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“卫星资料应用” 专题系列

GPS无线电掩星资料特点

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GPS（Global Positioning System）指全球（卫星）定位系统，最初的设计是为了美国军方的精确定位，于1980年代与1990年代早期开始应用。GPS共由距地球表面约20200km高度的6个轨道上运行的24颗卫星组成，这些卫星以2个L波段频率（f_1=1.57542GHz，f_2=1.22760GHz）持续发射电磁波。GPS为将无线电掩星（Radio Occultation）技术应用到地球大气领域提供了基础。

GPS发射的无线电信号传播在真空中是一条直线。但实际射线从GPS卫星发射，途经地球电离层和中性大气层时，受电离层电子密度分布和大气折射率的影响， 路径有不同程度的弯曲，从而延迟这些信号到达低轨（Low Earth Orbiting，LEO）接受卫星的时间。基于卫星的精确位置与运行速度，可以导出总的弯角（bending angle）。由于GPS发射卫星和低轨接受卫星的相对运动，从大气顶部到地球表面的整个大气层都有射线穿过，因此可以获得弯角的垂直廓线（图1）。GPS无线电信号的波长较长，大约为20cm，故这些信号传播途经大气层时不受气溶胶和云雨的影响。通过把两个波段的信号传播延迟量进行一种线性组合，可以消除电离层对信号传播路径的影响。剩余的无线电信号传播延迟量便仅仅包含中性大气中大气折射率的影响。

图1给出了掩星观测事件示意图，GPS轨道局地高度为20200km，低轨卫星轨道局地高度在500～800km之间。红线表示GPS射线路径，射线经过大气层时受大气折射率的影响而弯曲，被安装在LEO卫星上的接收机接收到。射线上最接近地球表面的点称之为切点，将这些切点连成一条线（图1紫色线），即是GPS掩星的探测印痕（footprint）。GPS掩星在每一个切点的观测值其实就是射线路径方向上积分的信息，同一观测廓线射线的切点位置随高度变化而变化。由图1可见，GPS掩星观测是一种临边探测技术。

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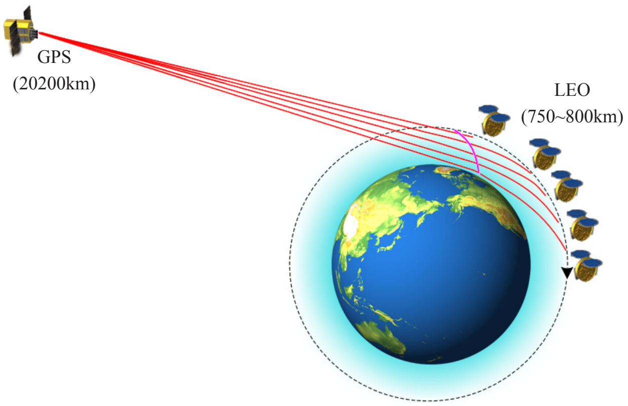

图1 掩星事件示意图（虚线表示低轨卫星（LEO）的轨道；红线表示GPS射线路径；紫色线代表各个射线上离地球最近点的连线，即GPS 五线电掩星观测垂直廓线；蓝色阴影区代表大气层）

Fig. 1 A schematic illustration of a GPS RO event, shown are ray paths (red), a vertical profile of perigee points (purple), LEO orbit (black dashed) and the atmospherc layer (shaded in cyan)

至今，已成功执行了多个GPS掩星资料测量计划，其中包括美国的GPS/MET（GPS/Meteorology）， 德国的CHAMP（Challenging Minisatellite Payload），阿根廷的SAC-C（Satellite de Aplicaciones Cientifico），德国/美国合作的GRACE-A（Gravity Recovery and Climate Experiment），中国台湾/美国合作计划FORMOSAT-3/COSMIC（Constellation Observing System for Meteorology, Ionosphere and Climate）， 欧洲的Metop-A（Meteorological Operational Satellite），和德国的TerraSAR-X。这些GPS掩星计划发射时间和有可用资料范围见表1。早期的GPS/MET的掩星实验，每天大约可以获得100～150个掩星垂直廓线。随后的

表1 GPS掩星计划发射时间和有可用资料范围

Table 1 GPS Occultation Lunch Time and Range of Available Data

掩星计划	发射时间	资料起始时间	资料终止时间
GPS/MET	1995-04-03	1995-04-21	1997-02-16
CHAMP	2000-07-15	2001-05-19	2008-09-03
SAC-C	2000-10-21	2001-08-03	2011-08-13
GRACE-A	2002-03-17	2006-02-28	2006-06-29
COSMIC	2006-04-14	2006-07-13	至今
Metop-A	2006-10-19	2007-09-30	至今
TerraSAR-X	2007-06-15	2008-02-10	至今

CHAMP和SAC-C一起每天可提供350个掩星廓线。与其他GPS掩星计划不同，COSMIC有6颗低轨卫星，每天可得到大约3000个廓线，这个数字是全球探空资料的3～4倍。目前，还在健康运行的装载有GPS接受器的低轨卫星只有COSMIC、Metop-A和TerraSAR-X，每天提供的总廓线数已经减至1000～1500根。原计划于2012年升空的COSMIC 2由于各种原因推迟，FORMOSAT-7/COSMIC-2计划可能将于2016和2018年各发射6颗低轨卫星。如果FORMOSAT-7/COSMIC-2发射成功，全球每天将可以获得12000根掩星观测廓线（可参考http://www.cosmic.ucar.edu/cosmic2/index.html）。

目前，COSMIC数据分析存储中心（COSMIC Data Analysis and Archive Center，CDAAC）负责GPS数据的监测和存储，并为用户提供数据下载服务。GPS掩星产品按照产品等级来分，分为一级（L1）和二级（L2）。一级产品（L1）主要包括LEO卫星测量数据，地面基站跟踪数据，导航数据，LEO精密星历表，以及L1和L2相位残差和信噪比。二级产品包括弯角、折射率、压强、反演的温度和水汽等，被广泛应用在气象业务和气象研究的各个方面。按照其时效性来看，GPS掩星产品还包括实时产品和后处理产品。实时产品是用于天气监测和预报的临近数据，一般观测时间90min后可以拿到。后处理产品由于更准确更有效，在气象研究中得到更广泛地关注，一般2～3个月后可以下载。GPS二级掩星反演产品主要包括的变量有弯角、折射率、影响参数、射线切线方向与正北方向的夹角，以及其反演产品干空气温度、气压、湿空气温度和水汽压。为了便于和GPS掩星产品进行比较，CDAAC将NCEP GFS分析资料、ECMWF TOGA和ERA-40 Interim再分析资料和无线电探空资料插值到掩星观测廓线的平均位置。

GPS无线电掩星观测得到的折射率N是大气温度T，气压p，水汽压p_w，云水含量q_{lwc}和冰水含量q_{iwc}的函数：

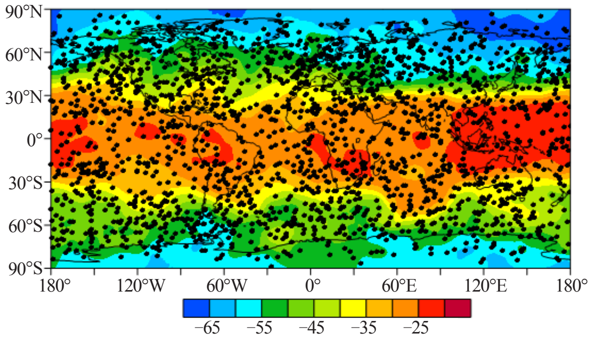

图2 2007年1月1日9km高度处 COSMIC GPS 掩星观测廓线（黑点）和温度反演（彩色阴影）的全球分布

Fig. 2 Global distribution of COSMIC GPS ROs (black dot) and temperature retrieval at 9 km (shaded)

$$N=77.6\frac{p}{T}+3.73\times10^5\frac{p_w}{T^2}+1.45\,q_{lwc}+0.69\,q_{iwc} \quad （1）$$

其中，T，p，p_w，q_{lwc}，q_{iwc}的单位分别为K，hPa，hPa，g·m^{-3}，g·m^{-3}。因此，通过GPS无线电掩星资料同化，可以得到中性大气中T，p，p_w，q_{lwc}和q_{iwc}的有用信息。然而，与同化任何一种资料一样，GPS无线电掩星资料同化效果与质量控制、同化方法和结果的正确检验有密切的关系。而做好以上这三方面工作的必要条件是对该资料的基本特点有充分的了解。GPS无线电掩星资料质量控制和同化方法的一些研究结果见文献[1-9]。

GPS无线电掩星资料有以下几个值得注意的属性：（1）GPS掩星的每个垂直廓线的观测时间约为1min；（2）水平分辨率约300km，切点处的大气折射率对整个信号路径的弯角影响最大；（3）平流层内的垂直分辨率约为1.5km，在对流层低层增加到0.2km。GPS掩星资料误差主要来源于测量误差、资料处理过程中的误差传播、资料处理中所用近似假定引起的误差。测量误差包括随机误差与系统误差。GPS掩星资料的系统误差主要来自于局地多路径的出现、卫星的位置误差、卫星运行速度误差和反演误差。GPS无线电掩星资料的资料处理流程和资料误差细节见文献[10]。

GPS无线电掩星资料的一些基本特点通过图2－6进行了简单描述。图2给出了2007年1月1日9km高度处COSMIC GPS 掩星观测廓线和温度反演的全球分布。注意到COSMIC 掩星资料在中高纬度最密集。与探空廓线类似，GPS 掩星观测廓线的观测位置随高度变化而变化。图2中给出的是平均位置。图3和4分别给出了2007年1月1日的某个 COSMIC GPS 掩星廓线观测位置的三维和二维分布。 图4还给出了不同观测高度上的无线电信号传播路径在近地面点的切线方向。由图可见，不仅掩星观测廓线的观测位置随高度变化而变化，切线方向也随高度变化而变化。每个掩星观测资料反应的是该方向上大约300km长、1.4km宽的范围内的大气状态对无线电信号传播的总效应。不同位置上的大气状态对掩星观测资料的影响大小不同，近地面点的贡献最大（图5），离近地面点越远贡献越小。图6给出了该掩星观测到的弯角、折射率、温度和水汽压随高度的变化。受低层水汽的影响，弯角有很大变动（图6a）。受大气密度的影响，折射率随高度呈指数递减（图6b）。图6c和6d是根据弯角反演的温度和水汽压垂直廓线。由于具有高垂直分辨率，GPS掩星观测资料能非常精确地确定对流层顶的高度。

对数值预报和气候变化研究而言，GPS掩星观测这种临边探测资料对星下点探测卫星资料可以起到一个很好的互补作用。GPS掩星资料还具有其应用于气候变化研究的其他三个独特优点：（1）SI-可追溯

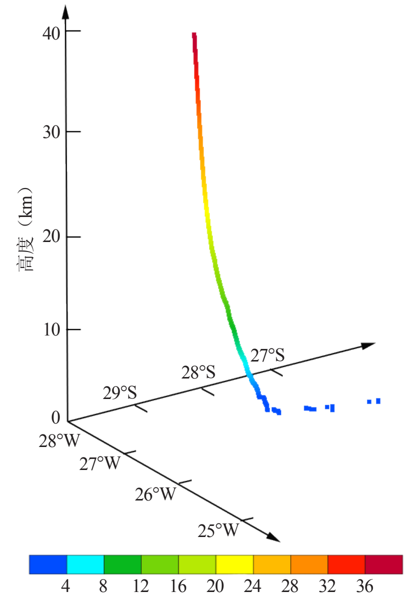

图3 与图2同一 COSMIC GPS 掩星廓线观测资料的空间位置三维分布（观测高度由垂直坐标和彩色阴影同时表示）

Fig. 3 A three–dimensional （3D）distribution of a GPS RO event that occurred on January 1, 2007（The height of the GPS RO profile is indicated in both z–axis and color）

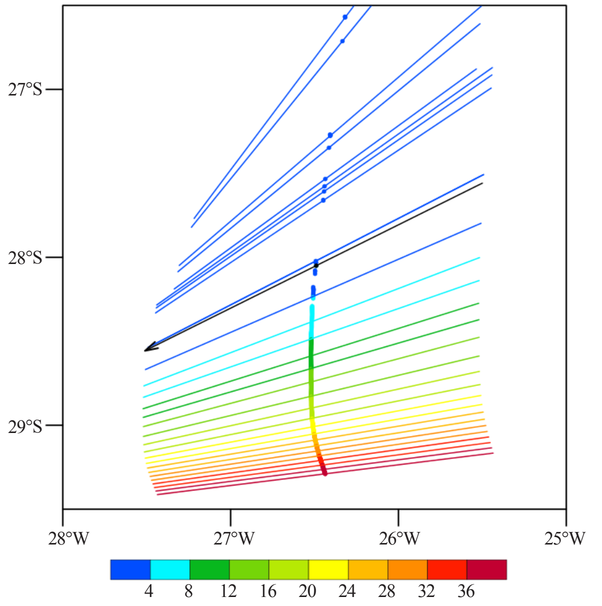

图4 与图2同一 COSMIC GPS 掩星廓线观测点（点）和不同观测高度上的无线电信号传播路径在近地面点的切线方向（直线）的二维分布

Fig. 4 A two–dimensional projection of the profile in Fig. 2. Also shown are tangent directions （straight lines）plotted at an interval of 20 ray paths above the height of 1.5 km. The mean position of the RO is at the height of 1.8 km（black arrow）

性（SI-traceability）。GPS 掩星观测的原始数据是时间，其值由根据国际标准单位的原子钟校准过的地面参考时钟来决定。所以，GPS RO资料具有SI可追溯性。（2）GPS掩星资料不受GPS接受仪器（GPS receiver）类型的影响，所检测到的气候信号不随时间衰减，没有随卫星平台变化而变化的系统偏差。（3）在对流层上层和平流层内，湿度对折射率的贡献可忽略，根据折射率廓线可以反演出精确度非常高（约0.1K）的大气气压与温度廓线。由于以上这些独特属性，GPS掩星资料可以作为气候变化研究的基准资料，用来对卫星微波温度计资料进行校准。再通过一维变分同化，经过校准了的卫星微波温度计资料，可以得到长达30多年的、能精确描述对流层和平流层温度气候变化趋势的均一化温度气候数据纪录。

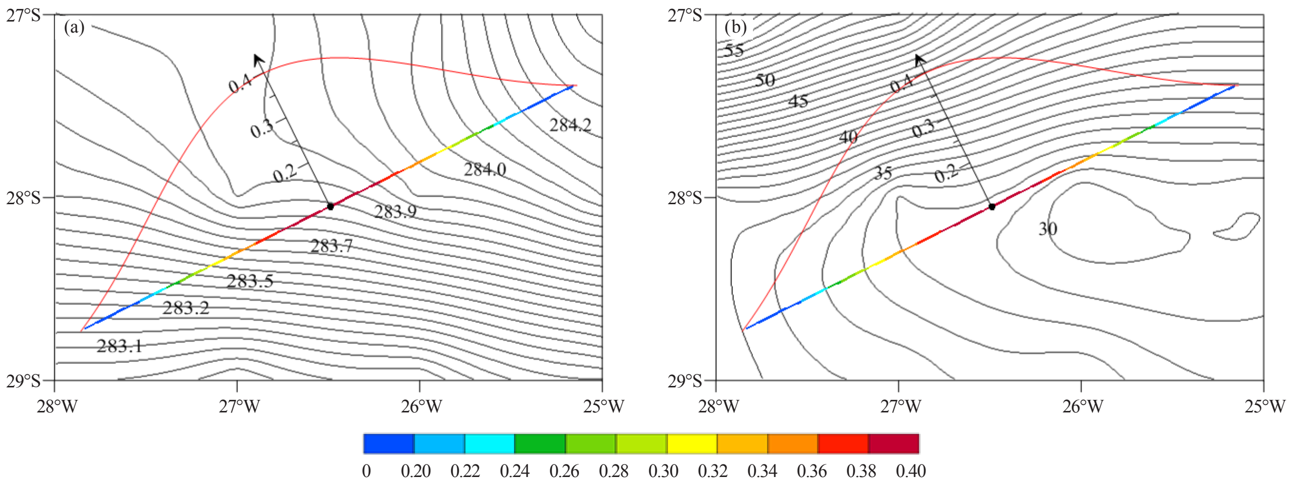

图5 大气温度（a，单位：K）和相对湿度（b，单位：%）
（直线表示以平均位置为中心，长300km、宽1.4km的切线方向；直线上的颜色表示权重）

Fig. 5 NCEP GFS （a）temperature （unit: K） and （b）relative humidity （unit: %）
（The tangent direction at the mean position with a length of 300 km and width of 1.4 km is shown in both （a） and （b）, and the color on the line indicates relative weights of the atmosphere to the measured refractivity）

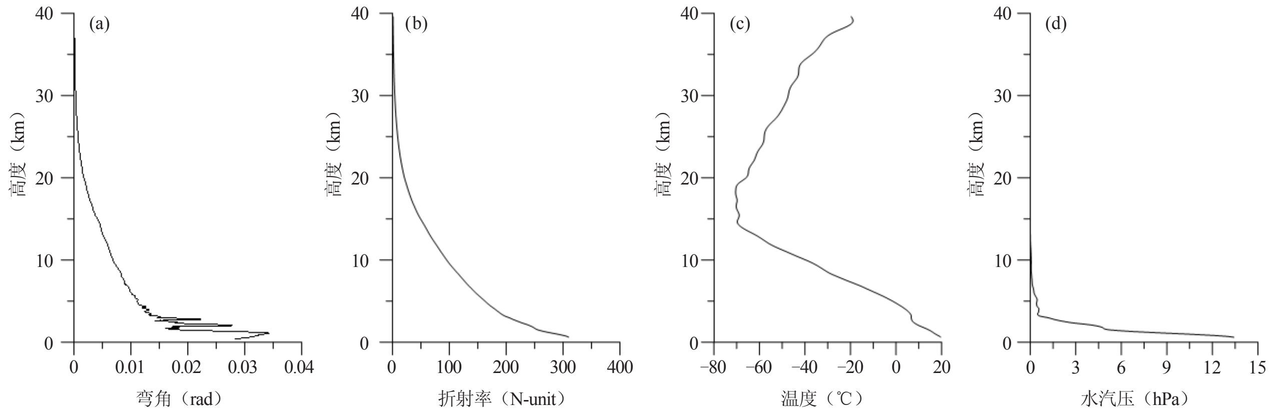

图6 2007年1月1日COSMIC 掩星观测廓线
（a）弯角，（b）折射率，（c）温度，（d）水汽压
Fig. 6 Vertical profiles of（a） bending angle,（b） refractivity,
（c） temperature, and （d） water vapor pressure retrieved from the same COSMIC GPS RO shown in Fig. 3

Serial of Applications of Satellite Observations

GPS RO Data Characteristics

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GPS stands for Global Positioning System. It came into use in 1980s and early 1990s. Initially, it was designed for accurate positioning in US army. This system is composed of 24 satellites circling on six orbits at about 20200 km high above the earth. These satellites continuously emit radio electromagnetic waves through two L-band frequencies (f_1=1.57542 GHz and f_2=1.22760 GHz). GPS provides a practical foundation for applying radio occultation (RO) technique to the observation of the Earth's atmosphere.

The radio signal emitted from GPS transmits linearly in vacuum. However, when the signal passes through the ionosphere and neutral atmosphere, its transmitting path bends at varying degrees according to the electron density distribution in the ionosphere and the influence of atmospheric refractivity. As a result, the time when the signal reaches a receiver onboard a low-earth-orbiting (LEO) satellite is delayed. The total bending angle can be derived from the precise positions and moving speeds of both satellites emitting and receiving this signal. Because of the relative movement of GPS transmitting satellite and the receiving satellite at low earth orbit, the radio signal penetrates through the whole atmospheric layer from the earth surface to the top of the atmosphere. Therefore, a vertical profile of the bending angle can be obtained (Fig. 1). The GPS signals have long wavelength of about 20cm and could thus pass through aerosols, cloud and precipitation in the atmosphere. A linear combination of the signal delay at two wavelengths could eliminate the impact of ionosphere on signal transmitting path. The residual delay accounts for the delay caused by the atmospheric refractivity in the neutral atmosphere.

Fig. 1 provides a schematic illustration of an RO event. The GPS orbits at 20200 km height above the earth, while the LEO satellite is 500~800 km above the earth. Red line indicates the GPS radio signal path. The signal path bends because of the impact from atmospheric refractivity when passing through the atmosphere. The GPS receiver placed on a Low Earth Orbit (LEO) satellite will receive the signal. The nearest point to the earth on the signal ray path is defined as the tangent point. When all the tangent points are connected together (the purple line showed in Fig. 1), it becomes the footprint of a GPS RO observation. It is emphasized that an GPS RO measurement is a measure of an integrated effect of the atmospheric refractivity along the ray path of about 300~500 km long centered at the tangent point. The position of tangent point on the same observation profile varies with height. From Fig. 1, it is seen that GPS RO is a limb sounding technique.

So far, several GPS RO missions were successfully implemented, including American GPS/MET (GPS/Meteorology), German CHAMP (Challenging Minisatellite Payload), Argentine SAC-C (Satellite de Aplicaciones Cientifico), GRACE-A (Gravity Recovery and Climate Experiment) cooperated by Germany and US, FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) cooperated by Taiwan and US, European Metop-A (Meteorological Operational Satellite), and German TerraSAR-X. Table1 lists the launch times and mission periods of these GPS RO missions. The early GPS/MET RO experiment provided about 100~150 occultation vertical profiles every day. Subsequent missions such as CHAMP and SAC-C together provide 350 profiles daily. Unlike other GPS RO programs, COSMIC employs six LEO satellites, and provides about 3000 profiles globally, which is 3~4 times more than any other GPS RO mission with a single LEO satellite carrying a GPS receiver. At present, COSMIC, MetOp-A and TerraSAR-X are LEOs, each LEO being equipped with a single GPS receiver, and are still healthily functioning. But the amount of profiles provided daily has decreased to 1000~1500. The COSMIC-2, planned to launch in 2012, was delayed for various reasons. Program FORMOSAT-7/COSMIC-2 might launch six LEO satellites in 2016 and 2018, respectively. If FORMOSAT-7/COSMIC-2 were launched successfully, we could obtain 12000 RO profiles globally every day (see http://www.cosmic.ucar.edu/cosmic2/index.html).

The COSMIC Data Analysis and Archive Center (CDAAC) is responsible for the monitoring and storage of GPS data, and provides download services for users. The GPS occultation data products are classified as Level-1 and Level-2. Level-1 products include LEO satellite measurement data, tracking data from ground-based station, navigation data, LEO precise ephemeris, residual phase and SNR (Signal to Noise Ratio). Level-2 products include bending angle, refractive index, pressure, retrieved temperature and water vapor, etc., which are extensively used in both operational and research centers. In terms of timeliness, the GPS occultation products also include real-time products and post-processing products. The real-time products are instant data obtained in 90 minutes after observing times and are used in operational weather monitoring and forecasting. Post-processing data can be downloaded in 2~3 months and are more precise and effective than real-time data. They are more useful for meteorological research. Level-2 products mainly include the retrieved variables such as bending angle, refractive index, influence parameter, angle between tangential direction of the radio signal and the due north direction, dry air temperature, pressure, wet air temperature and water vapor pressure. For convenience, CDAAC interpolated NCEP GFS analysis data, ECMWF TOGA and ERA-40 Interim reanalysis data to the average position of each RO observation profiles.

The refractive index (N) observed by GPS RO technique is a function of atmospheric temperature (T), pressure (p), water vapor pressure (p_w), cloud water content (q_{lwc}) and ice water content (q_{iwc}):

$$N = 77.6\frac{p}{T} + 3.73\times10^5\frac{p_w}{T^2} + 1.45\,q_{lwc} + 0.69\,q_{iwc}$$

The unit measurements of T, p, p_w, q_{lwc}, q_{iwc} are K, hPa, hPa, g·m^{-3}, g·m^{-3} respectively. Therefore, through the GPS RO data assimilation technique, useful information about T, p, p_w, q_{lwc} and q_{iwc} in neutral atmosphere could be obtained. Like the assimilation of any other data, an effective GPS RO data assimilation is determined largely by how are quality control, observation operator and appropriate validation of assimilation method and result done. It is essential to have a full knowledge of that data. [1-9] provided several methods of both quality control and GPS RO data assimilation.

There are several noticeable features of radio occultation data: (1) the observing time of an entire vertical profile of GPS RO is about 1 minute; (2) its horizontal resolution is about 300 km, and the refractive index at tangent point influence the bending angle of the whole signal path most; (3) vertical resolution is about 1.5 km in the stratosphere, and increases to 0.2 km in the low troposphere. Error sources of GPS RO data include instrument errors, error propagation through data processing process and errors introduced due to approximation assumptions used in data retrieval from raw measurements. The instrument errrors consist of random errors and systematic errors. The later is associated with the presence of multi-paths, satellite position and velocity errors, and retrieval errors. A detailed description of GPS RO data processing procedure and observation errors can be found in [10].

Several basic features of GPS RO data are briefly discussed below through Figs. 2-6. Fig. 2 provides a global distribution of COSMIC GPS RO profiles (dotted) and temperature retrieval (shaded) at 9-km height on 1

January 2007. It is noticed that COSMIC RO data are most densely distributed at middle and high latitudes. Similar to radiosonde profiles, the latitudinal and longitudinal position of a single GPS RO profile varies with altitude. A vertically averaged position of each RO is plotted in Fig. 2, 3 and 4 show three-dimensional (3D) and 2D distributions of an arbitrarily chosen COSMIC GPS RO profile. Tangent directions at the perigee point of a radio propagation path of different sounding heights are also provided in Fig. 4. It can be inferred that not only the sounding positions of occultation sounding profile but also the tangent directions vary with height. Every RO sounding data reflects an integrated effect of the atmospheric state along the ray path of about 300~500 km long and 1.4 km wide centered at the perigee point. The effects of the atmospheric conditions at different positions of the ray are different. The atmosphere near the perigee point contributes mostly to the total bending (see Fig. 5). The further away from the earth, the less the atmosphere contributes. The weights reflecting such a different effect is schematically shown by the vertical coordinate and colored shadows in Fig. 5. A more detailed theoretical and numerical description was provided in Shao et al[3]. Fig. 6 illustrates how an observed bending angle, refractive index, temperature and water vapor pressure varied with altitude. Bending angle is quite sensitive to lower water vapor (Fig. 1a). Influenced by atmospheric density, the refractive index shows an exponential decrease as altitude increases. Figure 6c and 6d are vertical profiles of temperature and water vapor pressure retrieved from bending angle profile using a one-dimensional variation (1D-Var) data assimilation algorithm. Due to its very high vertical resolution, the GPS occultation sounding data can very precisely determine the height of tropopause.

As a limb-sounding method, GPS RO and satellite nadir-looking data are quite complementary for both numerical weather prediction and climate change research applications. There are three exclusive advantages to apply GPS RO sounding data in climate change research: (1) SI-traceability. The original data of GPS occultation sounding is time, which is determined by a reference clock calibrated to atomic clock based on international standard unit. (2) GPS RO sounding data is not sensitive to GPS receiver type; the observed climate signal is not weakened by time; and systematic deviation caused by the change of satellite platform does not exist. (3) The contribution of humidity to refractive index in the upper troposphere and stratosphere is negligible. Atmospheric pressure and temperature profiles can be highly accurately inverted from GPS RO refractivity data. Because of these stated features, GPS RO data can be used as a baseline data for climate change research, and can also be used for calibrating satellite microwave temperature sounding instruments. Through a 1D-Var retrieval, the well calibrated satellite microwave temperature sounding data can be assimilated to provide a homogenous temperature climate data record of more than 30 years, precisely illustrating the temperature climate change trend in the troposphere and stratosphere.

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