s11214-006-9039-4.

Gurnett, D. A., et al. (2004), The Cassini radio and plasma wave investigation, *Space Sci. Rev.*, *114*(1–4), 395–463.

Hartle, R. E., E. C. Sittler, K. W. Ogilvie, J. D. Scudder, A. J. Lazarus, and S. K. Atreya (1982), Titan's ion exosphere observed from Voyager 1, *J. Geophys. Res.*, *87*, 1383–1394.

Modolo, R., J.-E. Wahlund, R. Bolström, P. Canu, W. S. Kurth, D. Gurnett, G. R. Lewis, and A. J. Coates (2007a), Far plasma wake of Titan from the RPWS observations: A case study, *Geophys. Res. Lett.*, *34*, L24S04, doi:10.1029/2007GL030482.

Modolo, R., G. M. Chanteur, J.-E. Wahlund, P. Canu, W. S. Kurth, D. Gurnett, A. P. Matthews, and C. Bertucci (2007b), Plasma environment in the wake of Titan from hybrid simulation: A case study, *Geophys. Res. Lett.*, *34*, L24S07, doi:10.1029/2007GL030489.

Ness, N. F., M. H. Acuña, and K. W. Behannon (1982), The induced magnetosphere of Titan, *J. Geophys. Res.*, *87*, 1369–1381.

Neubauer, F., D. A. Gurnett, J. D. Scudder, and R. E. Hartle (1984), Titan's magnetospheric interaction, in *Saturn*, edited by T. Gehrels and M. S. Matthews, pp. 760–787, Univ. of Ariz. Press, Tucson.

Neubauer, F. M., et al. (2006), Titan's near magnetotail from magnetic field and electron plasma observations and modeling: Cassini flybys TA, TB, and T3, *J. Geophys. Res.*, *111*, A10220, doi:10.1029/2006JA011676.

Saunders, M. A., and C. T. Russell (1986), Average dimension and magnetic structure of the distant Venus magnetotail, *J. Geophys. Res.*, *95*, 5589–5604.

Sonnerup, B. U. Ö., and M. Scheible (1998), Minimum and maximum variance analysis, in *Analysis Methods for Multi-Spacecraft Data*, *ISSI Sci. Rep.*, vol. SR-001, edited by G. Paschmann and P. W. Daly, pp. 185–215, ESA Publ., Noordwijk, Netherlands.

Szego, K., Z. Bebesi, C. Bertucci, A. J. Coates, F. Crary, G. Erdos, R. Hartle, E. C. Sittler Jr., and D. T. Young (2007), Charged particle environment of Titan during the T9 flyby, *Geophys. Res. Lett.*, *34*, L24S03, doi:10.1029/2007GL030677.

Wei, H. Y., C. T. Russell, J.-E. Wahlund, M. K. Dougherty, C. Bertucci, R. Modolo, Y. J. Ma, and F. M. Neubauer (2007), Cold ionospheric plasma in Titan's magnetotail, *Geophys. Res. Lett.*, *34*, L24S06, doi:10.1029/2007GL030701.

Young, D. T., et al. (2004), Cassini plasma spectrometer investigation, *Space Sci. Rev.*, *114*(1–4), 1–112.

C. Bertucci and M. K. Dougherty, Space and Atmospheric Physics Group, Imperial College London, Exhibition Road, London SW7 2BZ, UK. (c.bertucci@imperial.ac.uk)

A. J. Coates, Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK.

W. S. Kurth, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA.

F. M. Neubauer, Institute of Geophysics and Meteorology, Universität zu Köln, Albertus-Magnus-Platz, D-50923 Köln, Germany.

K. Szego, RMKI-KFKI, P.O. Box 49, H-1525 Budapest, Hungary.

J.-E. Wahlund, Swedish Institute of Space Physics, Uppsala Division, Box 537, SE-75121 Uppsala, Sweden.

D. T. Young, Southwest Research Institute, 6220 Culbra Road, P.O. Drawer 28510, San Antonio, TX 78228–0510, USA.