

A 2-dimensional Data Detrending Technique for Equatorial Plasma Bubble Studies Using GOLD Far Ultraviolet Observations

Rezy Pradipta¹, Chaosong Huang², and Keith M. Groves²

¹Boston College

²Air Force Research Laboratory

March 18, 2024

1 A 2-dimensional Data Detrending Technique for
2 Equatorial Plasma Bubble Studies Using GOLD Far
3 Ultraviolet Observations

Rezy Pradipta¹, Chaosong Huang², and Keith M. Groves¹

Corresponding author: Rezy Pradipta, Institute for Scientific Research, Boston College,
140 Commonwealth Avenue, Chestnut Hill, MA 02467, USA (rezy.pradipta@bc.edu)

The views expressed are those of the authors and do not necessarily reflect the official policy or position of the Department of the Air Force, the Department of Defense, or the United States government. Approved for public release; distribution is unlimited. Public Affairs release approval AFRL-2023-3729.

¹Institute for Scientific Research, Boston
College, Chestnut Hill, Massachusetts, USA

²Air Force Research Laboratory, Kirtland
AFB, Albuquerque, New Mexico, USA

Key Points.

- A 2-dimensional data detrending method based on mechanical analogy of rolling a spherical ball on rough and uneven surface is formulated
- The data detrending method may be effective for revealing large-scale equatorial plasma bubble structures in 135.6 nm GOLD observation data
- Enhanced equatorial plasma bubble structures in nighttime GOLD images may be useful for development of more advanced practical applications

4 **Abstract.** We formulate a numerical data detrending technique that can
 5 be used to help reveal large-scale equatorial plasma bubble (EPB) structures
 6 in 2-dimensional data from the Global-scale Observations of the Limb and
 7 Disk (GOLD) mission. This GOLD data detrending technique is inspired by
 8 and is a generalization of a previous rolling-barrel data detrending method
 9 for 1-dimensional total electron content (TEC) observations on individual
 10 global positioning system (GPS) satellite passes. This 2-dimensional GOLD
 11 data detrending technique treats the observed 135.6 nm radiance as a func-
 12 tion of longitude and latitude as an uneven terrain, where EPBs appear as
 13 deep but narrow elongated valleys. The unperturbed background radiance
 14 is inferred by rolling a ball on the 2-dimensional terrain to skip over the EPB
 15 valleys. The two degrees-of-freedom possessed by the rolling ball allow it to
 16 smoothly trace the edges of EPB depletions, without falling into the deep
 17 valleys. Surface interpolation of radiance values at the ball's contact points
 18 onto the whole domain produces the baseline radiance. Subtracting the base-
 19 line from the original radiance data yields the net detrended radiance. As
 20 a result of the detrending, sharper contrast is present between EPB deple-

21 tions and the ambient surroundings. As such, this new 2-dimensional GOLD
22 data detrending may potentially open the door to the development of other
23 more advanced techniques for automated EPB detection and tracking, or data
24 assimilation into low-latitude space domain awareness (SDA) information
25 ecosystems.

1. Introduction

26 In the present paper, we introduce a new numerical data detrending technique that
27 can be applied to the analysis of 2-dimensional nighttime airglow data from the Na-
28 tional Aeronautics and Space Administration (NASA) Global-scale Observations of the
29 Limb and Disk (GOLD) mission [e.g. *Eastes et al.*, 2017, 2019, 2020]. The formulation
30 of this GOLD data detrending technique was motivated by the need to reliably identify
31 and track dark bands (depletions) associated with equatorial plasma bubbles (EPBs) in
32 the nighttime GOLD observations [e.g. *Karan et al.*, 2020, 2023; *Martinis et al.*, 2020;
33 *Rodriguez-Zuluaga et al.*, 2021; *Sousasantos et al.*, 2023]. Although the EPB-associated
34 depletions are often already visible in the original GOLD images, a proper data detrending
35 process will make the EPB structures significantly clearer and much more easily identi-
36 fiable. The main reason for this propensity is the fact that the low-latitude ionosphere
37 is highly inhomogeneous, with two large crests of equatorial ionization anomaly (EIA)
38 at approximately $\pm 15^\circ$ magnetic latitude on either side of the geomagnetic equator line
39 [*Appleton*, 1946; *Rishbeth*, 2000; *Balan et al.*, 2018 and references therein]. This inhom-
40 geneous plasma density configuration causes EPB structures to be highly visible at the
41 EIA crests but much less identifiable anywhere else. For this reason, data detrending can
42 be performed as a part of preliminary data processing in EPB studies [e.g. *Portillo et al.*,
43 2008; *Seemala and Valladares*, 2011; *Magdaleno et al.*, 2012; *Tang and Chen*, 2022].

44 For total electron content (TEC) data from global navigation satellite system (GNSS)
45 observations, the data detrending process is usually performed on the TEC time series
46 along individual satellite passes. In order to reveal the TEC depletions associated with

47 EPBs effectively, here one can use e.g. a special detrending technique described in *Pradipta*
48 *et al.* [2015] for the TEC data detrending process during each GPS satellite pass. The net
49 detrended Δ TEC is obtained by subtracting the inferred TEC baseline from the original
50 TEC values. The final products in the form of 2-dimensional Δ TEC maps themselves
51 are usually assembled after all the TEC data detrending process along individual GNSS
52 satellite passes have been completed. On the other hand, the situation for the GOLD data
53 is rather different because the observations inherently come in 2-dimensional form. As
54 such, an effective data detrending method with operational principles that equally match
55 the 2-dimensional nature of the GOLD measurements is desired.

56 In principle, the detrending of GOLD FUV images to reveal EPB-associated depletions
57 can also be performed using the regular 1-dimensional rolling barrel technique [*Pradipta*
58 *et al.*, 2015], as recently demonstrated by *Adkins and England* [2023]. In the aforemen-
59 tioned work [*Adkins and England*, 2023], GOLD FUV images were first transformed from
60 geographic longitude/latitude (GLON/GLAT) coordinate into quasi-dipole geomagnetic
61 (QDLON/QDLAT) coordinate, and the 1-dimensional rolling-barrel detrending technique
62 was applied consecutively for each QDLAT — one QDLAT slice at a time. A slight draw-
63 back may potentially arise in this case because the detrending process for each QDLAT
64 slice is done separately/independently of other QDLAT slices. This slice-by-slice rastering
65 could create a 2-dimensional baseline with slightly “fibrous/filamentous” texture that runs
66 along magnetic east/west orientation, unless some additional smoothing is applied. The
67 new 2-dimensional rolling-ball detrending method is intended to remedy this potential
68 issue. Here, the aforementioned issue would be avoided by the 2 degrees-of-freedom of

69 the rolling ball, which naturally incorporate data points from different LON/LAT slices
 70 at once when inferring the baseline.

71 The following sections below present a systematic description of this proposed GOLD
 72 data detrending technique. In Section 2, we describe the basic mathematical formulation
 73 and the numerical procedures for this data detrending technique. In Section 3, we provide
 74 an illustrative step-by-step working example of this data detrending procedure, and discuss
 75 a potential application of the detrended GOLD images produced by the procedure. In
 76 Section 4, we present the conclusion.

2. Basic Principles

77 Figure 1 illustrates the general idea of this new data detrending technique, which is
 78 intended for the analysis of nighttime 135.6 nm far ultraviolet (FUV) radiance data from
 79 the NASA GOLD mission. As mentioned above, the main goal of this data detrending
 80 technique is to help reveal large-scale field-aligned depletions associated with EPBs. This
 81 new data detrending technique is a 2-dimensional generalization of a similar rolling-barrel
 82 data detrending technique [*Pradipta et al.*, 2015] that operates in 1-dimension only. In the
 83 present case, the rolling barrel is replaced with a rolling ball with two degrees of freedom
 84 to navigate an uneven 2-dimensional terrain defined by the nighttime NASA GOLD FUV
 85 airglow radiance data. Here we describe the underlying mathematical principles behind
 86 this new data detrending technique.

87 In this data detrending procedure, the GOLD FUV radiance \mathcal{R} (in Rayleighs, R) as
 88 a function of latitude Λ and longitude Φ is first transformed via variable scalings. The
 89 variable scalings are useful for creating a “terrain” with geometrical features that have
 90 comparable scale sizes in all 3 dimensions. In particular, we apply the following set

Figure 1

91 of transformations: $x = \text{longitude}/\Phi_0$; $y = \text{latitude}/\Lambda_0$; and $z = \log_{10}[(\mathcal{R} + g_0)/G_0]$.
 92 The most suitable scaling factors (determined by trial-and-error) for this purpose were
 93 $\Phi_0 = 12^\circ$, $\Lambda_0 = 5^\circ$, $g_0 = 24 \text{ R} + \min(\mathcal{R})$, and $G_0 = 0.012 \text{ R}$. In this xyz -space, the
 94 radius of the rolling ball is $R_0 = 1$ by default. This transformation compresses the
 95 dynamic range of the “terrain height” (representing the radiance values), and gives us
 96 a controlled way to select the effective size of the rolling ball relative to the terrain. It
 97 would facilitate the rolling ball to produce good contact points for inferring the baseline
 98 level. In the Supplementary Material, we provide an example illustrating different effects
 99 between untransformed radiance versus logarithmic transformation for the terrain height
 100 z in the detrending process.

101 In the rolling-barrel detrending, we work with 1-dimensional data (e.g. TEC as a
 102 function of time) that is treated as an imaginary terrain/surface for the barrel to roll
 103 on. When encountering a valley in the terrain (i.e. depletion or negative excursion in
 104 the data), a sufficiently large barrel would be able to skip over the valley. Based on the
 105 contact points made between the barrel and the terrain/surface, this mechanical rolling
 106 motion enables us to infer a baseline that is unaffected by the presence of such valley(s).
 107 In the rolling-ball detrending, we extend the same concept for 2-dimensional case (e.g.
 108 radiance as a function of longitude and latitude). Similar to a barrel, a ball is essentially a
 109 collection of circular disks/wheels — which makes the extension of this concept possible.
 110 In Figure 1, we illustrate the geometrical configuration of such ball (with cross-sectional
 111 disks/wheels shown) on a terrain that contains some depletions. A large enough ball will
 112 be able to skip over these depletions.

113 Unlike in the 1-dimensional case of rolling-barrel detrending where only one unique
 114 circular disk is involved in the mathematical formulation, in this 2-dimensional case of
 115 rolling-ball detrending we are forced to consider not only the central wheel but also the
 116 off-center wheel(s). In Figure 1, the central wheel is shown in blue and an off-center
 117 wheel in red. This additional consideration is needed because the full mechanics of a
 118 rolling ball opens the possibility for different off-center wheel(s) to make contact with the
 119 terrain, depending on the chosen direction of the roll and the exact shape of the terrain.
 120 In the diagram, the radius of an off-center wheel is denoted as R_1 and the distance of the
 121 off-center wheel from the center wheel is denoted as d_{\perp} .

122 Figure 2 shows a bird’s eye view of the situation faced by the rolling ball at any given
 123 point while navigating over the terrain. The current contact point of the ball is at (x_0, y_0) ,
 124 and the roll direction is at a bearing angle φ . The immediate forward area of the roll
 125 (i.e. the “hit zone”) is a circle with the same radius as the ball, placed at a forward offset
 126 such that the circle is tangential to the pivot axis line. A grid point on the terrain is
 127 highlighted as a possible next contact point (i.e. a “hit candidate”). In fact, all the grid
 128 points within the immediate forward area are considered in the contact point calculation.

Figure 2

129 In the xy -coordinate, the equation for the main line of this roll direction (aligned with
 the central wheel) is given by

$$130 \quad y = y_0 + \frac{(x - x_0)}{\tan \varphi}. \quad (1)$$

131 The distance d_{\parallel} between the pivot axis of the roll and the “hit candidate” is given by the
 132 dot product between two vectors $\vec{\mathbf{d}} = [x - x_0, y - y_0]$ and $\hat{\mathbf{e}}_r = [\sin \varphi, \cos \varphi]$ with the base
 133 of these vectors placed at (x_0, y_0) . The first vector $\vec{\mathbf{d}}$ is pointing from the current contact
 134 point to the “hit candidate” point, and the second vector $\hat{\mathbf{e}}_r$ is a unit vector pointing

135 along the forward roll direction. Here, the dot product works because d_{\parallel} is a sideways
 136 projection of $\vec{\mathbf{d}}$ onto the line of forward roll direction. This line projection via dot product
 operation yields

$$137 \quad d_{\parallel} = [x-x_0, y-y_0] \cdot [\sin \varphi, \cos \varphi] = (x-x_0) \sin \varphi + (y-y_0) \cos \varphi. \quad (2)$$

In addition, we also have the following identity:

$$138 \quad d_{\parallel}^2 + d_{\perp}^2 = (x-x_0)^2 + (y-y_0)^2, \quad (3)$$

139 as both sides of the equation equal the Euclidean distance (via the Pythagorean theorem)
 140 between the current contact point and the “hit candidate” point.

141 Figure 3 shows a diagram illustrating the basic mechanics that controls the rolling
 142 process. At each step in the rolling process, the problem is to determine which point on
 143 the terrain will be the next contact point for the ball. This is done by considering a subset
 144 of grid points on the terrain within the immediate forward-rolling zone of the ball. For
 145 each grid point within this area, we determine the corresponding off-center wheel that
 146 could hit the grid point as the ball rolls forward. We then compute the angle $\delta \equiv \beta - \theta$
 147 as depicted in the diagram. The grid point on the terrain with the smallest δ -angle will
 148 be the next contact point for the ball.

149 With a given d_{\perp} , the radius R_0 of the central wheel and the radius R_1 of the off-center
 150 wheel are related via $R_0^2 = R_1^2 + d_{\perp}^2$ based on the Pythagorean theorem. It means that the
 151 relation $R_1 = \sqrt{R_0^2 - d_{\perp}^2}$ holds. Here, the pivot point is at a coordinate (x_0, y_0, z_0) and
 152 the candidate for next contact point is at a coordinate (x, y, z) . For convenience, we may
 153 also define a set of increments to relate the two coordinates via $x = x_0 + \Delta x$, $y = y_0 + \Delta y$,
 154 and $z = z_0 + \Delta z$.

Figure 3

155 Of main interest to us is the angle $\delta \equiv \beta - \theta$, as mentioned previously. The expression
 156 for the angle θ is quite straightforward to find, which is given by

$$157 \quad \tan \theta = \frac{\Delta z}{d_{\parallel}} = \frac{\Delta z}{\Delta x \sin \varphi + \Delta y \cos \varphi}. \quad (4)$$

158 Meanwhile, the expression for the angle β requires more effort to find. Here it is useful to
 159 consider a triangle connecting the pivot axis of the roll, the ball's main axis \mathcal{Q} , and the
 160 point \mathcal{H} on the leading edge that would land the hit. This special triangle is shown in the
 161 inset of Figure 3.

162 With γ defined as the complementary angle of β (i.e. $\gamma + \beta = 90^\circ$), we can apply the
 163 cosine rule in order to obtain $R_1^2 = R_0^2 + s^2 - 2R_0 s \cos \gamma = R_0^2 + s^2 - 2R_0 s \sin \beta$. Hence,
 the angle β can be expressed as

$$164 \quad \sin \beta = \frac{s^2 + R_0^2 - R_1^2}{2R_0 s}. \quad (5)$$

165 Using the known geometrical relations $s^2 = d_{\parallel}^2 + \Delta z^2$ and $R_1 = \sqrt{R_0^2 - d_{\perp}^2}$ (both come
 from the Pythagorean theorem), we can make some more simplification:

$$166 \quad \sin \beta = \frac{d_{\parallel}^2 + \Delta z^2 + R_0^2 - (R_0^2 - d_{\perp}^2)}{2R_0 \sqrt{d_{\parallel}^2 + \Delta z^2}} = \frac{(d_{\parallel}^2 + d_{\perp}^2) + \Delta z^2}{2R_0 \sqrt{d_{\parallel}^2 + \Delta z^2}}. \quad (6)$$

167 Making use of the identity $d_{\parallel}^2 + d_{\perp}^2 = (x-x_0)^2 + (y-y_0)^2 = \Delta x^2 + \Delta y^2$ (cf. Equation 3) and
 168 the expression $d_{\parallel} = (x-x_0) \sin \varphi + (y-y_0) \cos \varphi$, we can further modify the expression
 for β to yield

$$169 \quad \sin \beta = \frac{\Delta x^2 + \Delta y^2 + \Delta z^2}{2R_0 \sqrt{(\Delta x \sin \varphi + \Delta y \cos \varphi)^2 + \Delta z^2}}. \quad (7)$$

Hence the complete expression for the angle $\delta \equiv \beta - \theta$ is given by

$$170 \quad \delta = \sin^{-1} \left[\frac{\Delta x^2 + \Delta y^2 + \Delta z^2}{2R_0 \sqrt{(\Delta x \sin \varphi + \Delta y \cos \varphi)^2 + \Delta z^2}} \right] - \tan^{-1} \left[\frac{\Delta z}{\Delta x \sin \varphi + \Delta y \cos \varphi} \right]. \quad (8)$$

171 For all the terrain points located within the ball’s immediate forward-rolling zone, we
172 must find one with the smallest δ -angle in order to determine the next contact point for
173 the rolling ball.

174 Using the aforementioned basic mechanics, we will roll the ball around the whole terrain
175 in xy -space and mark the contact points. We will then take the radiance values at the
176 contact points and interpolate them onto the entire terrain grid. This interpolation will
177 establish the baseline radiance level that excludes the EPB depletions — i.e. an essentially
178 “depletion-free” baseline radiance. Subtracting this baseline from the original data will
179 give us the net radiance values and reveal the EPB depletions with greater clarity.

3. Illustrative Examples

180 Figure 4 shows a working example of this data detrending process. Figure 4a shows the
181 original 135.6 nm GOLD FUV radiance data (in geographic latitude/longitude coordinate)
182 from observations made on 2 February 2022 at 21:40 UTC. The dynamic range of the
183 observed radiance value is generally between 0 R and 100 R, with higher radiance values
184 coming from the crests of the equatorial ionization anomaly (EIA). The EIA crests may
185 also exhibit some variations that are recognizable in the GOLD FUV data [*Eastes et al.*,
186 2023]. A number of EPB-related depletions are already visible in the data, and EPB
187 analysis could be performed with these original GOLD images [e.g. *Aa et al.*, 2020].
188 However, these depletions can be enhanced further by the data detrending. Figure 4b
189 shows the result of rastering process by the rolling ball as it navigates around the terrain
190 in the xy -space. White circle indicates the size of the ball, and magenta dots mark the
191 ball’s contact points. The rastering process begins at the highest point on the terrain,
192 and we start rolling the ball toward a randomly selected direction at an initial bearing

Figure 4

193 angle $\varphi = \varphi_0$. After each roll, we vary the bearing angle φ by a random variable uniformly
 194 distributed between $\pm\Delta\varphi$. The magnitude of this “scattering amplitude” is initially set
 195 to be quite small at $\Delta\varphi = 20^\circ$, which remains constant while the number of executed
 196 rolls are still below 20% of the total number of grid points in the terrain. After that,
 197 we progressively increase the magnitude of $\Delta\varphi$ by an additional 10° when the number
 198 of executed rolls reach 20%, 40%, 60%, and 80% of the total number of grid points in
 199 the terrain, respectively. This randomized “scatter-after-each-roll” policy is intended to
 200 prevent the ball from being accidentally trapped in a closed loop. When the ball arrives
 201 at the outer boundary, it will be turned back toward the interior of the computational
 202 domain, at a new randomly selected bearing angle. The rastering process ends when the
 203 number of executed rolls reach the total number of grid points in the terrain. A few
 204 additional plots illustrating more details on the progression of the rolling-ball rastering
 205 process are provided in the Supplementary Material. In general, there is freedom to
 206 implement different strategies for rolling the ball across the terrain.

207 Figure 4c depicts the 2-dimensional baseline radiance level, obtained by interpolating
 208 the radiance values at the contact points onto the whole terrain grid (in regular geographic
 209 latitude/longitude coordinate). A bilinear numerical interpolation was used for computing
 210 the baseline radiance level. Higher background radiance values are naturally found at the
 211 two EIA crests, consistent with the $\sim n_e^2$ dependence of the 135.6 nm OI volume emission
 212 rate from ionospheric F-region altitudes, where n_e is the electron density [*Tinsley and*
 213 *Bittencourt, 1975; Melendez-Alvira et al., 1999; Qin et al., 2015*]. Finally, Figure 4d
 214 shows the 2-dimensional net radiance profile that was obtained by subtracting the inferred
 215 baseline level from the original radiance data (expressed in geographic latitude/longitude

coordinate). The typical dynamic range of the net detrended radiance value is between
–40 R and 4 R, with deeper depletions generally occurring around the EIA crest locations.
In the net radiance data, sharper contrast is present between EPB-associated depletions
and the unperturbed regions. This enhanced contrast may help significantly in terms of
EPB detection, either visually or computationally, compared to working directly with the
original radiance data.

The depth of the elongated depletions in detrended GOLD images may be used to
quantify the intensity of EPBs. This concept is aligned with an analysis conducted by
Aa et al. [2023], in which the differential radiance $\Delta\mathcal{R}$ was obtained by subtracting a
running average baseline. The standard deviation of normalized $\Delta\mathcal{R}$ was then used as
a Bubble Index to quantify the EPB intensity. In the future, the same could be tried
with $\Delta\mathcal{R}$ obtained using the present rolling-ball detrending technique, which may offer
some improvement since the EPBs would be more accurately manifested as depletions
(i.e. negative excursions) in $\Delta\mathcal{R}$ rather than large-amplitude oscillatory signals (with
both hills and valleys).

Other, more advanced applications may also be developed based on the enhanced EPB
features observed in the net detrended GOLD FUV images. An example of such applica-
tion is a 3-dimensional volumetric representation of the large-scale EPB structures. Here
we provide a basic conceptual illustration of this particular potential usage of the net
detrended GOLD FUV images.

Figure 5 shows a case example to illustrate this potential application. Figure 5a displays
a detrended GOLD image on 2 February 2022 at 00:22 UTC, which shows a sequence of
large-scale EPB depletion structures between 80°W-20°W longitude. Enhanced by the

239 data detrending process, some branching/bifurcations are also revealed at the tips of
 240 these EPB structures. Figure 5b displays the same detrended GOLD image, but with
 241 the skeletons/spines of the observed EPB structures added as green line segments on the
 242 image. For the purpose of this illustrative example, these EPB spines were determined
 243 by manually profiling the observed EPB structures in the detrended GOLD image. In
 244 the future, automated profiling of complex EPB spines might potentially be achievable
 245 through computational algorithm(s). The profiled EPB spines will be a key ingredient for
 246 assembling the 3-dimensional volumetric representation.

247 Figure 5c shows a visualization plot containing two planar projections of the EPB
 248 structures, one along a horizontal plane at 300 km altitude (nominally taken as the 135.6
 249 nm OI emission source height) and the other along a vertical E/W plane at 5°S latitude.
 250 Magenta dots at $z = 0$ km are the shadow of the EPB plume structures projected onto
 251 ground level. For visualization purposes, we assume that the plasma density is fully
 252 depleted at the spine lines. In the neighborhood of each spine line, the depletion is
 253 set to subside as a function of distance following a bivariate Gaussian profile with a
 254 standard deviation of $\sigma = 0.25^\circ$ in latitude/longitude. In the far-field away from any spine
 255 line, there is practically no depletion in plasma density. The simplified depletion profiles
 256 were subsequently projected along the geomagnetic field lines using the International
 257 Geomagnetic Reference Field (IGRF) model [*Thebault et al.*, 2015; *Alken et al.*, 2021].
 258 On the two planar projections, the relative plasma density values (Rel. N_e) are indicated
 259 with colormap.

260 Figure 5d shows a similar visualization plot, this time displaying a 3-dimensional volu-
 261 metric representation of the observed EPB structures. Here, the 3-dimensional morphol-

ogy of the EPBs (which resemble a series of arches) is represented using isosurface at Rel.
 $N_e = 0.6$ level. The alpha color transparency was set at 0.15 to make the isosurfaces
translucent. The depleted part of ionospheric plasma is essentially the volume contained
within the arches. The arches are elongated roughly along the N/S direction, turned
slightly sideways following the magnetic declination angle. Like in Figure 5c, magenta
dots at $z = 0$ km are the shadow of these arches projected onto ground level. This volumetric representation illustrates how the EPB-associated magnetic flux tubes occupy the
3-dimensional space.

Animations that provide additional perspectives on the visualization shown in Figure 5d,
viewing the 3-dimensional volumetric structures dynamically from different angles, are
included in the Supplementary Material.

For a more comprehensive data assimilation, similar concept can be applied but a few
aspects need to be modified. Aspects that would be subject to modifications are as
follows. (1) The numerical value of relative depletions at the spine lines will have to be
determined empirically from the net radiance and baseline radiance data arrays. (2) The
process will no longer be only about the relative level of depletions, but the end result is
going to be expressed in terms of ionospheric plasma density and/or TEC values. (3) The
background plasma density and/or TEC may be obtained from ionosphere models such
as IRI, NeQuick, NET, TIE-GCM, or WAM-IPE [Coisson *et al.*, 2006; Nava *et al.*, 2008;
Quan et al., 2014; *Bilitza et al.*, 2022; *Fang et al.*, 2018; *Smirnov et al.*, 2023]. Aside from
these few modifications, the process would be quite straightforward: the relative depletion
profile is going to be stamped onto the smooth background plasma density and/or TEC

284 profile. This procedure will produce a model ionosphere that contains a representation of
285 the EPB plume structures.

286 In the conceptual example discussed above, the 3-dimensional volumetric representa-
287 tion of EPB structures may potentially have its practical usage in the context of space
288 situational awareness (SSA) and space domain awareness (SDA) information ecosystems.
289 This potential usage might be directed toward actual implementation if the SSA/SDA
290 system has a focus on low-latitude regions, and concerns not only the physical survivabil-
291 ity of space assets in orbit but also their state of radio connectivity in VHF/UHF bands
292 to various terrestrial components [e.g. *Bishop et al.*, 2004; *Belehaki et al.*, 2015; *Mendillo*
293 *et al.*, 2018; *Bahar et al.*, 2022].

4. Conclusion

294 We have formulated a new 2-dimensional data detrending method that can be used in
295 the analysis of nighttime GOLD FUV emission data to help reveal large-scale EPB struc-
296 tures. A generalization of a previous GPS TEC data detrending technique in 1-dimension
297 [*Pradipta et al.*, 2015], this new GOLD data detrending method works by a mechanical
298 analogy of rolling a spherical ball on an uneven terrain surface. The rolling ball's ability
299 to skip over EPB-associated depletions (deep-but-narrow valleys in the terrain surface)
300 allows the data detrending method to deduce suitable baseline level to exclude the EPBs.
301 The detrending process enhances the contrast between EPB depletions and the ambient
302 surroundings, making the detrended GOLD images a powerful resource for those conduct-
303 ing EPB research in the South American and Atlantic sectors.

304 Another objective carried by the proposed GOLD FUV data detrending method is to
305 enable and/or facilitate the development of other, more advanced applications. We have

306 discussed a conceptual example of such potential applications, involving 3-dimensional
307 volumetric representation of EPB structures over a wide range of longitudes. The given
308 example highlights the potential utility of assimilating detrended GOLD FUV images into
309 SSA/SDA information ecosystems. Future work will be directed toward exploring other
310 potential applications of the 2-dimensional GOLD data detrending method. It is hoped
311 that many practical applications using detrended GOLD images (or airglow images more
312 generally) can be realized in the future.

5. Open Research

313 The NASA GOLD Level 1C observation datafiles for this study are available from the
314 GOLD mission webpage at <https://gold.cs.ucf.edu/data/> or from the NASA Space
315 Physics Data Facility webpage at <https://spdf.gsfc.nasa.gov/pub/data/gold/level1c/>.

316 **Acknowledgments.** This work was supported by the NASA GOLD-ICON Guest In-
317 vestigators (GIGI) program under grant #NNH22OB17A.

318 **Disclaimer:** The views expressed are those of the authors and do not necessarily
319 reflect the official policy or position of the Department of the Air Force, the Department
320 of Defense, or the U.S. government.

References

321 Aa, E., Zou, S., Eastes, R., Karan, D. K., Zhang, S.-R., Erickson, P. J., and Coster,
322 A. J. (2020), Coordinated ground-based and space-based observations of equatorial
323 plasma bubbles, *Journal of Geophysical Research: Space Physics*, 125, e2019JA027569,
324 <https://doi.org/10.1029/2019JA027569>.

- 325 Aa, E., Zhang, S.-R., Liu, G., Eastes, R. W., Wang, W., Karan, D. K., et al. (2023),
326 Statistical analysis of equatorial plasma bubbles climatology and multi-day period-
327 icity using GOLD observations, *Geophysical Research Letters*, 50, e2023GL103510,
328 <https://doi.org/10.1029/2023GL103510>.
- 329 Adkins, V. J., and England, S. L. (2023), Automated detection and tracking of
330 equatorial plasma bubbles utilizing Global-Scale Observations of the Limb and
331 Disk (GOLD) 135.6 nm Data, *Earth and Space Science*, 10, e2023EA002935,
332 <https://doi.org/10.1029/2023EA002935>.
- 333 Alken, P., Thebault, E., Beggan, C. D., et al. (2021), International Geomag-
334 netic Reference Field: the thirteenth generation, *Earth Planets Space*, 73, 49,
335 <https://doi.org/10.1186/s40623-020-01288-x>.
- 336 Appleton, E. V. (1946), Two anomalies in the ionosphere, *Nature*, 157, 691,
337 <https://doi.org/10.1038/157691a0>.
- 338 Bahar, A., Dear, V., Husin, A., Faturahman, A., Harjosuwito, J., and Pradipta, R.
339 (2022), Exploring an Extension of Space Situational Awareness in Southeast Asian
340 Region Utilizing EAR Observation Data, In: Yulihastin, E., Abadi, P., Sitom-
341 pul, P., Harjupa, W. (eds), Proceedings of the International Conference on Radio-
342 science, Equatorial Atmospheric Science and Environment and Humanosphere Science
343 (INCREASE) 2021, *Springer Proceedings in Physics*, vol 275, Springer, Singapore,
344 https://doi.org/10.1007/978-981-19-0308-3_21.
- 345 Balan, N., Liu, L. and Le, H. (2018), A brief review of equatorial ionization
346 anomaly and ionospheric irregularities, *Earth and Planetary Physics*, 2: 257-275,
347 <https://doi.org/10.26464/epp2018025>.

- 348 Belehaki, A., Tsagouri, I., Kutiev, I., Marinov, P., Zolesi, B., Pietrella, M., Themelis, K.,
349 Elias, P., and Tziotziou, K. (2015), The European Ionosonde Service: nowcasting and
350 forecasting ionospheric conditions over Europe for the ESA Space Situational Awareness
351 services, *J. Space Weather Space Clim.*, 5, A25, <https://doi.org/10.1051/swsc/2015026>.
- 352 Bilitza, D., Pezzopane, M., Truhlik, V., Altadill, D., Reinisch, B. W., and Pignal-
353 beri, A. (2022), The International Reference Ionosphere model: A review and de-
354 scription of an ionospheric benchmark, *Reviews of Geophysics*, 60, e2022RG000792,
355 <https://doi.org/10.1029/2022RG000792>.
- 356 Bishop, G., Bullett, T. W., Groves, K. M., Quigley, S., Doherty, P. H., Sexton, E., Scro,
357 K., Wilkes, R., and Citrone, P. (2004), Operational Space Environment Network Display
358 (OpSEND), *Radio Sci.*, 39, RS1S26, <https://doi.org/10.1029/2002RS002836>.
- 359 Coisson, P., S. M. Radicella, R. Leitinger, and B. Nava (2006), Topside electron den-
360 sity in IRI and NeQuick: Features and limitations, *Adv. Space Res.*, 37(5), 937-942,
361 <https://doi.org/10.1016/j.asr.2005.09.015>.
- 362 Eastes, R. W., McClintock, W. E., Burns, A. G., Anderson, D. N., Andersson, L., Co-
363 drescu, M., Correira, J. T., Daniell, R. E., England, S. L., Evans, J. S., Harvey, J.,
364 Krywonos, A., Lumpe, J. D., Richmond, A. D., Rusch, D. W., Siegmund, O., Solomon,
365 S. C., Strickland, D. J., Woods, T. N., Aksnes, A., Budzien, S. A., Dymond, K. F.,
366 Eparvier, F. G., Martinis, C. R., and Oberheide, J. (2017), The Global-scale Observa-
367 tions of the Limb and Disk (GOLD) mission, *Space Science Reviews*, 212(1-2), 383-408,
368 <https://doi.org/10.1007/s11214-017-0392-2>.
- 369 Eastes, R. W., Solomon, S. C., Daniell, R. E., Anderson, D. N., Burns, A. G., England,
370 S. L., et al. (2019), Global-scale observations of the equatorial ionization anomaly,

- 371 *Geophysical Research Letters*, 46, 9318-9326, <https://doi.org/10.1029/2019GL084199>.
- 372 Eastes, R. W., McClintock, W. E., Burns, A. G., Anderson, D. N., Andersson, L., Aryal,
373 S., et al. (2020), Initial observations by the GOLD mission, *Journal of Geophysical*
374 *Research: Space Physics*, 125, e2020JA027823, <https://doi.org/10.1029/2020JA027823>.
- 375 Eastes, R. W., Karan, D. K., Martinis, C., Daniell, R. E., Gan, Q., Burns, A. G., and Mc-
376 Clintock, W. E. (2023), GOLD observations of longitudinal variations in the nighttime
377 equatorial ionization anomaly (EIA) crests' latitudes, *Journal of Geophysical Research:*
378 *Space Physics*, 128, e2022JA031007, <https://doi.org/10.1029/2022JA031007>.
- 379 Fang, T.-W., Fuller-Rowell, T., Yudin, V., Matsuo, T., and Viereck, R. (2018), Quanti-
380 fying the sources of ionosphere day-to-day variability, *Journal of Geophysical Research:*
381 *Space Physics*, 123, 9682-9696, <https://doi.org/10.1029/2018JA025525>.
- 382 Karan, D. K., Daniell, R. E., England, S. L., Martinis, C. R., Eastes, R. W.,
383 Burns, A. G., and McClintock, W. E. (2020), First zonal drift velocity mea-
384 surement of equatorial plasma bubbles (EPBs) from a geostationary orbit using
385 GOLD data, *Journal of Geophysical Research: Space Physics*, 125, e2020JA028173,
386 <https://doi.org/10.1029/2020JA028173>.
- 387 Karan, D. K., Eastes, R. W., Daniell, R. E., Martinis, C. R., and McClintock,
388 W. E. (2023), GOLD mission's observation about the geomagnetic storm effects
389 on the nighttime equatorial ionization anomaly (EIA) and equatorial plasma bub-
390 bles (EPB) during a solar minimum equinox, *Space Weather*, 21, e2022SW003321,
391 <https://doi.org/10.1029/2022SW003321>.
- 392 Magdaleno, S., Herraiz, M., and Radicella, S. M. (2012), Ionospheric bubble seeker:
393 A java application to detect and characterize ionospheric plasma depletion from

- 394 GPS data, *IEEE Transactions on Geoscience and Remote Sensing*, 50(5), 1719-1727,
395 <https://doi.org/10.1109/TGRS.2011.216896>.
- 396 Martinis, C., Daniell, R., Eastes, R., Norrell, J., Smith, J., Klenzing, J., et al. (2021),
397 Longitudinal variation of postsunset plasma depletions from the global-scale observa-
398 tions of the limb and disk (GOLD) mission, *Journal of Geophysical Research: Space*
399 *Physics*, 126, e2020JA028510, <https://doi.org/10.1029/2020JA028510>.
- 400 Melendez-Alvira, D. J., Meier, R. R., Picone, J. M., Feldman, P. D., and McLaughlin,
401 B. M. (1999), Analysis of the oxygen nightglow measured by the Hopkins Ultraviolet
402 Telescope: Implications for ionospheric partial radiative recombination rate coefficients,
403 *J. Geophys. Res.*, 104(A7), 14901-14913, <https://doi.org/10.1029/1999JA900136>.
- 404 Mendillo, M., Hickey, D., Martinis, C., Wroten, J., and Baumgardner, J.
405 (2018), Space weather nowcasting for area-denied locations: Testing all-sky imag-
406 ing applications at geomagnetic conjugate points, *Space Weather*, 16, 47-56,
407 <https://doi.org/10.1002/2017SW001741>.
- 408 Nava, B., P. Coisson, and S. M. Radicella (2008), A new version of the NeQuick ionosphere
409 electron density model, *J. Atmos. Sol. Terr. Phys.*, 70(15), 1856-1862.
- 410 Portillo, A., Herraiz, M., Radicella, S. M., and Ciralo, L. (2008), Equato-
411 rial plasma bubbles studied using African slant total electron content obser-
412 vations, *Journal of Atmospheric and Solar-Terrestrial Physics*, 70(6), 907-917,
413 <https://doi.org/10.1016/j.jastp.2007.05.019>.
- 414 Pradipta, R., Valladares, C. E., and Doherty, P. H. (2015), An effective TEC
415 data detrending method for the study of equatorial plasma bubbles and travel-
416 ing ionospheric disturbances, *J. Geophys. Res. Space Physics*, 120, 11,048-11,055,

417 <https://doi.org/10.1002/2015JA021723>.

418 Qin, J., Makela, J. J., Kamalabadi, F., and Meier, R. R. (2015), Radiative transfer
419 modeling of the OI 135.6 nm emission in the nighttime ionosphere, *J. Geophys. Res.*
420 *Space Physics*, 120, 10116-10135, <https://doi.org/10.1002/2015JA021687>.

421 Qian, L., Burns, A.G., Emery, B.A., Foster, B., Lu, G., Maute, A., Richmond,
422 A.D., Roble, R.G., Solomon, S.C. and Wang, W. (2014), The NCAR TIE-GCM:
423 A Community Model of the Coupled Thermosphere/Ionosphere System, In *Modeling*
424 *the Ionosphere-Thermosphere System* (eds J. Huba, R. Schunk and G. Khazanov),
425 <https://doi.org/10.1002/9781118704417.ch7>.

426 Rishbeth, H. (2000), The equatorial F-layer: Progress and puzzles, *Ann. Geophys.*, 18,
427 730, <https://doi.org/10.1007/s00585-000-0730-6>.

428 Rodriguez-Zuluaga, J., Stolle, C., Yamazaki, Y., Xiong, C., and England, S. L. (2021), A
429 synoptic-scale wavelike structure in the nighttime equatorial ionization anomaly, *Earth*
430 *and Space Science*, 8, e2020EA001529, <https://doi.org/10.1029/2020EA001529>.

431 Seemala, G. K., and Valladares, C. E. (2011), Statistics of total electron content depletions
432 observed over the South American continent for the year 2008, *Radio Sci.*, 46, RS5019,
433 <https://doi.org/10.1029/2011RS004722>.

434 Smirnov, A., Shprits, Y., Prol, F. et al. (2023), A novel neural network model of Earth's
435 topside ionosphere, *Sci Rep*, 13, 1303, <https://doi.org/10.1038/s41598-023-28034-z>.

436 Sousasantos, J., Gomez Socola, J., Rodrigues, F.S., et al. (2023), Severe L-band scintil-
437 lation over low-to-mid latitudes caused by an extreme equatorial plasma bubble: joint
438 observations from ground-based monitors and GOLD, *Earth Planets Space*, 75, 41,
439 <https://doi.org/10.1186/s40623-023-01797-5>.

- 440 Tang, L., and Chen, G. (2022), Equatorial plasma bubble detection using
441 vertical TEC from altimetry satellite, *Space Weather*, 20, e2022SW003142,
442 <https://doi.org/10.1029/2022SW003142>.
- 443 Thebault, E., Finlay, C. C., Beggan, C. D., et al. (2015), International Ge-
444 omagnetic Reference Field: the 12th generation, *Earth Planet Sp*, 67, 79,
445 <https://doi.org/10.1186/s40623-015-0228-9>.
- 446 Tinsley, B. A., and Bittencourt, J. A. (1975), Determination of F region height and peak
447 electron density at night using airglow emissions from atomic oxygen, *J. Geophys. Res.*,
448 80(16), 2333-2337, <https://doi.org/10.1029/JA080i016p02333>.

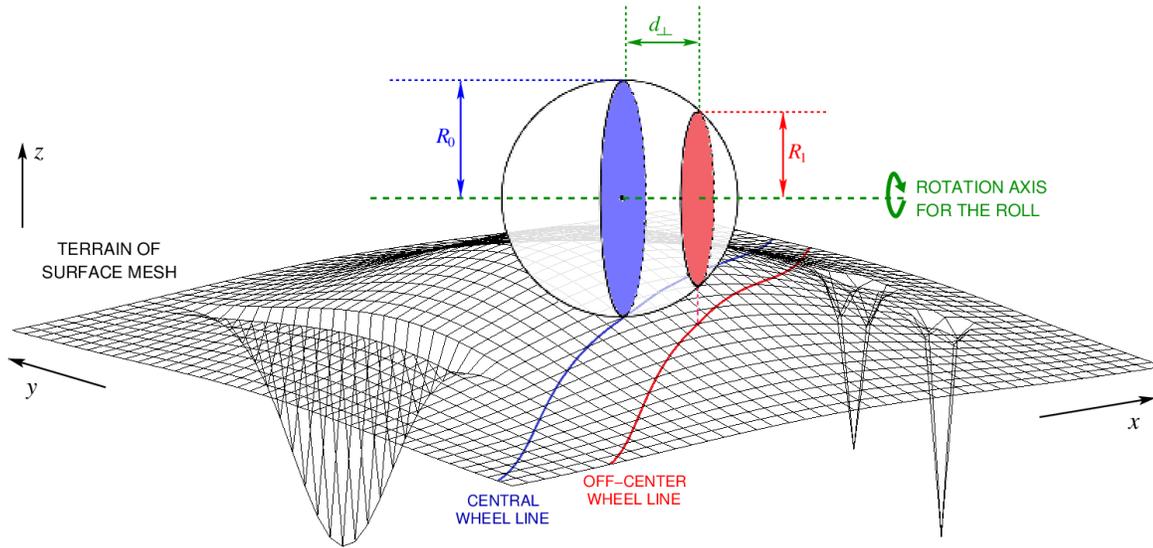


Figure 1. Graphical illustration of 2-dimensional data detrending process using mechanical analogy of a rolling ball on an uneven terrain. A ball with sufficiently large radius should be able to skip/roll over deep-but-narrow valleys, which correspond to EPB depletions in the case of GOLD FUV data.

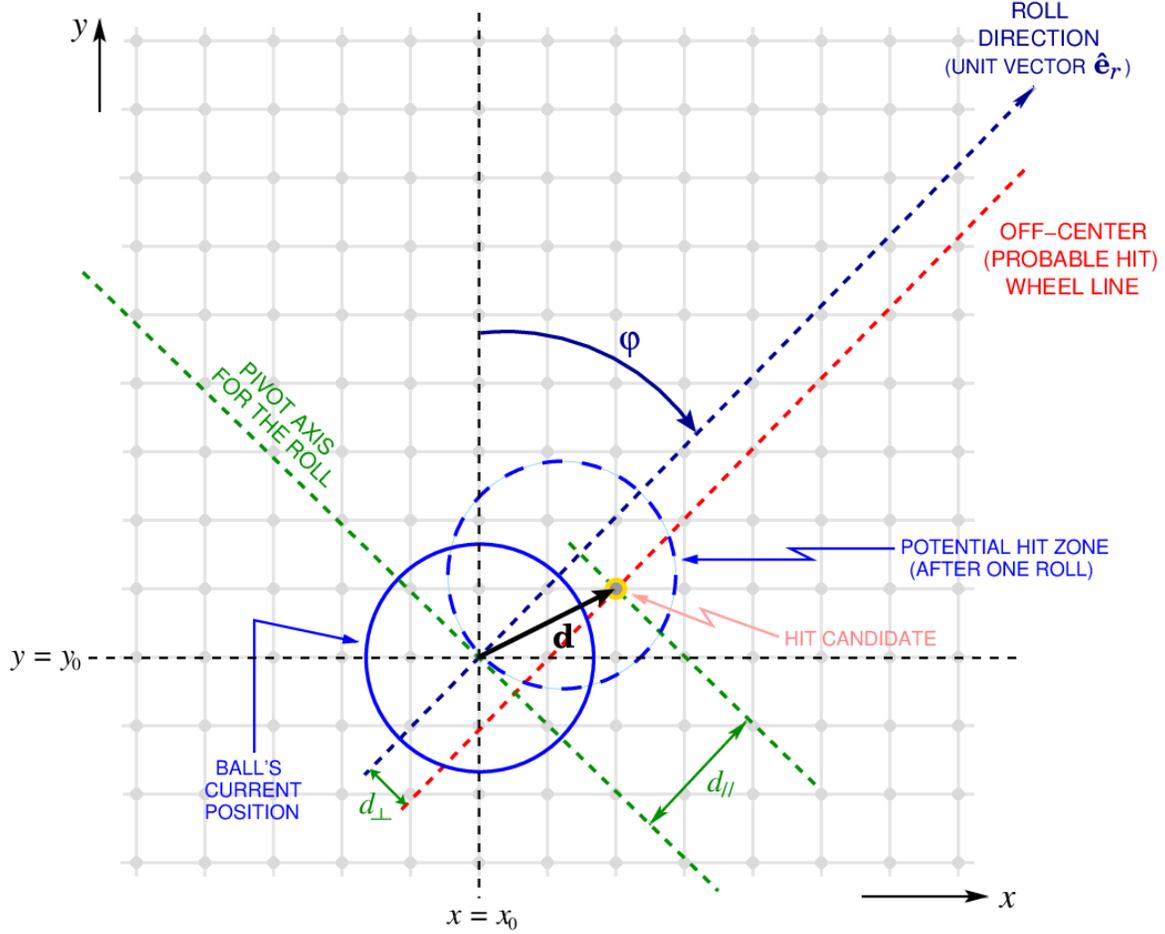


Figure 2. Bird's eye view of the rolling ball on the terrain grid, showing the starting position of the ball (solid circle), the chosen roll direction (at bearing angle φ relative to the y -axis), and the potential hit zone (dashed circle) where one of the grid points would make contact with the ball next. The displacement vector \vec{d} denotes the relative position of a “hit candidate” from the current contact point (x_0, y_0) . The roll direction is associated with the unit vector $\hat{e}_r = [\sin \varphi, \cos \varphi]$.

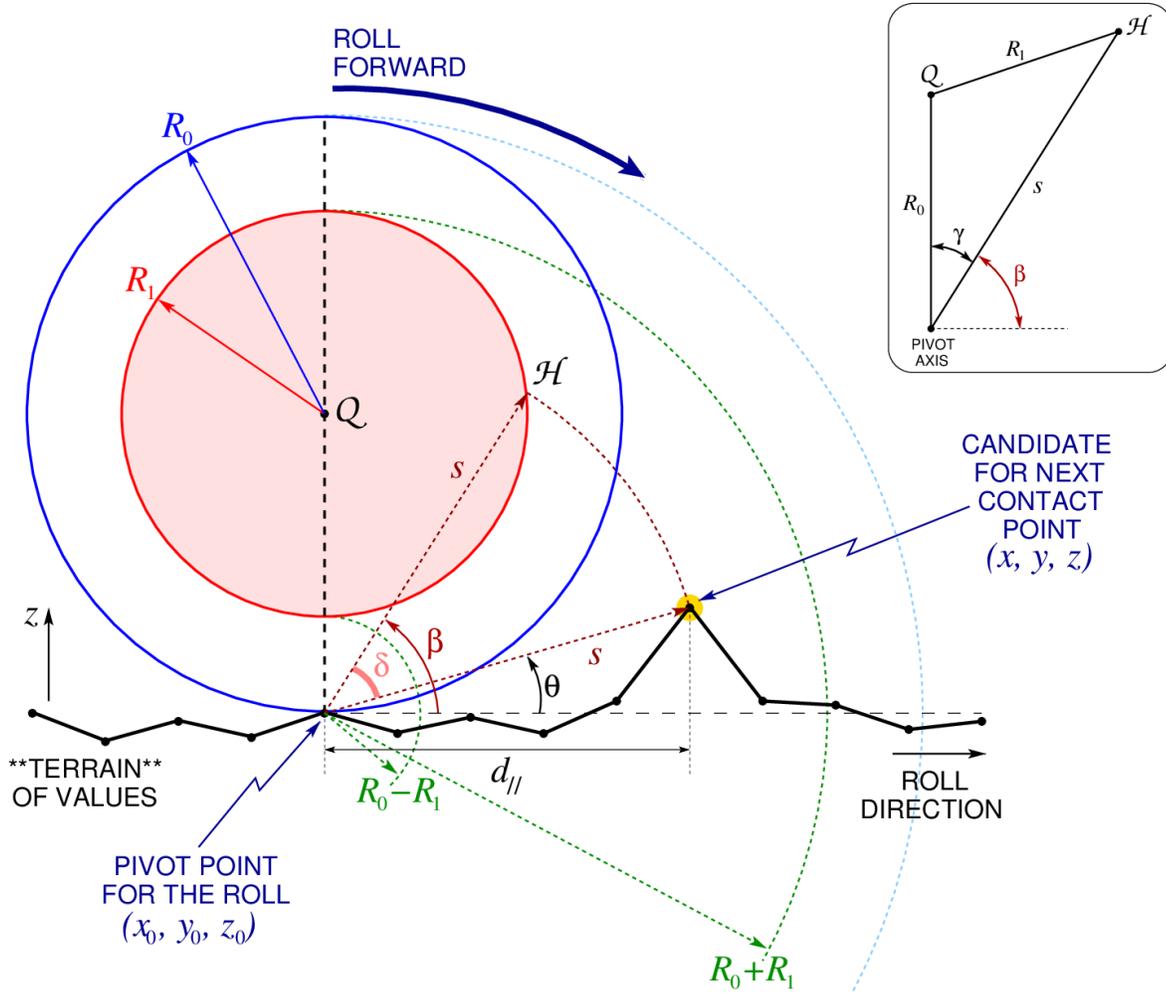


Figure 3. Detailed cross-sectional sideways view of the rolling ball, with one of the grid points on the terrain under focus as a contact candidate. The corresponding off-center wheel (shaded circle) in alignment with the said grid point is shown, where potential contact may happen at the point marked \mathcal{H} . Determining the next contact point of the rolling ball is equivalent to finding the grid point with the smallest δ -angle to its corresponding wheel.

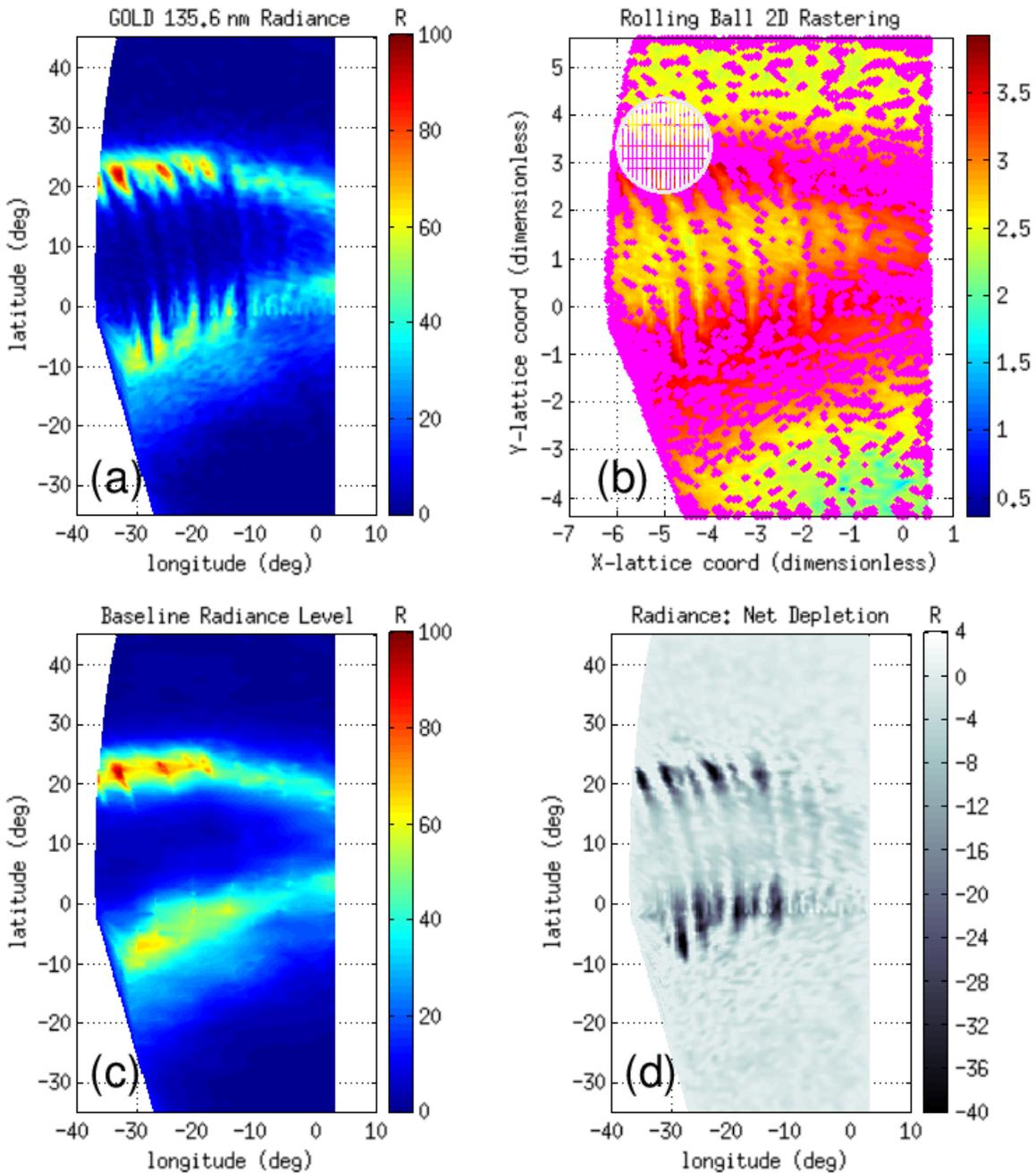


Figure 4. Step-by-step working illustration of the data detrending procedure. (a) Original GOLD radiance data. (b) Navigation/rastering process by the rolling ball over the proverbial terrain. (c) Baseline level obtained by interpolating radiance values at the contact points onto the whole grid. (d) Net radiance values obtained by subtracting the baseline from the original GOLD data.

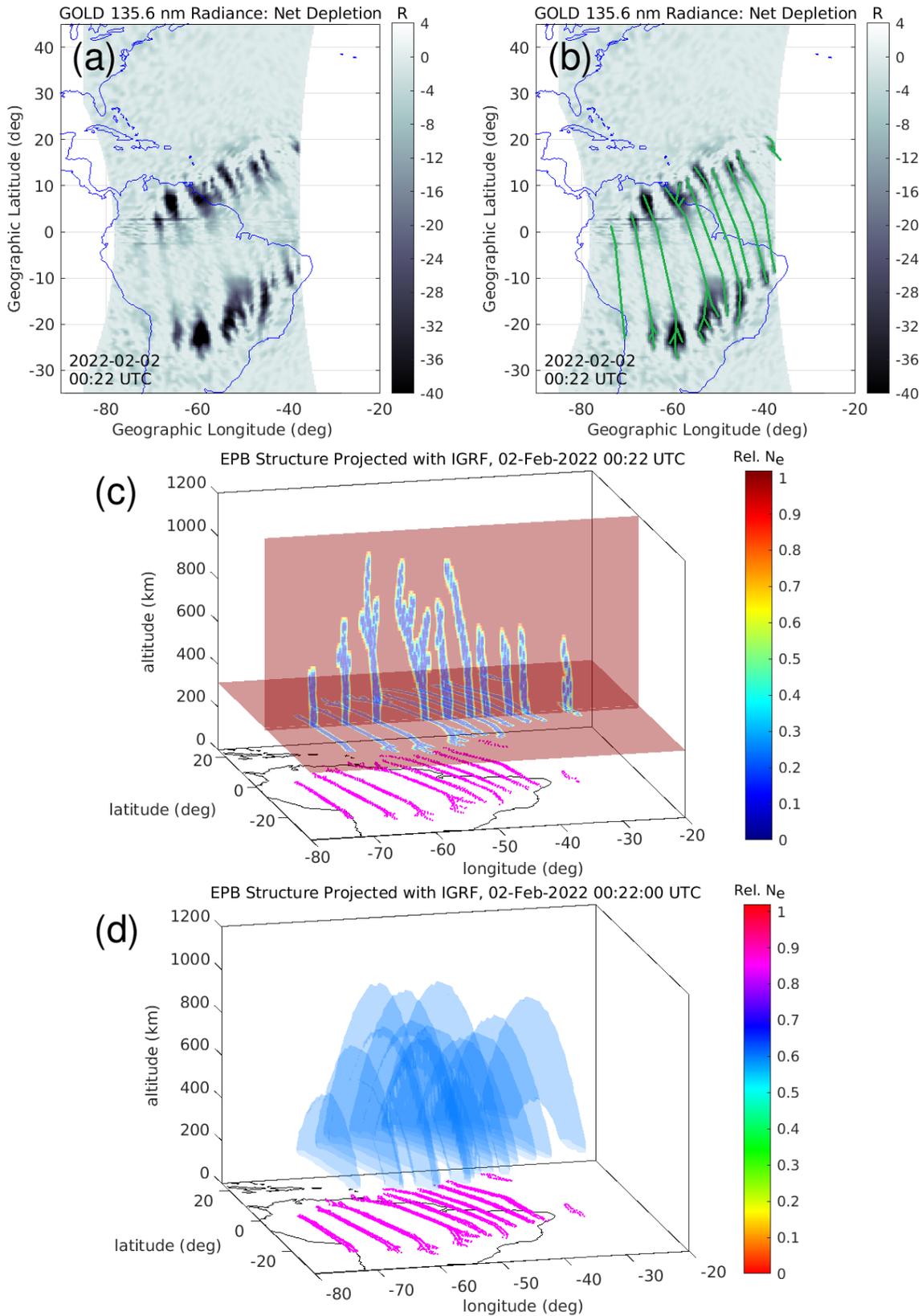


Figure 5. (a) Detrended GOLD image on 2 February 2022 at 00:22 UTC, showing several large-scale EPB structures. (b) The same GOLD image with skeletons/spines of the EPB structures profiled. (c) Horizontal and vertical planar projections of the observed EPB structures using IGRF. (d) A 3-dimensional volumetric representation of the observed EPB structures using IGRF.