

1 **Forward modeling of bending angles with a**
2 **two-dimensional operator for GNSS airborne radio**
3 **occultations in atmospheric rivers**

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15 **Key Points:**

- 16 • A two-dimensional forward model allows improved representation of bending an-
17 gle profiles collected in critical areas of atmospheric rivers.
- 18 • Forward modeling with the tangent point drift mitigates bending angle departures
19 of 5 % at the top of profiles.
- 20 • Significant contributions of horizontal gradients in the vicinity of atmospheric rivers
21 can lead to departures of up to 20 %.

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Abstract

The Global Navigation Satellite System (GNSS) airborne radio occultation (ARO) technique is used to retrieve profiles of the atmosphere during reconnaissance missions for atmospheric rivers (ARs) on the west coast of the United States. The measurements are a horizontal integral of refractive index over long ray-paths extending between a spaceborne transmitter and a receiver onboard an aircraft. A specialized forward operator is required to allow assimilation of ARO observations into numerical weather prediction models to support forecasting of ARs. A two-dimensional (2D) bending angle operator is proposed to enable capturing key atmospheric features associated with strong ARs. Comparison to a one-dimensional (1D) forward model supports the evidence of large bending angle departures within 3-7 km impact heights for observations collected in a region characterized by the integrated water vapor transport (IVT) magnitude above $500 \text{ kg m}^{-1}\text{s}^{-1}$. The assessment of the 2D forward model for ARO retrievals is based on a sequence of six flights leading up to a significant AR precipitation event in January 2021. Since the observations often sampled regions outside the AR where moisture is low, the significance of horizontal variations is obscured in the average bending angle statistics. However, examples from an individual flight preferentially sampling the cross-section of an AR further support the need for the 2D forward model for targeted ARO observations. Additional simulation experiments are performed to quantify forward modeling errors due to tangent point drift and horizontal gradients suggesting contributions on the order of 5 % and 20 %, respectively.

Plain Language Summary

Atmospheric rivers (ARs) bring intense rainfall to the west coast of the United States. Reconnaissance missions make additional measurements from aircraft, such as dropsondes, in the near storm environment within the high moisture region of ARs. An airborne radio occultation (ARO) observation system was installed on the same aircraft to use Global Navigation Satellite System (GNSS) signals such as the Global Positioning System (GPS) to retrieve additional profile observations during flights. In order to use the ARO observations for weather forecasting, an observation operator is required to simulate observations based on the current atmospheric state and compare them to the actual measurements. In the region near the core of the AR where there are large horizontal contrasts in moisture, an accurate forward model must take into account the two-dimensional (2D) structure of atmosphere. This paper describes the development and testing of the 2D observation operator for ARO observations. The performance of the operator is verified based on a case study of a long sequence of six flights on consecutive days. The 2D forward model is shown to better represent observations collected in ARs, especially when sampling a well-formed mid-latitude AR with a large contrast in properties across the cold front.

1 Introduction

Atmospheric rivers (ARs) play a vital role in the global water cycle by transporting tropical moisture poleward (Guan et al., 2021). In particular, landfalling ARs are the key drivers of floods and provide the majority of the water supply in western North America, where they frequently produce significant amounts of rainfall or snow over mountainous regions (Gershunov et al., 2017; Dettinger et al., 2011; Ralph et al., 2006). An AR is defined as a long, narrow filament of high integrated vapor transport (IVT) often identified by an IVT minimum threshold of $250 \text{ kg m}^{-1} \text{ s}^{-1}$ (Ralph et al., 2019). Accurate predictions of AR landfall location and intensity are required to support flood mitigation and water resource management. To support accurate weather predictions, global operational numerical weather prediction (NWP) models assimilate observations to improve their representation of the initial state of the atmosphere. There are limited con-

72 ventional meteorological observations over the remote areas of the northeast Pacific Ocean
73 where ARs typically develop, and hence, there is a high reliance on remotely sensed ob-
74 servations from satellites. These satellites may fail to capture key atmospheric features
75 of a particular event due to their spatial and temporal sampling characteristics, or have
76 difficulty observing through the clouds and hydrometeors that are often associated with
77 ARs (Zheng, Delle Monache, Wu, et al., 2021). Near-surface and all-weather observa-
78 tions of high vertical resolution are required to supplement satellite radiance in regions
79 of dense clouds (Ralph et al., 2017) to accurately observe AR characteristics and struc-
80 ture since most of the water vapor transport within an AR occurs in the lowest 3 km.

81 The Atmospheric River Reconnaissance (AR Recon) program is a collaborative in-
82 ternational, interagency effort led by the Center for Western Weather and Water Extremes
83 (CW3E) that was developed in part to address this observation gap. AR Recon is aimed
84 at improving predictions of ARs and their impacts at lead times of 1-5 days by collect-
85 ing targeted observations disseminated in real-time for operational assimilation into NWP
86 models (Zheng, Delle Monache, Cornuelle, et al., 2021). The foundational AR Recon ob-
87 servations are dropsonde profiles (Ralph et al., 2020; Office, 2022). Complementary re-
88 mote sensing observations using the GNSS airborne radio occultation (ARO) technique
89 in a limb-viewing geometry allow simultaneous retrieval of atmospheric profiles that sam-
90 ple the near storm environment surrounding the dropsondes at no additional expend-
91 able cost (Haase et al., 2014). The closely matched geolocations of in-situ soundings from
92 dropsondes also provide an independent nearby reference for improved understanding
93 of the information collected in AR events with ARO. A number of sensitivity studies have
94 been carried out to assess ARO measurement uncertainties and optimize retrieval method-
95 ologies for sampling AR environments or other challenging atmospheric phenomena (Xie
96 et al., 2008; Muradyan et al., 2011; Xie et al., 2018). Further improvements in the re-
97 ceiver software algorithms through the implementation of the open-loop (OL) tracking
98 (Wang et al., 2016) and development of radio-holographic inversion methods (Adhikari
99 et al., 2016; Wang et al., 2017) allowed sensing the lowermost troposphere with ARO while
100 reducing the inversion errors due to multipath propagation. This additional OL track-
101 ing capability is currently being added to ARO operations as part of AR Recon. Ulti-
102 mately, ARO measurements can benefit AR science through their assimilation into NWP
103 models, thus contributing to improvements in model initial conditions and forecast skill
104 (Haase et al., 2021; X. M. Chen et al., 2018).

105 In order to achieve this goal, a computationally efficient and accurate forward op-
106 erator is needed to allow realistic modeling of observations in strongly varying AR en-
107 vironments. Following developments in assimilation methods for spaceborne RO (Healy
108 & Thépaut, 2006; Cucurull et al., 2007, 2013; Healy et al., 2007), the geophysical vari-
109 able of bending angle is preferred over refractivity since bending angle is a more "raw"
110 observable affected by fewer assumptions about the state of the atmosphere and gener-
111 ally has simpler error characteristics (Eyre et al., 2022). However, bending angle op-
112 erators are inherently more complex and computationally demanding than those for re-
113 fractivity. This is due to bending angle being derived from numerical integration of a pro-
114 file of refractive index from a given background atmospheric state using the Abel inte-
115 gral (Fjeldbo et al., 1971; Melbourne et al., 1994; Kursinski et al., 1997). Among the as-
116 sumptions implicit in the Abel integral is a horizontally symmetric atmosphere, leading
117 to any observation operator employing it to be one-dimensional (1D). In contrast, the
118 refractivity operator is essentially an interpolation of standard meteorological variables
119 from an atmospheric model grid to locations of the ARO retrieval which is an interme-
120 diate step in the forward modeling of bending angles. More sophisticated, two-dimensional
121 (2D) bending angle operators can account for horizontal gradients (Healy, 2001; Poli,
122 2004) in the atmosphere along the propagation path by solving the ray equations with
123 numerical ray-tracing methods. In addition, the ARO profiles are not vertical, so to avoid
124 that approximation, the operator can also take into account the drift of the tangent point
125 location representing the ray-path position of the closest approach to the Earth's sur-

126 face. Since the same principle applies to both spaceborne and airborne RO measurement
 127 concepts, the existing state-of-the-art bending angle operators (Healy et al., 2007; Rus-
 128 ton & Healy, 2021) used in the assimilation of neutral atmosphere profiles from leading
 129 satellite missions could be as well adapted for airborne RO retrievals after accounting
 130 for key differences in the measurement geometry. These are used operationally for the
 131 Formosa Satellite Mission 7 (FORMOSAT-7)/Constellation Observing System for Me-
 132 teorology, Ionosphere and Climate 2 (hereafter COSMIC-2; (Anthes & Schreiner, 2019;
 133 Schreiner et al., 2020)), the European Organisation for the Exploitation of Meteorolog-
 134 ical Satellites (EUMETSAT)’s Meteorological Operational satellites program (MetOp;
 135 (von Engeln et al., 2009)), and commercial constellations.

136 The following study demonstrates the first implementation of forward modeling of
 137 ARO bending angles based on a modified 2D operator originally designed for spaceborne
 138 RO retrievals. This approach is motivated by the incorporation of the spaceborne 2D
 139 operator in the Joint Effort for Data assimilation Integration framework (JEDI;(Trémolet
 140 & Auligné, 2020)), led by the Joint Center for Satellite Data Assimilation (JCSDA), that
 141 implements observation operators as independent modules that are model-agnostic. Im-
 142 plementing the complementary version of the ARO 2D operator in JEDI makes it ac-
 143 cessible to all operational NWP centers that are migrating to the new JEDI platform.
 144 Secondly, simulations with the newly developed forward model will aid in quantifying
 145 contributions of horizontal refractivity gradients to ARO bending angle retrievals. Third,
 146 the operator will allow an overall quality assessment of bending angle retrievals from ARO
 147 contributing to potential adjustments of existing observation error models required by
 148 data assimilation systems. Fourth, the assessed error characteristics will provide feed-
 149 back and insight on how to improve ARO retrieval methodologies to further reduce the
 150 measurement uncertainties of targeted observations collected within ARs to benefit fu-
 151 ture AR Recon or tropical cyclone field campaigns.

152 In this work, we first describe the observational datasets collected during the 2021
 153 AR Recon campaign followed by a synoptic overview of a specific high impact AR event
 154 in section 3. In section 4 we outline key characteristics of the 2D bending angle obser-
 155 vation operator for ARO. Section 5 presents observation minus simulated (also commonly
 156 referred to as innovations or residuals) bending angle statistics to support the estima-
 157 tion of the observation error model. Forward modeling errors due to the effect of tan-
 158 gent point drift and horizontal refractivity gradients are discussed in section 6. A case
 159 study analysis is provided in section 7 and the conclusions are given in section 8.

160 2 Observational Datasets

161 Specially targeted weather reconnaissance flights took place over the northeast Pa-
 162 cific Ocean as a part of AR Recon 2021 in support of operational NWP forecasts of AR
 163 events in the western United States (Ralph et al., 2020). Of the 29 intensive observa-
 164 tion periods (IOPs) during AR Recon 2021, six are selected for the present study from
 165 IOP03 through IOP08. These IOPs are part of a sequence that sampled an impactful
 166 AR on consecutive days from early in its development on 23 January 2021 through land-
 167 fall in central California on 28 January 2021 (Figure 1). These sequential flights were
 168 planned based on research showing that the impact of dropsonde observations on fore-
 169 casts is higher when the event is sampled on multiple consecutive days (Zheng, Delle Monache,
 170 Cornuelle, et al., 2021).

171 Each of these six IOPs is centered at 0000 Coordinated Universal Time (UTC) and
 172 includes observations from the National Oceanic and Atmospheric Administration (NOAA)
 173 Gulfstream IV (G-IV) aircraft, which has an average cruising altitude of 14 km. In ad-
 174 dition to the NOAA G-IV, two United States Air Force Reserve Command 53rd Weather
 175 Reconnaissance Squadron WC-130J aircraft, which have an average cruising altitude of
 176 9 km, are deployed during IOP04 and a single WC-130J is employed during IOP07 and

177 IOP08. Observations collected from all of these aircraft include dropsondes profiles of
 178 pressure, temperature, humidity, and wind. The NOAA G-IV is equipped with a GNSS
 179 receiver to retrieve geophysical profiles from ARO measurements for all of these IOPs.
 180 The ARO receiver deployed onboard the NOAA G-IV aircraft during AR Recon 2021
 181 has the capability of tracking dual-frequency signals from GPS, GLONASS, and Galileo
 182 constellations, providing more occultations and thus resulting in improved spatial and
 183 temporal sampling relative to conventional GPS-only observations. The G-IV flight level
 184 in-situ observations of pressure, temperature, and humidity are used in the retrieval of
 185 the ARO profiles.

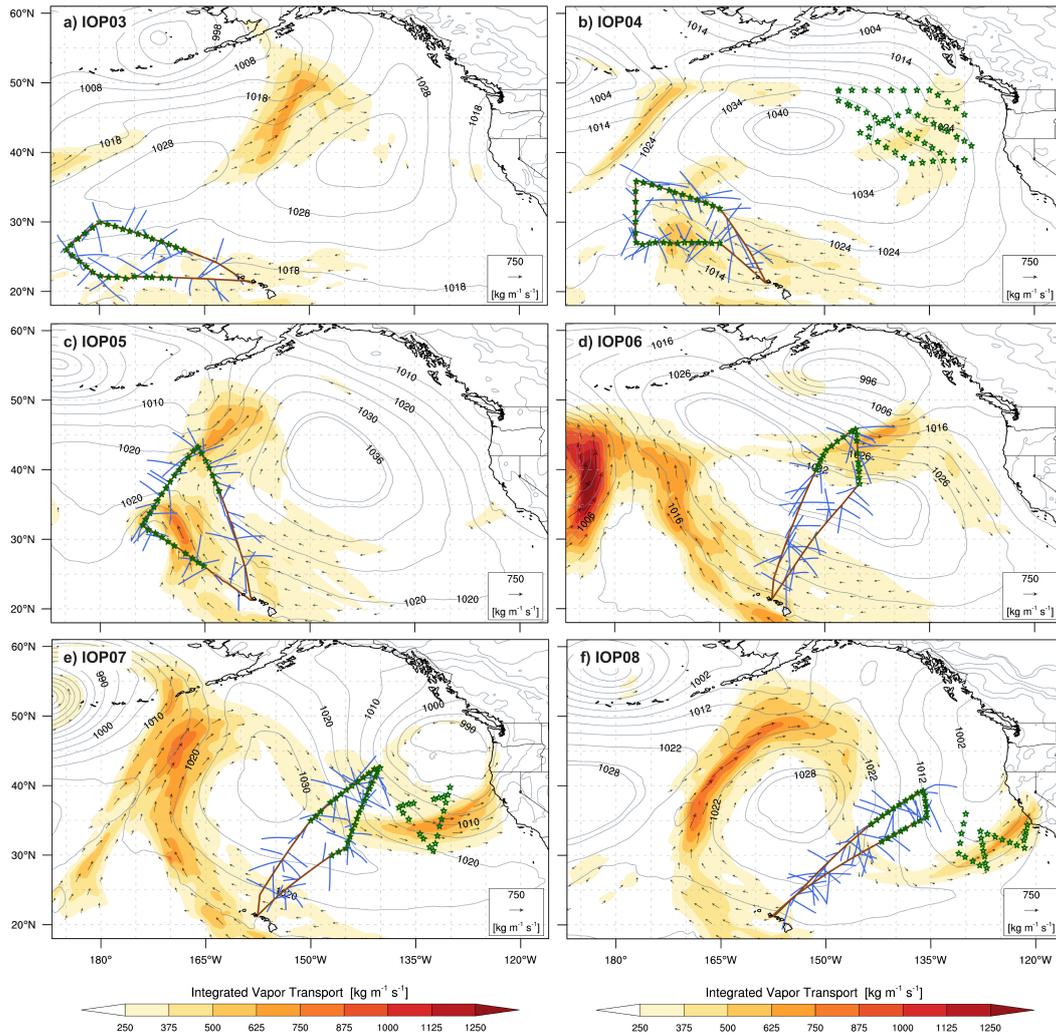


Figure 1. Overview of the six consecutive intensive operating periods (IOPs) selected from the AR Recon 2021 campaign that were centered at 00 UTC on 23 through 28 January 2021. Integrated vapor transport ($\text{kg m}^{-1} \text{s}^{-1}$, shaded and vectors) and mean sea level pressure (hPa, grey contours) are shown with the locations of dropsondes (green stars), airborne radio occultation tangent point profiles (blue lines), and the flight path of the NOAA G-IV aircraft (brown lines) overlain. The flight path(s) of WC-130J aircraft are not shown though dropsondes from these flights are indicated.

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2.1 Airborne radio occultations

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ARO retrievals result in significantly slanted profiles due to the aircraft flying at much slower speeds relative to GNSS satellites resulting in a horizontal spread of observations within a single ARO event. The point of the closest approach to the Earth's surface for an individual ray-path is referred to as the tangent point. The tangent point is near the aircraft at the top of the profile and the furthest from the aircraft at the lowest point. Figure 1 shows a total of 280 ARO profiles that are retrieved from six IOPs, with occultation counts per flight varying from 36 for IOP03 to 51 for IOP06. An ARO profile is referenced to a single representative location indicated by the reference tangent point that corresponds to the lowermost observed profile point in the ARO retrieval. In addition, an ARO profile contains individual geolocations at each height to enable assimilation that accounts for tangent point drift.

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The ARO equipment deployed includes a GNSS signal recorder for making very low altitude observations, however the results presented here are from the ARO receiver which tracks signals with a phase-locked loop. Phase fluctuations from complex atmospheric multipath propagation typically terminate phase-locked loop signal tracking before sampling the lowest part of the troposphere, such that retrieved profiles reach an average of 4 km above the surface (Fig. 2). Fewer than 20 occultations penetrate to the lowermost troposphere below 2 km. In the retrieval procedure, the aircraft position is first estimated with an accuracy better than 30 cm using Precise Point Positioning with ambiguity resolution (Geng et al., 2019), then the excess path length of the radio signal is calculated relative to a straight-line distance between the aircraft and a GNSS satellite. The first-order ionospheric delay in the neutral atmosphere retrievals is mitigated by the linear combination of dual-frequency observations and applied to the excess phase at each sample time (B. Murphy et al., 2015). Prior to inversion to the bending angle, the excess phase is smoothed with a second-order Savitzky-Golay filter in an 11 s window to eliminate fluctuations with scales shorter than the first Fresnel zone (Cao et al., 2022). Then the ionosphere-corrected smoothed excess phase is inverted to bending angle in the geometrical optics approach assuming single-ray propagation (Xie et al., 2008).

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The bending accumulated inside the atmosphere below the aircraft height along two symmetrical sections of the ray path around the tangent point corresponds to the ARO observable of 'partial' bending angle. The refraction along the ray-path section continuing outwards to the higher atmosphere in the direction of a GNSS transmitter contributes to the additional bending, which together with the 'partial' bending yields the 'full' bending angle of the ray-path. In general, the magnitude of the 'partial' bending is slightly smaller than that of the corresponding 'full' bending angle due to relatively small refractivity contributions above the aircraft height. However, the bending above the receiver cannot be measured directly from observed Doppler shifts. Instead, this additional contribution needs to be separated with the use of auxiliary atmospheric information to derive the 'partial' bending angle. This can be either from an ARO ray-path arriving at the antenna at the same angle above the horizon as the observation is below the horizon, assuming spherical symmetry (Healy et al., 2002), or from ray-tracing of an assumed profile above the aircraft height (B. Murphy et al., 2015). Retrieved bending angles can be further inverted to profiles of refractive index with the modified Abel transform (Healy et al., 2002; Xie et al., 2008) under the assumption of local spherical symmetry. Since the aircraft is flying within the atmosphere, the Abel inversion is constrained at the top of the profile by in-situ refractivity calculated from flight-level pressure, temperature, and moisture measurements retrieved from meteorological sensors onboard the aircraft (Cao et al., 2024). When in-situ moisture measurements are unreliable at high altitudes, the moisture contribution to in-situ refractivity is neglected. According to sensitivity studies (Xie et al., 2008), the in-situ measurement error mostly affects ARO retrievals within 1 km of the aircraft flight level. No statistical optimization is applied to

238 ARO retrievals as the ionospheric residual noise is generally not expected to exceed the
 239 atmospheric contribution to the bending at or below the aircraft height.

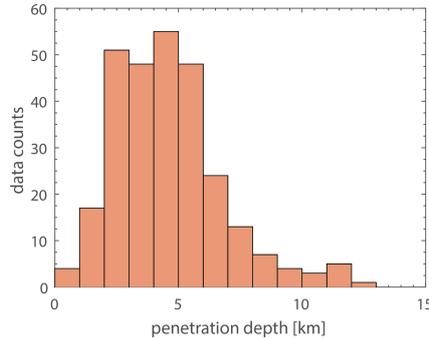


Figure 2. Histogram showing the lowest geometric altitude sampled by the ARO profiles from six IOPs during AR Recon 2021.

240 2.2 Reanalyses

241 The reanalysis product chosen to represent the state of the atmosphere during AR
 242 Recon 2021 is the European Centre for Medium-Range Weather Forecasts (ECMWF)
 243 Renalysis 5 (ERA5; Hersbach et al. (2020)). The ERA5 reanalysis has been shown to
 244 provide a useful representation of precipitation for North America with quality compa-
 245 rable to observations (Tarek et al., 2020). The atmospheric state depicted in the ERA5
 246 is used for simulating the ARO bending angle for the comparisons shown herein. These
 247 are obtained from the ECMWF data catalogue already interpolated to a regular latitude-
 248 longitude grid with $0.25^\circ \times 0.25^\circ$ resolution in the horizontal, on the native 137 hybrid
 249 sigma levels in the vertical, and at 1-hourly temporal resolution. Meteorological variables
 250 used from ERA5 are the temperature, specific humidity, geopotential, integrated water
 251 vapor (IWV) and the magnitude of IVT which was derived from the components of the
 252 IVT vector in the zonal and meridional directions. The atmospheric pressure at each level
 253 is calculated with the use of surface pressure provided in the form of natural logarithm
 254 and model-defining coefficients at the interfaces (half-levels) between the native levels
 255 of the model.

256 3 Synoptic overview of the atmospheric river event

257 The aforementioned AR event chosen as the case study for evaluation of the ARO
 258 operator made landfall in California on 27 January 2021 and brought widespread impacts
 259 throughout the state. Parts of central California were under AR conditions for almost
 260 48 hours with AR2 conditions on the AR scale (Ralph et al., 2019). The AR was asso-
 261 ciated with over 175 mm of precipitation in parts of the Sierra Nevada, Central Coast,
 262 and Transverse mountain ranges. This led to flooding with damaging debris flows and
 263 road closures in central and southern California.

264 The sampling of this event by a reconnaissance aircraft began on 23 January 2021
 265 (IOP03, Fig. 1), in which the target of the NOAA G-IV was the region of development
 266 of an extratropical cyclone (ETC) as indicated by model forecasts and sensitivity met-
 267 rics (not shown) monitored during AR Recon (Reynolds et al., 2019). The targeted ETC
 268 began forming at lower latitudes near the Hawaiian Islands as a Kona Low (Daingerfield,
 269 1921; Simpson, 1952; Ramage, 1962). While the development and track of Kona Lows
 270 have proven difficult for NWP models to predict, they can be a key element driving the
 271 evolution of ARs (Morrison & Businger, 2001; S. Chen et al., 2022) and hence an excel-

272 lent target for AR Recon. By 25 January (IOP05) a closed mean sea level pressure (MSLP)
 273 contour can be seen at 31°N , 173°W indicating the presence of the Kona Low at the sur-
 274 face on the southwestern flank of a large anticyclone centered at 42°N , 146°W . This area
 275 was among the target regions sampled by the G-IV on this day as part of IOP05. The
 276 next day, a different ETC was intensifying in the Gulf of Alaska to the northeast of the
 277 anticyclone and the IVT in a developing AR in the region of enhanced MSLP gradient
 278 between the ETC in the Gulf of Alaska and the anticyclone was sampled by the G-IV
 279 aircraft as part of IOP06. By 0000 UTC on 27 January the AR was making landfall in
 280 California and was sampled by a WC-130J aircraft (Fig. 1 green stars without a brown
 281 flight track underneath) while the main target of the G-IV was the trough to the west
 282 of the AR, a feature often associated with regions of high sensitivity to PV and poten-
 283 tial temperature errors in forecasts for AR precipitation (Reynolds et al., 2019). On 28
 284 January, again the target of the G-IV aircraft was a region of model sensitivity in the
 285 trough, and a WC-130J aircraft sampled the AR as it continued to make landfall as part
 286 of IOP08. In general during this sequence of IOPs, the focus of the G-IV is on the ETC
 287 and upper level dynamical features that could modulate AR structure and evolution, in
 288 addition to sampling the AR itself, while the WC-130J aircraft is focused on transects
 289 of the AR.

290 **4 Two-dimensional bending angle forward model**

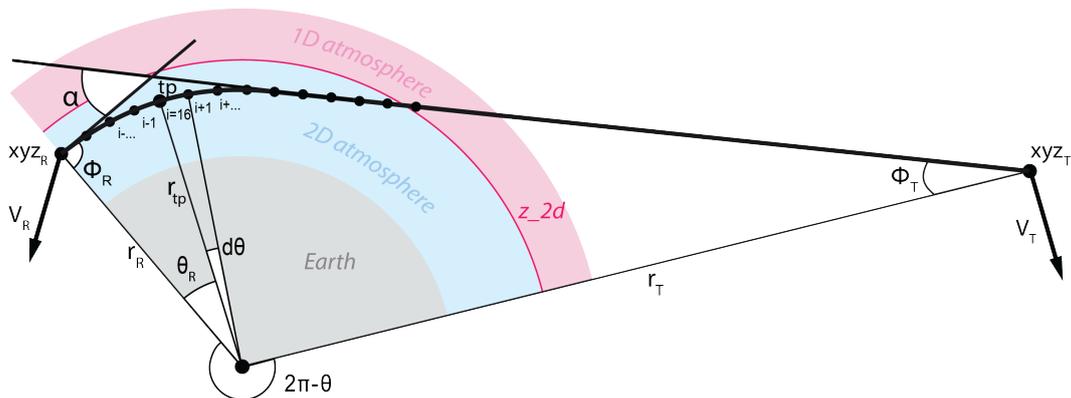


Figure 3. Schematic illustration of the geometry for airborne radio occultations. The central angle θ can be derived given known positions of the receiver xyz_R and the transmitter xyz_T at radii r_R , r_T , respectively. The angular separation $d\theta$ determines the points at which to extract model profiles between ray-path points i , $i + 1$ along the occultation plane centered at $i = 16$ corresponding to the location of the observed tangent point (tp) having a radius r_{tp} . The central angle θ_R between the tangent point location and the receiver will not exactly match the angular separation $15 \times d\theta \approx 600$ km since model profiles are extracted beyond the receiver location (ray-path points not shown). The bending angle α is the difference between the incoming and outgoing ray-path direction. z_{2d} indicates the altitude limit for the 2D simulations and the atmosphere is assumed to be spherically symmetrical above.

291 Before we describe the key characteristics of the ARO forward model, the general
 292 features are recalled first to outline the configuration used in simulations of bending an-
 293 gles. The adopted forward model is based on the bending angle operator developed by
 294 ECMWF for spaceborne RO (Healy et al., 2007; Eyre, 1994). The operator, together with
 295 other forward modules, is available as a part of the Radio Occultation Processing Pack-
 296 age (ROPP) (Culverwell et al., 2015) provided by the Radio Occultation Meteorology

346 as the upper limit of integration of bending angle over impact parameter for all the ray-
 347 paths (B. Murphy et al., 2015; Haase et al., 2014). This is not strictly true, however the
 348 NOAA G-IV aircraft cruise altitude is generally maintained throughout the flight for long
 349 segments with infrequent, short ascents of 200-300 m. B. J. Murphy (2015) showed that
 350 when the standard deviation of the aircraft height averaged over the duration of the oc-
 351 culation was less than about 150 m, the effect of the height variation was less than the
 352 limiting aircraft velocity error. Occultation profiles with large aircraft height variations
 353 are eliminated in the quality control and evaluation of the ARO dataset.

354 The asymmetry in the geometry of the ray-path in the atmosphere that is specific
 355 to ARO will affect the approach to the numerical solution of the ray-path equations when
 356 propagating the ray through the atmospheric model (Rodgers, 2000):

$$\begin{aligned} \frac{dr}{ds} &= \cos\phi, \\ \frac{d\theta}{ds} &= \frac{\sin\phi}{r}, \\ \frac{d\phi}{ds} &= -\sin\phi \left[\frac{1}{r} + \frac{1}{n} \left(\frac{\partial n}{\partial r} \right)_{\theta} \right] + \frac{\cos\phi}{nr} \left(\frac{\partial n}{\partial \theta} \right)_r, \end{aligned} \quad (3)$$

357 where n describes the refractive index of the atmosphere at a point on the ray-path, r
 358 and θ are polar coordinates of the point with origin at the center of curvature, s is the
 359 distance from the point to the next along the ray-path, ϕ is the angle between the lo-
 360 cal radius vector and the tangent to the ray-path at the point. The ray equation is in-
 361 tegrated numerically starting from the observation tangent point location to the two end-
 362 points: (1) one on the side of the aircraft and (2) one on the side of the GNSS satellite
 363 as depicted in Fig. 3. The differential equations are solved with the fourth-order Runge-
 364 Kutta method. Once the radius of the aircraft is reached by the ray-path propagating
 365 in the direction of the receiver, the integration is terminated and the other side is eval-
 366 uated. If the ray equation was terminated at the same radius on the side propagating
 367 toward the transmitter, the simulated geophysical variable would correspond to the 'par-
 368 tial' bending angle for ARO which is used in the refractivity retrieval. For the 'full' bend-
 369 ing angle simulations, the ray-path continues propagating beyond the radius of the air-
 370 craft up to the height controlled by the parameter z_2d . For the simulations in this study
 371 z_2d is set to 20 km to be always above the typical aircraft cruising altitude of the NOAA
 372 G-IV at ~ 14 km. The bending of the ray-path above the height z_2d is computed un-
 373 der the assumption of spherical symmetry using the Abel integral

$$\Delta\alpha_{1d}(p) = -p \int_{r_c+z_2d}^{\infty} \frac{d \ln(n(\chi))}{d\chi} \frac{d\chi}{\sqrt{\chi^2 - p^2}}, \quad (4)$$

374 that is given in terms of Gaussian error function, with the refractive index n sourced from
 375 the nearest model profile at the central angle θ . The bending above the model top that
 376 for ERA5 with 137 levels typically reaches ~ 75 km is accounted for by extrapolating

$$\Delta\alpha_{top} = 10^{-6} \sqrt{2\pi p k_j N_j} \exp(k_j(\chi_j - p)) [1 - \text{erf}(k_j(\chi_j - p))], \quad (5)$$

377 where the inverse of refractivity scale-height between subsequent model levels $j, j+1$
 378 being at the model top is expressed with $k_j = \ln(N_j/N_{j+1})/(\chi_{j+1}/\chi_j)$. The sum of bend-
 379 ing of three segments of the ray-path (1) from the tangent point to the receiver, (2) from
 380 the tangent point to z_2d and (3) from z_2d to the model top with the extrapolation above
 381 yields the 'full' bending angle.

382 5 Characteristics of observation errors in ARO retrievals

383 Profiles of bending angle collected during the six IOPs are simulated with the ob-
 384 servation operator using the ERA5 reanalysis for the assessment of uncertainties. The

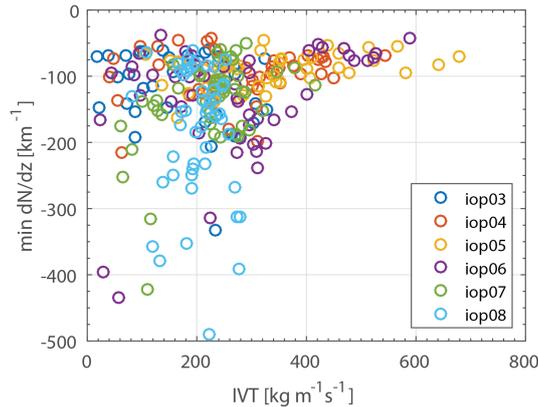


Figure 4. Relationship between IVT magnitudes and minimum vertical refractivity gradients (dN/dz) based on ERA5 profiles collocated with ARO retrievals at the location of reference tangent point.

385 statistics are computed as observed minus simulated bending angle for differences in ab-
 386 solute units, which are further divided by simulated value for fractional differences. Typ-
 387 ically, the quality of RO observations is assessed based on globally distributed profiles
 388 that might capture variable atmospheric conditions from challenging vertical structures
 389 in the tropics to significantly drier environments in higher latitudes and polar regions.
 390 The two simplifying assumptions that are often made are that (1) the atmosphere is spher-
 391 ically symmetric and (2) there is no tangent point drift. Contributions of those assump-
 392 tions to overall bending angle statistics when using an atmospheric model or reanaly-
 393 sis product as a reference have not yet been studied for ARO retrievals. Therefore, both
 394 (1) horizontal refractivity gradients and (2) tangent point drift are accounted for when
 395 simulating ARO observations at each observed tangent point location with the modified
 396 2D forward model. This is particularly important for ARO targeted observations from
 397 AR Recon which are collected within AR environments associated with the high humid-
 398 ity pre-frontal low-level jet where strong gradients in moisture, and thus refractivity, are
 399 observed (Haase et al., 2021). Challenging atmospheric conditions for GNSS RO signal
 400 propagation are encountered in the presence of strong vertical gradients in the refrac-
 401 tivity, where $dN/dz < -157 \text{ km}^{-1}$ (Sokolovskiy, 2003). The advantage of using a 2D ob-
 402 servation operator for spaceborne RO in ARs was quantified for bending angle innova-
 403 tions calculated from background forecasts from the operational Global Forecast Sys-
 404 tem (GFS) model (M. J. Murphy et al., 2024) with the impact of the 2D operator in-
 405 creasing with increasing IVT.

406 The minimum in the refractivity gradient is a useful diagnostic for the detection
 407 of planetary boundary layer height (Xie et al., 2012; Basha & Ratnam, 2009) because
 408 the magnitude of dN/dz can be used to describe its sharpness (Guo et al., 2011). The
 409 condition $dN/dz < -157 \text{ km}^{-1}$ suggests anomalous radio propagation associated with super-
 410 refraction which might result in large RO retrieval errors in the lowermost troposphere
 411 (Beyerle et al., 2003; Ao, 2007). We use the magnitude of dN/dz as an indicator of po-
 412 tential large bending angle deviations. Figure 4 shows the correspondence of IVT mag-
 413 nitudes to minimum refractivity gradients based on ERA5 profiles extracted at the lo-
 414 cation of reference tangent points for ARO observations during the six IOPs. The as-
 415 sessment shows that IVT magnitudes are weakly inversely correlated with refractivity
 416 gradients developing in the lower troposphere. The minima in dN/dz are often found be-
 417 low 4 km altitude with the strongest gradients developing at ~ 1.5 km. The majority of
 418 strong dN/dz values occur in atmospheric conditions outside of ARs determined by the

419 IVT $< 250 \text{ kg m}^{-1} \text{ s}^{-1}$ criterion. Most of the points with the strongest gradients of less
 420 than -200 km^{-1} are during IOP08 where IVT magnitudes are on the order of 200 kg m^{-1}
 421 s^{-1} and the aircraft sampled the dry and cold post-frontal region in the trough behind
 422 the targeted AR, where a sharp boundary layer typically develops. All the flights with
 423 strong negative gradients, IOP06, IOP07, and IOP08, flew a significant ferry over a sub-
 424 tropical pressure high northeast of Hawaii, where subsidence would also lead to a sharp
 425 boundary layer. In contrast, the intense AR sampled during IOP05 with IVT $> 400 \text{ kg m}^{-1}$
 426 s^{-1} is characterized by refractive conditions with $dN/dz \approx -100 \text{ km}^{-1}$. The assess-
 427 ment of the dN/dz distribution is consistent with previously reported evidence of strong
 428 gradients developing in the lower troposphere outside of ARs based on dropsondes and
 429 spaceborne RO retrievals (Murphy Jr & Haase, 2022; Haase et al., 2021).

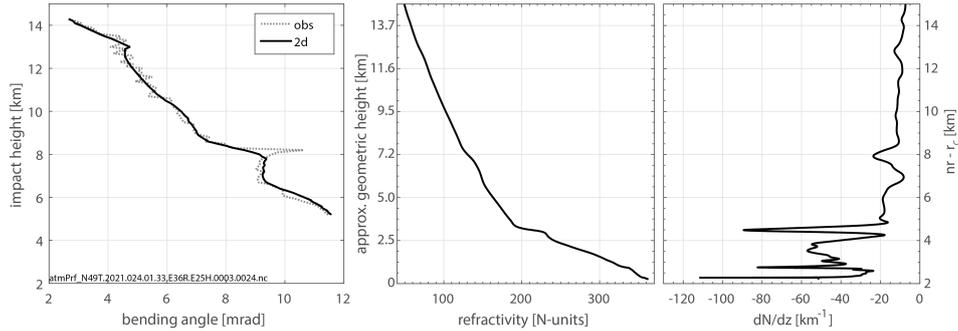


Figure 5. (left) Observed and 2D simulated bending angle profiles for one ARO occultation during IOP04. (middle) Refractivity calculated from ERA5 at the location of the central profile and (right) corresponding vertical refractivity gradient.

430 An example of an ARO bending angle profile from IOP04 in Fig. 5 is character-
 431 ized by a prominent feature at $\sim 8 \text{ km}$ impact height producing a bending angle
 432 spike that is typically observed in the presence of an inversion layer. The bending angle vari-
 433 ation is reflected fairly well in the corresponding simulations. The refractivity field from
 434 the ERA5 at the height of the bending angle spike has a homogeneous horizontal distri-
 435 bution as indicated by the similarities between simulation results in 2D and 1D (not
 436 shown as it cannot be visually distinguished). The existence of an inversion layer is sup-
 437 ported by several of the nearby dropsonde profiles at 168°N , 33°W on the east side of
 438 the low level moisture plume (see supplementary material and refer to [https://cw3e](https://cw3e.ucsd.edu/arrecon_data/)
 439 [.ucsd.edu/arrecon_data/](https://cw3e.ucsd.edu/arrecon_data/) for more dropsonde profiles and upper air charts). The in-
 440 version at $\sim 8 \text{ km}$ is likely associated with the temperature difference between the air mass
 441 containing the upper level southwesterly jet with and the air mass beneath it with southerly
 442 winds. The inversion seen at 3 km in both the dropsonde and ERA5 appears to be the
 443 explanation for the termination of the ARO profile.

444 The penetration depth of the observed bending angle profile in Fig. 5 is affected
 445 by gradients developing in the lower troposphere with multiple inversion layers at and
 446 below 4 km , also observed in the nearby dropsonde profiles. The moderate magnitude
 447 of $dN/dz > -120 \text{ km}^{-1}$ from the ERA5 does not indicate super-refraction would occur,
 448 however, the dropsonde profiles illustrate the actual gradients could have larger magni-
 449 tude. The dropsonde IVT of $340 \text{ kg m}^{-1} \text{ s}^{-1}$ indicates that the profile captures the tropi-
 450 cal moisture export associated with the Kona low that eventually contributes to an AR.

451 The bending angle deviations between observations and 2D simulations for the six
 452 IOPs during AR Recon 2021 are presented in Fig. 6. We limit our assessment of obser-
 453 vation errors to a more statistically representative range above 4 km impact height due
 454 to less than 10 % of the ARO profiles penetrating down to 2.5 km impact height ($\sim 1 \text{ km}$

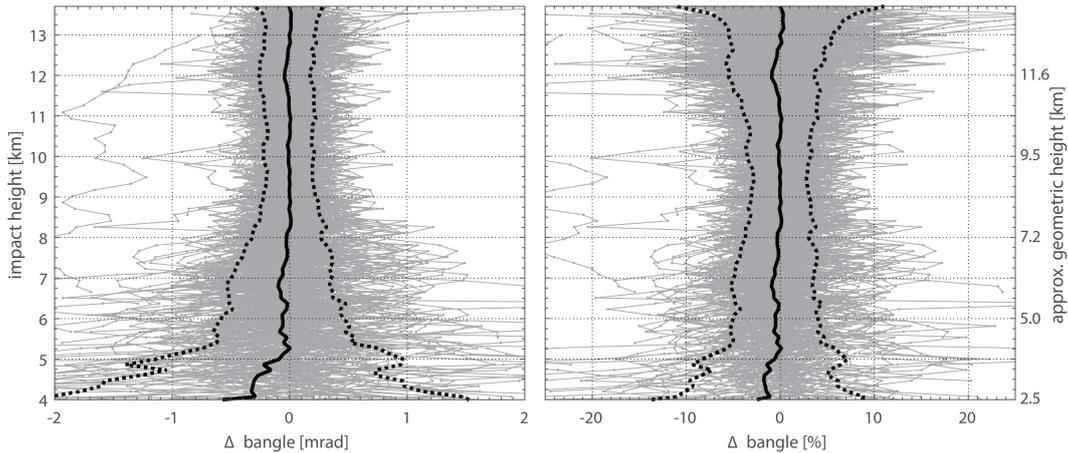


Figure 6. Observed minus 2D simulated bending angle deviations in (left) absolute and (right) fractional units for six IOPs during AR Recon 2021. Grey lines correspond to bending angle differences for individual profiles, the solid black line is the mean difference and dotted black lines show standard deviation.

geometric altitude in Fig. 2). The GNSS receiver measurements terminate due to challenging signal tracking conditions in the presence of strong refractivity gradients. Their existence further motivates future efforts towards analysis of data collected from the ARO advanced GNSS recorder and implementation of advanced radio-holographic ARO retrieval methods (Wang et al., 2016, 2017) to enable detection of inversion layers in the lowermost troposphere associated with ARs. The standard deviation at 4 km impact height is on the order of 10 % corresponding to absolute bending angle differences of 2 mrad. The standard deviation generally decreases with height up to ~ 10 km. There is a slight increase in the standard deviation at 5 km due to outlying observations being affected by errors close to the lowest observed height where many of the ARO profiles terminate (Fig. 2). The mean difference also increases towards the surface, showing negative bias below 5 km impact height of -1.5 % which is equivalent to -0.3 mrad. The standard deviation in the middle troposphere is generally below 4 %. The increased error above 10 km impact height, visible in the fractional deviations, is expected due to the decrease in the magnitude of the bending angle relative to the limiting errors in knowledge of the aircraft velocity. Velocity errors map into excess Doppler (Muradyan et al., 2011) and can partially explain the oscillatory characteristics of the observed bending angles (Fig. 5). This potentially contributes to the slight negative bias not exceeding -1 % (-0.1 mrad) in bending angles at 12 km impact height. However, the noise level does affect the capability of ARO to resolve smaller amplitude atmospheric features above 10 km (Fig. 5). The optimal use of noise filtering methods (Cao et al., 2022) is required to further improve bending angle observations in the upper levels while preserving the vertical sensitivity of ARO. Despite this, ARO observations are effective at retrieving precise vertical information about variations in tropopause height in ARs (Haase et al., 2021) and in the equatorial atmosphere from balloon-borne RO (Cao et al., 2022), because of the large magnitude of the tropopause temperature variations.

In order to study the potential contribution of horizontal refractivity inhomogeneities to bending angle deviations, simulations utilizing 2D atmospheric fields from ERA5 are compared with results based on a 1D atmosphere. The spherically symmetrical refractivity field was provided as an input to the 2D forward model to simulate corresponding 1D bending angle profiles. For this case, the ERA5 refractivity at the central profile of the 2D field is repeated for 31 locations along the occultation plane. Figure 7 shows

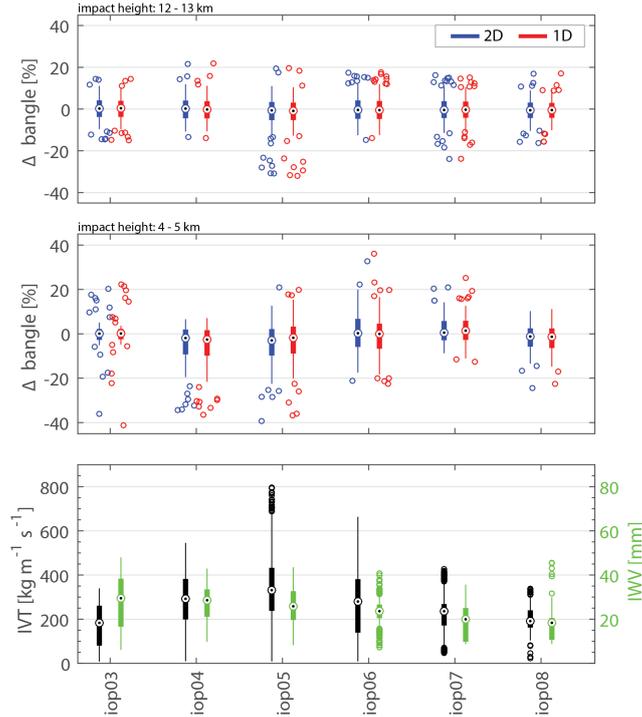


Figure 7. Boxplots showing observed minus simulated bending angle deviations for individual IOPs computed at two representative impact height levels: (top) within 12-13 km of the profile top, and (middle) between 4-5 km in the troposphere. (bottom) IVT magnitudes and corresponding IWV values are from ERA5. The thick line indicates the interquartile range, and the thin line shows minimum and maximum values excluding points falling outside 1.5 times the interquartile range, shown as circles.

487 statistics computed separately for individual IOPs at two impact height levels: (1) at
 488 12-13 km, which is representative of the top of ARO profiles, and (2) at 4-5 km, repre-
 489 sentative of the lower troposphere. Statistics are supported by analyzing IWV values and
 490 IVT magnitudes which characterize the strength of AR conditions, where the value of
 491 IVT and IWV is extracted from the ERA5 at the location of the reference tangent point
 492 (lowermost profile point). The spread in bending angle deviations at 4-5 km, in terms
 493 of the interquartile range (thick line), is larger for IOP05 and IOP06 that are both rel-
 494 atively strong AR environments with the maximum IVT (thin line) reaching or exceed-
 495 ing $600 \text{ kg m}^{-1} \text{ s}^{-1}$ (Fig. 7). In contrast, the bending angle deviation for IOP07 and IOP08
 496 are significantly smaller, which have both lower IVT and lower IWV. Bending angle mea-
 497 surements at 4-5 km impact height are likely more susceptible to loss of lock or multi-
 498 path errors due to moisture gradients in the troposphere for the phased-locked loop GNSS
 499 receivers at the lowest part of the profile. Visual inspection of individual profiles based
 500 on Fig. 8 reveals larger deviations between observed and simulated bending angles than
 501 between 1D and 2D simulations, which are generally in close agreement. Some of the largest
 502 differences are shown for IOP04 and are associated with the height of the upper level tem-
 503 perature inversions at about 6-7 km altitude.

504 The ARO retrieval method utilizes in-situ measurements as a constraint in both
 505 the bending angle inversion and the refractivity inversion (Cao et al., 2024). Any error
 506 in the in-situ meteorological sensor on-board the aircraft, can affect the overall bending
 507 angle statistics due to the non-negligible contribution of errors in refractivity at the top

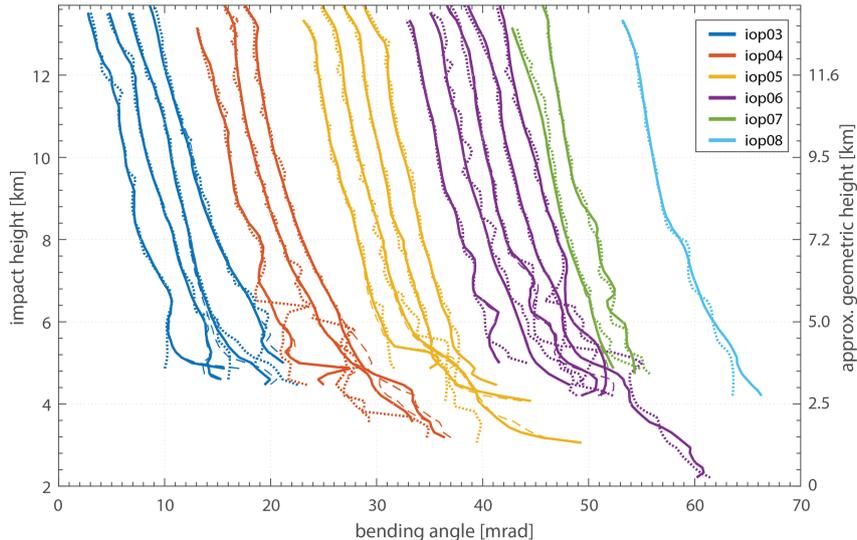


Figure 8. Profiles of observed bending angles (dotted line) for which the individual deviations at 4-5 km impact height relative to 2D simulations (solid line) exceed the corresponding one sigma standard deviation based on statistics for all occultations during six IOPs. Results for 1D simulations are presented for reference (dashed line). Consecutive profiles within each IOP are shifted by 2 mrad for visibility, while the first profiles for given IOPs are separated by 10 mrad.

508 of a given ARO profile to the retrieval. We investigate whether observations that have
 509 large differences relative to simulations are profiles that have unreliable in-situ measure-
 510 ments. Unreliable in-situ measurements (e.g. due to a malfunctioning humidity sensor)
 511 would show up as a large difference between in-situ and retrieved ARO refractivity at
 512 the top of the profile (green points in Figure 9). These might also be expected to show
 513 up as large differences between in-situ and ERA5 (orange points in Fig. 9). For the most
 514 part, high agreement between retrieved and measured refractivity values can be explained
 515 by the fact that the ARO retrieval method utilizes in-situ measurements as a constraint
 516 in both the bending angle inversion and the refractivity inversion. The median shows
 517 unbiased characteristics throughout all six IOPs with relatively small spread in terms
 518 of interquartile range. The refractivity statistics should be contrasted with bending angle
 519 angle deviations computed at the upper impact height level in Fig. 7 to determine whether
 520 uncertainties in in-situ values could account for large bending angle errors. Figure 7 shows
 521 a relatively large sample of outliers with underestimated observations of bending angle
 522 relative to forward modeled profiles, especially for IOP05. The in-situ refractivity dif-
 523 ferences show outliers of $\pm 2-3\%$ relative to retrieved as well as ERA5 values. However,
 524 they are not specific to IOP05 nor are they large enough to account for -25% bending
 525 angle differences in Fig. 7 so we conclude that uncertainties in in-situ measurements are
 526 not responsible.

527 The fairly distinctive positive bias for IOP08 with overall larger spread in the re-
 528 fractivity should be regarded as a result of inaccurate representation of the atmospheric
 529 state since ARO retrieved values agree well with the observed in-situ values. The other
 530 IOPs all have outliers with relatively large differences, with no systematic explanation.
 531 The flights transition across the tropopause between Hawaii and the furthest northern
 532 points on the flight track, which in IOP04 to IOP07 reach the upper level trough. This
 533 could create highly variable temperature and/or tropopause height in the in-situ and ARO
 534 measurements that may not be reflected in the reanalysis fields.

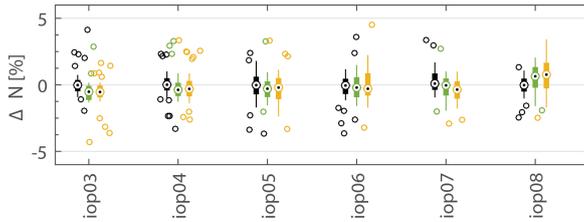


Figure 9. Refractivity deviations in percentage at the aircraft height for each IOP computed as (black) retrieved minus in-situ, (green) retrieved minus ERA5 and (orange) in-situ minus ERA5.

6 Analysis of forward modeling errors

The methods for simulating the bending angle used by the forward model (observation operator) are not exact and thus contribute to errors when analyzing the bending angle deviations. There are two main approximations to consider: (1) the approximation of spherical symmetry made in the 1D observation operator, and (2) the approximation of a vertical profile when the tangent points are drifting horizontally. We examine these approximations for a particularly challenging case where there is a strong vertical gradient in refractivity of limited horizontal extent. The occultation in question is on the northeast side of the IOP04 flight track in Fig. 1. The tangent point drifts towards the northwest, from the highest tangent point at the flight track to the lowest tangent point at 37.19°N , 170.57°W , across an elongated IVT feature with IWV ~ 25 mm and IVT > 375 $\text{kg m}^{-1} \text{s}^{-1}$. A slice of the refractivity field calculated from the ERA5 is used for the 2D ray-tracing for the lowest tangent point (Fig. 10). It clearly indicates an inversion layer in the lowermost troposphere manifested by a vertical gradient $dN/dz = -130$ km^{-1} . The lowest penetration depth of the observed ARO profile coincides with the top of the inversion layer at ~ 3 km impact height.

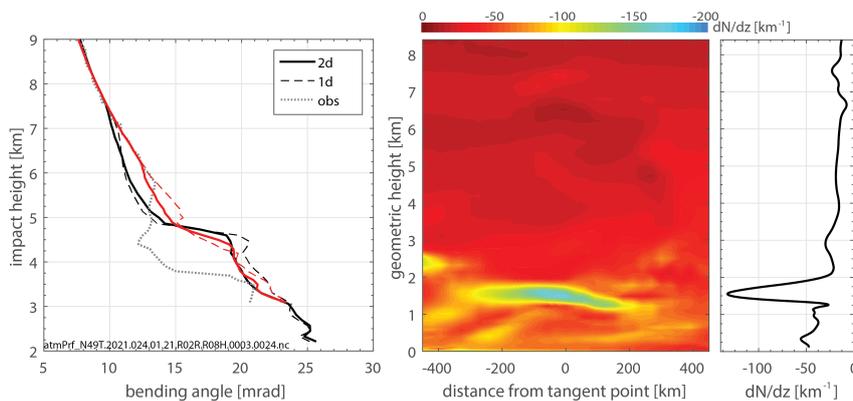


Figure 10. (left) Observed bending angle profile (dotted line) at 37.2°N , 170.5°W during IOP04 simulated with tangent point drift (red line) and without tangent point drift (black line). Simulations in a 2D atmosphere are marked with solid lines, while 1D results are shown in dashed lines. (middle) 2D field of vertical refractivity gradient (dN/dz) with respect to geometric height. The approximate correspondence to impact height is achieved by scaling the vertical extent of both figures. (right) The profile of dN/dz at the center of the refractivity field shown in the middle panel.

551 The atmospheric variability is reflected in the differences among simulated bend-
 552 ing angles when incorporating tangent point drift (black) versus ignoring tangent point
 553 drift (red) in Fig. 10. In map view in Fig. 1 for IOP04 the tangent points at high alti-
 554 tudes near the aircraft location drift into a region of higher IVT and moisture at inter-
 555 mediate heights (see supplemental material). The higher moisture corresponds to higher
 556 refractivity which likely explains why the bending angle calculated with tangent point
 557 drift (red) is greater than the bending calculated without tangent point drift (black) in
 558 the impact height range from ~ 7.5 km down to about 5 km. The observations closely
 559 match the bending angle profiles simulated with the tangent point drift above 6 km im-
 560 pact height. This demonstrates high sensitivity of ARO observations to atmospheric fea-
 561 tures in the middle troposphere that can be well captured even with a closed-loop GNSS
 562 receiver as previously demonstrated in the example in Fig. 5. The effect of tangent point
 563 drift contributes to 10 % bending angle differences at 6.5 km impact height even though
 564 the horizontal variations in refractivity gradient do not appear to be large at that height
 565 (Fig. 10 center).

566 The observed profile deviates significantly from all of the simulated profiles below
 567 5 km impact height, where the simulations indicate a steep increase in bending angle.
 568 The change in gradient near that height could lead to multipath potentially causing cy-
 569 cle slips in the receiver tracking. This ultimately produces unreliable observations be-
 570 low 5 km height with less accumulated delay and less bending. This type of error could
 571 likely be eliminated in the future with open loop processing of the GNSS signal recorder
 572 data.

573 The effect of horizontal inhomogeneity in the refractivity field thus produces an er-
 574 ror in simulated bending angle when the tangent point drifts across regions with vary-
 575 ing atmospheric properties, and produces an error due to the integration along the ray-
 576 path where the ray-path traverses horizontally varying structure. This was anticipated
 577 based on simulations in an idealized cold frontal structure (Xie et al., 2008), and are seen
 578 here to occur in the more realistic ERA5 representations of the refractivity field in an
 579 AR. The two effects are studied separately to assess their individual contributions for
 580 the entire dataset based on specific configurations of the ARO forward model.

581 **6.1 Effect of tangent point drift**

582 In order to improve the computational efficiency of RO forward models, the im-
 583 pact of tangent point drift can be tested by assuming a single representative location for
 584 retrieved profile. For ARO, the reference tangent point position provided in the global
 585 attributes for the data products is the location of the lowest tangent point observed in
 586 the profile. Figure 11 shows the tangent point drift for ARO calculated as a difference
 587 between uppermost and lowermost observed points in each profile for the six IOPs of AR
 588 Recon 2021. The drift is on average ~ 350 km and can occasionally reach 700 km, sug-
 589 gesting that its contribution should not be neglected when the atmosphere varies hor-
 590 izontally. The 2D operator requires refractivity information extracted from an atmospheric
 591 model in a 2D plane along to the ray-path and calculates the bending angle for all ray
 592 paths assuming the tangent point does not drift. We assess this assumption with two
 593 simulation experiments. The non-drifting tangent point experiment uses the reference
 594 tangent point position at the lowest point for all ray-paths. For the drifting tangent point
 595 experiment, for each tangent point in the profile, we extract a different 2D planar refrac-
 596 tivity at the location of the individual tangent point, perform the simulation for bend-
 597 ing angle using the 2D operator, extract the bending corresponding to the height for that
 598 individual ray-path, then move to the next tangent point location in the profile and re-
 599 peat the procedure.

600 The assumption of no tangent point drift for ARO is more valid in the lower tro-
 601 posphere where tangent points are closer to the reference tangent point location. This

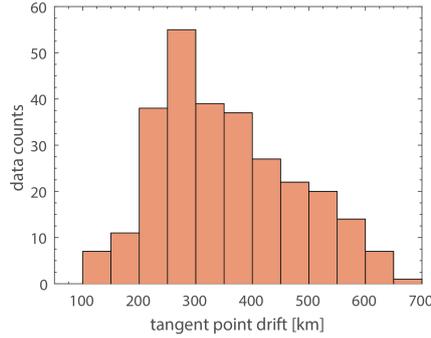


Figure 11. Histogram showing the tangent point drift calculated as a difference between uppermost and lowermost points for each ARO retrieval collected during the six IOPs of AR Recon 2021.

602 is reflected in the statistics presented in Fig. 12 as the impact of tangent point drift in
 603 the middle to the lower troposphere is shown to be relatively small generally, with relative
 604 bending angle standard deviation not exceeding 1.5 %. Since the tangent point drift
 605 in ARO retrievals generally increases with height and becomes the most significant at
 606 the upper levels, the disagreement in the simulated bending angles can exceed 5 % standard
 607 deviation and lead to -1.5 % bias at 13 km. The effect of tangent point drift at the
 608 top of the profile could be mitigated by choosing a reference tangent point that is more
 609 representative for the upper level retrievals, at the expense of introducing errors at lower
 610 tangent points. The assumption of no drift could reduce the computational cost of im-
 611 plementing the 2D forward model for ARO. However, the additional cost of the 2D drift-
 612 ing tangent point location for ARO is not prohibitive given that the total number of tan-
 613 gent points per profile is generally less than 150 given that heights are limited to ~ 14
 614 km with the diffraction limited vertical resolution of ~ 100 m for the geometrical optics
 615 retrieval.

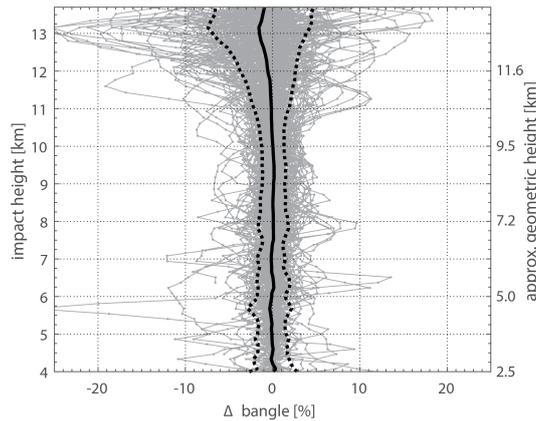


Figure 12. Bending angle differences in fractional units between 2D simulations without and with tangent point drift (drifting minus non-drifting). Grey lines correspond to bending angle differences for individual profiles, the solid black line is the mean difference and dotted black lines show standard deviation.

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6.2 Effect of horizontal gradients

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In order to assess the effect of horizontal refractivity gradients on bending angle profiles, results from two simulation schemes are compared based on forward modeling with the 2D operator. To distinguish the errors from those described in the previous section, the bending angles are simulated without considering the tangent point drift. The refractivity field used in the 2D simulation scheme is centered at the location of reference tangent point, and 15 profiles on either side are extracted in the occultation plane, as described in Section 4. In the corresponding 1D simulations, the central profile is replicated for 31 locations along the occultation plane replacing the horizontally varying refractivity field. The bending angles are simulated on a predefined impact height grid with exponentially varying vertical spacing of 120–190 m below 10 km. Figure 13 shows that contributions of horizontal gradients are generally small at the upper levels, resulting in 1 % standard deviation. Some profiles, however, have as much as 3–4 % deviation, likely associated with the tropopause. Below 10 km the deviations increase as the impact height decreases up to 5 % at 4 km impact height. The standard deviation between the 1D and 2D simulations computed within 4–5 km impact height is 3.75 %. This can be contrasted with corresponding bending angle deviations for ARO observations in Fig. 7, which have standard deviations of 8.34 % and 7.75 % relative to 1D and 2D simulations, respectively. The assessment of bending angle deviations due to horizontal refractivity inhomogeneities suggests that the application of the 2D forward model should be advantageous for assimilation of ARO observations. Below 4 km the deviations rapidly increase to exceed ± 20 % in the lowermost 2 km. The variations are mostly driven by large bending angle magnitudes (Sokolovskiy, 2003) caused by sharp inversion layers that are recognized to produce negative biases in spaceborne RO retrievals of refractivity in the presence of super-refraction (Beyerle et al., 2006; Ao, 2007). In order to mitigate this effect, in the operational use at Naval Research Lab (NRL) and ECMWF, the ROPP operator terminates simulating the profile below super-refraction layers indicated by vertical refractivity gradient less than -157 km^{-1} (Ruston & Healy, 2021).

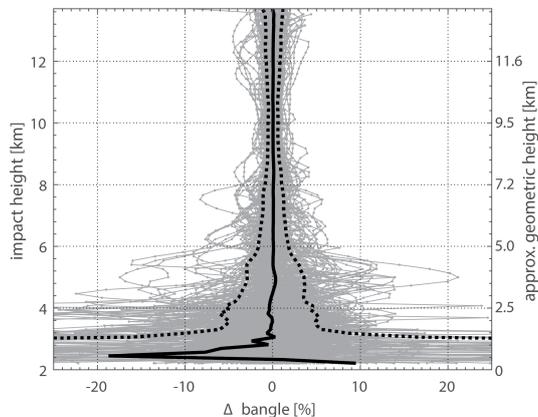


Figure 13. Bending angle differences in fractional units computed as 1D minus 2D simulations showing the effect of horizontal inhomogeneities. Grey lines correspond to bending angle differences for individual profiles for all eight IOPs, the solid black line is the mean difference and dotted black lines show standard deviation.

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7 Analysis of bending angle profiles in atmospheric rivers

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We hypothesized that the 2D bending angle operator would show large difference with respect to 1D in the vicinity of an AR because of the strong horizontal gradients

647 of moisture associated with the AR water vapor transport, and temperature gradients
 648 across the cold front. While this is ambiguous in Fig. 7 when broken down by IOP dur-
 649 ing a sequence of flights in 2021, the previous section suggests the moisture component
 650 of IVT (i.e. IWV) predominantly affects the deviations. We find that there are strong
 651 effects for a specific case where the transect of ARO observations crossed perpendicu-
 652 lar to the AR core. Figure 14 shows the deviations between 1D and 2D bending angles
 653 simulated with the effect of tangent point drift as a transect of profiles.

654 The transect crosses the drier region of high pressure south of the AR (A1), then
 655 crosses perpendicular to the AR tail (A2), then crosses back across the AR (A3), and
 656 then back across the high pressure (A4). The deviations are small for all profiles with
 657 low IVT, with the exception of occultation 026.00.20.G07, and are larger for transects
 658 A2 and A3 within the AR. In general, the occultations which cross the AR in transect
 659 A2 and A3 that are shown in red, for high IVT, have higher deviations than those in the
 660 surrounding regions. 45 % of the profiles within the AR have bending angle deviations
 661 greater than 5 % compared to 7 % of the profiles outside the AR. The largest deviations
 662 are between heights of 3–7 km (4–8 km impact height). Note that in the simulation, the
 663 observation operator is only run over the height range captured by observations.

664 Dropsondes were released during transects A2 and A3 of the flights. The dropsonde
 665 profile refractivity anomalies for transect A2 and A3 are shown in Figure 14b. Refrac-
 666 tivity anomaly is the difference between the dropsonde refractivity and the refractivity
 667 climatology for the month of January from the CIRA-Q model (Kirchengast G & W, 1999).
 668 Below 9 km, the moisture term dominates in the refractivity anomaly (B. Murphy et al.,
 669 2015). The regions shaded in red in panel (b) are the moisture rich boundary layer and
 670 the low level jet rising up to 3 km height in the AR core, similar to the spatial charac-
 671 teristics found by Haase et al. (2021). In this case, a dry intrusion (Raveh-Rubin & Catto,
 672 2019) can be seen behind the cold front on the north side of the AR, indicated in blue
 673 shading from 1-2 km in the center of the panel. In A3, the dropsonde in the deepest part
 674 of the AR core indicates moisture reaching up to 3 km. Interestingly, the ARO profile
 675 nearest that dropsonde (025.22.46.G24) extends to the surface. The tendency for RO pro-
 676 files in the AR core to penetrate deeper was observed in previous studies (Murphy Jr
 677 & Haase, 2022), probably because vertical mixing smooths out sharp vertical gradients
 678 that would otherwise cause multipath propagation and signal tracking loss.

679 The mid-to-upper level features of the vertical structure in the dropsonde profiles
 680 tend to increase with height moving away from the center of the diagram, as indicated
 681 by the blue shading and slanted blue lines. The center point of the diagram corresponds
 682 to the furthest north point where the aircraft completed transect A2 and started A3. For
 683 example, sharp gradients associated with dry layers can be tracked from one profile to
 684 the next. The height of the low level moisture in the AR changes with distance along
 685 the transect as well. Similarly the height of the maximum deviation between 1D and 2D
 686 varies from one profile to the next, as well as the height of the lowest tangent point.

687 Profile 026.00.20.G07 has a sharp positive deviation at 3.1 km altitude. Transects
 688 A1 and A4 cross the high pressure outside the AR so there is not a lot of moisture to
 689 cause large horizontal variations. These transects are far from the temperature varia-
 690 tions across the cold front, so these transects are in areas where the 1D and 2D simu-
 691 lations give close results. Occultation 026.00.20.G07 is a long occultation whose lowest
 692 ray-paths sample back towards the AR, so that sharp positive deviation could be indi-
 693 cating that it samples a dry layer at a different height.

694 This example shows that for a case (IOP06) where the flow within the AR is sim-
 695 ple and the sampling geometry is advantageous, it is possible to make a direct link be-
 696 tween the horizontal variations of refractivity and the deviations between 1D and 2D bend-
 697 ing angle simulations. For these cases, it is expected that implementing the newly de-
 698 veloped 2D bending operator will produce superior results in data assimilation exper-

699 iments. In this sequence of flights, only IOP06 flew across the core of a well-formed AR.
 700 The other flights (IOP03-IOP05) are sampling regions of tropical moisture export, which
 701 can also have high IWV and IVT but are more difficult to interpret. Two of the flights
 702 (IOP07-IOP08) sampled primarily in the 500 hPa trough associated with the low pres-
 703 sure system with less moisture overall.

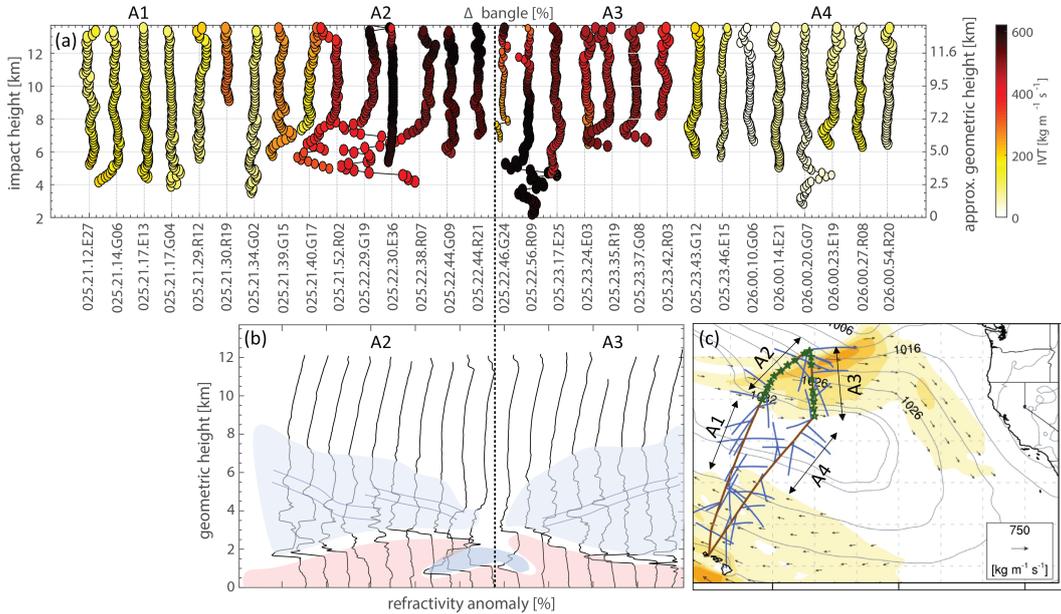


Figure 14. (a) Deviations between 1D and 2D bending angles simulated with tangent point drift for occultations along the transects across the AR indicated by A1, A2, A3, A4 as shown in panel (c). Each profile is shifted by 10 %. Individual tangent points are color-coded by the IVT beneath that point, and the size of each dot is scaled to corresponding IWV values. (b) Refractivity anomalies (observation minus climatology) for the dropsondes in transects A2 and A3. (c) Location of occultation profiles along transects A1 (outside the AR), A1 and A2 (inside the AR) and A4 (outside the AR).

8 Conclusions

704

705 The modification of the 2D forward model for ARO bending angle observations opens
 706 up a wide range of new applications for improved weather prediction using airborne and
 707 balloon-borne platforms. Because of the strong gradients in temperature and humidity
 708 found in ARs and their associated cold fronts, a sophisticated approach utilizing a two-
 709 dimensional structure of the atmosphere has been adopted in the forward model. The
 710 forward model is used to assess the importance of both vertical and horizontal refrac-
 711 tivity inhomogeneities to simulating ARO bending angle observations. Since the tangent
 712 point drift in ARO profiles is on average 350 km and can occasionally exceed 700 km,
 713 the profile cannot be assumed to be vertical. The contribution of tangent point drift in
 714 a horizontally varying structure to forward modeling errors has been addressed by con-
 715 sidering the values of bending angle at observed impact heights as individual observa-
 716 tions rather than a single vertical profile in the forward simulations. Neglecting this ef-
 717 fect is shown to contribute to bending angle deviations that exceed 5 % in terms of stan-
 718 dard deviation. Previous work used the approach of assimilating 2D varying excess phase
 719 (X. M. Chen et al., 2018) or refractivity (Haase et al., 2021), which were both based on
 720 retrieving partial bending angle, defined as the portion of the bending accumulated be-

low the aircraft flight altitude (Haase et al., 2014). This work demonstrates that there is significant reduction in error at the top of the profile if the full bending angle is used rather than partial bending. The application of a 2D operator is advantageous in simulating ARO profiles in the lower troposphere where the bending angle deviations can exceed 20 % relative to the simulations assuming a spherically symmetrical atmosphere. This will benefit future AR Recon campaigns once the open-loop tracking capability is available for ARO observations. With the current penetration depth of ARO profiles, typically down to 4 km impact height, the disagreement between 2D and 1D bending angles can reach 5 % in terms of standard deviation. The analysis of specific ARO profiles crossing an AR region characterized by high IVT magnitudes suggests that improvements on the order of 10 % are also expected in the middle troposphere due to the application of the 2D operator. While the use of the 2D forward model contributes to the overall complexity of the algorithm and reduces its computational efficiency, to date the increased cost has not been shown to be prohibitive for RO applications in NWP.

Data and software availability

The ARO data is available at <https://agsweb.ucsd.edu/gnss-aro/>. The dropsonde data is available at https://cw3e.ucsd.edu/arrecon_data/. The ROPP 2D operator is maintained and licensed by the EUMETSAT Radio Occultation Meteorology Satellite Application Facility (ROMSAF) at <https://rom-saf.eumetsat.int/ropp/>. The airborne radio occultation observation operator which relies on access to a ROPP license is available on request at <https://github.com/jhaaseresearch/sio-ropp>.

Acknowledgments

This work was carried out at the Scripps Institution of Oceanography, University of California San Diego, as part of the Atmospheric Rivers Program funded by the California Department of Water Resources. Paweł Hordyniec was supported in part by the Polish National Agency for Academic Exchange as part of the Bekker programme under the project entitled "Remote sensing of the atmosphere with airborne GNSS radio occultations" (PPN/BEK/2020/1/00250/U/00001). ARO data collection was made possible through Atmospheric Rivers Reconnaissance, a research and operations partnership between the Center for Western Weather and Water Extremes (CW3E) and the National Center for Environmental Prediction (NCEP). The primary facilities partners that make AR Recon possible are the United States Air Force Reserve Command 53rd Weather Reconnaissance Squadron and the NOAA Aircraft Operations Center. We thank the NOAA AOC for making observations possible from the NOAA G-IV and assisting in operation of the receivers. We thank the forecast and flight design teams and flight crews in planning and executing the targeted observation missions for the data collected for this paper, and Natalie Contreras (SIO) for assistance with data management. Additional funding for data collection and development of the ARO observation capability at Scripps was provided by NSF GRANT AGS-1642650 and AGS-1454125, NASA GRANT NNX15AU19G, and through a CW3E collaboration from the US Army Corps of Engineers. We would like to thank Sean Healy (ECMWF, UK) for his suggestions regarding potential modification of the existing 2D forward model for spaceborne RO. Dropsonde data were funded by AR Recon and made available by the NOAA Office of Marine and Aviation Operations (OMAO), and ERA5 reanalysis data were provided by the ECMWF. Additional computational resources were provided by the CW3E COMET computer facility and the NSF Cheyenne HPCMP facilities.

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