"卫星资料应用"专题系列

极轨气象卫星微波温度探测仪资料的分辨率

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2008年5月27日风云3号A星（FY-3A）的成功发射，标志着我国第二代风云3号（FY-3）极轨气象卫星系统的正式启动。两年后，即2010年11月5日，FY-3系列的第二颗卫星——风云3号B星（FY-3B）也成功发射升空。FY-3A与FY-3B一起实现了我国极轨气象卫星上下午星组网观测。与先前的风云1号系列卫星不同，风云3号A/B星均承载有可提供给数值天气预报（NWP）资料同化的以下三种重要微波大气探测仪资料：微波温度计（MWTS）、微波湿度计（MWTS）、微波成像仪（MWRI）[1]。MWTS可提供除强降水以外所有天气条件下的全球大气温度廓线信息。

FY-3A和FY-3B携带的MWTS的四个通道与美国国家海洋与大气局（NOAA）自1978年发射的早期极轨环境卫星（POES）（如从NOAA-6到NOAA-14）上微波探测装置（MSU）的四个通道类似，也与NOAA自1998年开始的近期POES（如NOAA-15/16/17/18/19）搭载的先进微波探测器（AMSU-A）15个通道中的四个通道（即通道3/5/7/9）相似。AMSU-A还搭载在2006年10月19日发射的欧洲第一颗极轨卫星MetOp-A上。AMSU-A的15个通道由AMSU-A1和AMSU-A2两个模块提供。AMSU-A1提供分布在50.3～57.3GHz氧气吸收带的12个通道，可提供从地表到42km（或2hPa）高度范围内的大气温度廓线；AMSU-A2则提供另外3个通道，频率分别为89，23.8和31.4GHz。MSU，AMSU-A和MWTS为数值天气预报[2, 3]和全球气候变化研究[4, 5]提供关键观测资料。图1分别展示了美国极轨气象卫星NOAA-6/7/8/9/10/11/12/14/15/16/17/18/19，欧州极轨气象卫星MetOp-A以及中国极轨气象卫星FY-3A/B的覆盖时间。文献[6]对建立卫星气候数据集的挑战和问题进行了广泛讨论。

气象卫星观测到的某个辐射量值表示在一段时间内来自特定大气体积内的上涌微波辐射总量。大气体积的大小和观测时间的长短即为该卫星观测辐射

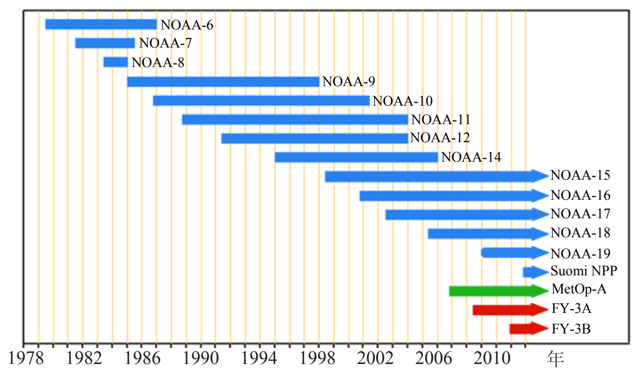

图 1 美国极轨气象卫星NOAA–6/7/8/9/10/11/12/14/15/16/17/18/19，欧州极轨气象卫星MetOp–A以及中国极轨气象卫星FY–3A/B的覆盖时间

Fig. 1 Time periods covered by US polar–orbiting satellites NOAA–6/7/8/9/10/11/12/14/15/16/17/18/19, European satellite MetOp–A, and Chinese satellites FY–3A and FY–3B.

量的观测分辨率。下面将进一步简述极轨气象卫星上的微波温度探测仪MSU，AMSU-A和MWTS的观测分辨率。这些微波温度探测仪得到的垂直分辨率由因通道频率而异的所谓权重函数（WF）决定；水平分辨率由视场大小（FOVs）表示。图2给出了将美国标准大气输入通用辐射传输模型（CRTM）[7, 8]计算得出的AMSU-A的15个通道的权重函数随气压的分布情况。可以看出，通道4～14的大气温度廓线的范围是从地表至约0.1hPa高度；而通道1～3和通道15对地表敏感度高，同时受到来自地表辐射和大气辐射的影响。MWTS的四个通道权重函数分别对应AMSU-A通道3/5/7/9。卫星观测到的辐射值是固定视场的不同大气层发射的上升微波辐射的加权和。观测到的辐射值对在权重函数最大的高度处的大气温度最为敏感。某个通道的权重函数越宽，则该通道的垂直分辨率越低。值得注意的是，不同通道的权重函数通常重叠，因此，通过反演得到比单通道高的垂直分辨率是可能的。怎样根据特定的天气和气候问题，通过优化得到垂直分辨率较高但数据噪音较小的资料有待进一步研究。然而，由于微波温度探测仪只有数量有限的通道，基于微波温度探测装置如MSU，AMSU-A和MWTS观测数据的大气温度廓线垂直分辨率通常都不会太高。

微波温度探测仪MSU，AMSU-A和MWTS均

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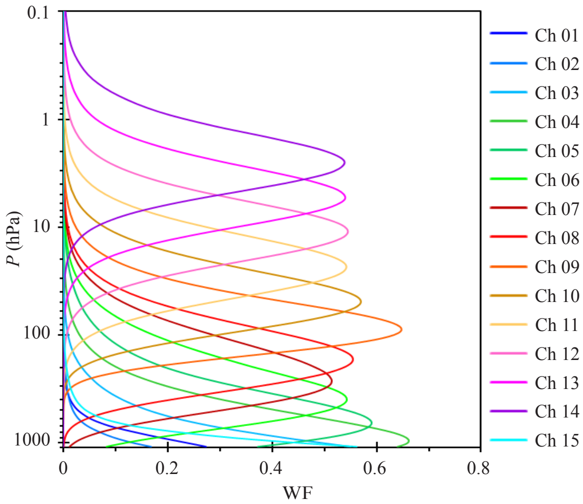

图2 AMSU-A的15个通道的权重函数（WF）

Fig. 2 WF distributions for the 15 AMSU-A channels calculated by the Community Radiative Transfer Model (CRTM) based on the US standard atmosphere

是跨轨扫描辐射计，它们在单条扫描线上的总视场（FOV）数分别是11，30和15。图3展示了FY-3A携带的MWTS在一条升轨轨道上的几条扫描线上的15个视场分布情况。FY-3A在离地836km的高度进行近轨循环运行。当FY-3A卫星向北（或升交点）运行时，其搭载的微波温度探测仪MWTS从左（西）至右（东）观测地球视场15次。第8个视场即为MWTS的星下点，卫星与地球之间的距离最短。视场FOV的大小随扫描角变化很大，他们由波束宽度、扫描角以及卫星高度决定。视场越大，则该视场的辐射观测水平分辨率越低。

图4是根据卫星NOAA-6，NOAA-18和FY-3A运行高度，以及MSU，AMSU-A和MWTS的波束宽度通过计算得到的准确视场大小分布图。可以看出，最低点的视场最小，表明跨轨扫描辐射计观测的水平分辨率在星下点最高。MSU、AMSU-A和MWTS的在星下点的视场跨轨迹半径分别为109，48和62km。视场跨轨迹半径随扫描角明显增大。例如，AMSU-A的第1或30视场的跨轨迹半径约为155km，比其星下点附近的第15和第16视场的跨轨迹半径约大三倍多。MSU，AMSU-A和MWTS的视场大小的差异主要由波束宽度差异引起，三者的波束宽度分别是7.5°，3.3°和6.9°。在同一扫描角上，MSU视场比MWTS视场要稍大。在跨轨扫描方向上，相邻视场无重叠。AMSU-A和MWTS在大扫描角度时在沿轨方向上有视场重叠。而且扫描角度越大，相邻扫描线间的视场重叠部分越多。需要注意的是，随着扫描角的增大，视场的跨轨迹半径比沿轨迹半径增大得更明显。图5就是AMSU-A的例证。在星下点，跨轨迹视场半径比沿轨视场半径稍小，但在扫描角最大时，跨轨视场半径差不多是沿轨视场半径的两倍大。

观测资料的时间分辨率由所谓的积分时间决定。积分时间是指微波辐射计看每一个地球视场的逗留时间间隔。MSU，AMSU-A1，AMSU-A2和MWTS的积分时间分别为1820，165，158和780ms。

三种不同微波温度探测仪资料的分辨率差异，应

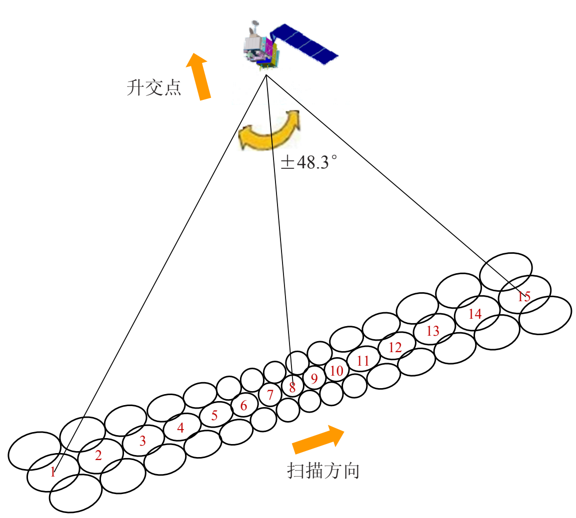

图3 MWTS在FY-3A一条升轨轨道上的几条扫描线上的15个视场分布情况，图中数字是依次扫描的视角数

Fig. 3 Schematic illustration of 15 FOVs along a scan line of the cross-tracking MWTS on board FY-3A/B for the ascending node

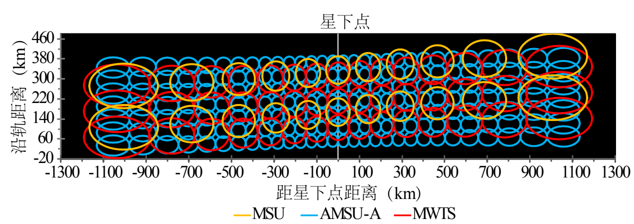

图4 根据卫星NOAA-6，NOAA-18和FY-3A运行高度，以及MSU，AMSU-A和MWTS的波束宽度通过计算得到的准确视场大小分布图

Fig. 4 FOV distributions and sizes for MSU (yellow), AMSU-A (blue) and MWTS (red)

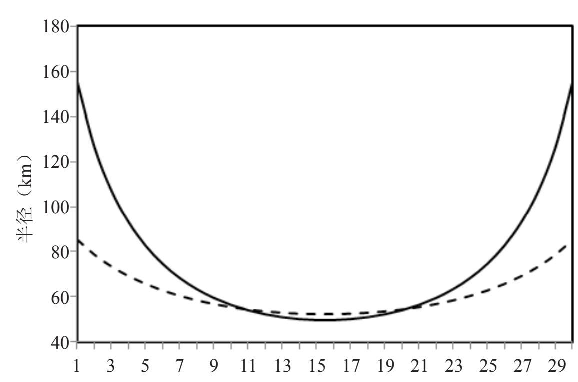

图5 跨轨迹视场半径（实线）和沿轨视场半径（虚线）随AMSU-A视场的变化

Fig. 5 The along-track (dashed) and across-track (solid) diameters of AMSU-A FOVs along a scan line

Serial of Applications of Satellite Observations

Observation Resolutions of Microwave Temperature Sounding Instruments Onboard Polar-Orbiting Meteorological Satellites

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The successful launch of the research and experimental satellite, Fengyun-3A (FY-3A), on May 27, 2008 marks the starting of the second generation of Chinese Fengyun-3 (FY-3) polar-orbiting satellite systems. Two years later, the second satellite in the FY-3 series, FY-3B, was launched on November 5, 2010. Satellites FY-3A and FY-3B cover the mid-morning and afternoon orbits, respectively. Different from previous Chinese satellites, both FY-3A/3B provide atmospheric sounding data for the first time[1] that are of particular interest for numerical weather prediction (NWP) data assimilation. Microwave Temperature Sounder (MWTS) is one of the three sounding instruments on board both FY-3A/3B and it provides global atmospheric temperature profiles under all weather conditions except for heavy precipitation.

The four MWTS channels on board FY-3A/3B are similar, but not identical, in channel specification to four MSU channels on board the early NOAA's Polar-Orbiting Environmental Satellites (POES) series which started in 1978 (e.g., NOAA-6 to NOAA-14) and Advanced Microwave Sounding Unit-A (AMSU-A) channels 3/5/7/9 on board the more recent NOAA's POES series which started in 1998 (e.g., NOAA-15/16/17/18/19). AMSU-A is also on board the first European polar-orbiting satellite, MetOp-A, which was launched on October 19, 2006. The AMSU-A component on board NOAA series and MetOp-A satellites consists of two modules, AMSU-A1 and AMSU-A2, providing a total of 15 channels. The AMSU-A1 provides 12 channels in the frequency range from 50.3 to 57.3 GHz oxygen band for atmospheric temperature profiling from the Earth's surface to about 42 km (or 2 hPa), and AMSU-A2 provides the other three channels located at 89, 23.8 and 31.4 GHz. Observations from MSU, AMSU-A and MWTS are key datasets for NWP data assimilation [2, 3] and investigation of global climate change [4, 5]. Time periods covered by US polar-orbiting satellites NOAA- 6/7/8/9/10/11/12/14/15/16/17/18/19, European satellite MetOp-A, and Chinese satellites FY-3A and FY-3B are shown in Fig.1. Challenges and issues in establishments of satellite climate data records (CDRs) were extensively discussed in [6].

A single value of satellite-measured radiance represents an amount of upwelling microwave radiation emitted from a certain volume of the atmosphere during a certain time period. The sizes of this volume and the length of this observing time represent the observation resolutions of satellite-measured radiances. For simplicity, observation resolutions of microwave temperature sounding instruments MSU, AMSU-A and MWTS on board polar-orbiting meteorological satellites are discussed here. The vertical resolutions of microwave temperature sounding observations are determined by the so-called weighting functions (WFs) that vary with channel frequencies. The horizontal resolutions of these measurements are represented by the field-of-view (FOV) sizes (FOVs). Figure 2 presents the WF distributions for the 15 AMSU-A channels calculated by the Community Radiative Transfer Model (CRTM) with the US standard atmosphere as its input[7, 8]. It is seen that channels 4~14 profile the atmospheric temperature from the surface to about 0.1 hPa, and channels 1~3 and 15 are surface-sensitive channels that include the radiation contributions from both the Earth's surface and the atmosphere. A satellite-measured radiance value is a weighted sum of the upwelling microwave radiation emitted from different layers of the atmosphere in a fixed field-of-view (FOV). The measured radiation is most sensitive to the atmospheric temperature at the altitude where WF

该会对数值预报同化应用和气候研究产生影响。有多大的影响，有待更深入的研究。由于MSU和MWTS资料在通道数上要明显小于AMSU-A，在对流层通过反演AMSU-A亮温资料得到的温度的垂直分辨率比MSU或MWTS反演的温度的分辨率要高。在平流层，AMSU-A的通道8～14可提供有用的温度廓线信息，MSU或MWTS只有一个（即通道４）包含了一些平流层信息，用它反演平流层温度廓线是不够的。

尽管微波探测仪可以进行除强降水以外的所有天气条件下的大气观测，但对其观测资料的同化仍然面临两大挑战：云辐射同化和地表敏感通道的辐射同化。云辐射同化的主要挑战在于与正演模式模拟和偏移订正有关，而地表通道辐射同化主要与地表发射率的不确定性有关。只有等到在云辐射和地表敏感通道辐射模拟和同化研究方面取得实质性进展后，才能全部发挥极轨卫星微波温度探测资料对提高数值天气预报水平的作用。

reaches the maximum value. The broader the weighting function is for a specific channel, the coarser the vertical resolution is for that channel measurements. It is noticed that WFs among different channels overlap. Therefore, an estimation of brightness temperatures at a higher vertical resolution than that of a single channel is possible. Further studies are required for optimizing the vertical resolution and data noise given each specific weather and climate problem. However, the vertical resolution for the atmospheric temperature profiling based on measurements from microwave temperature sounding instruments MSU, AMSU-A and MWTS will always be quite low due to a limited number of available channels.

All MSU, AMSU-A and MWTS are a cross-track scanning radiometer. The total number of FOVs on a single scan line is 11, 30 and 15 for MSU, AMSU-A and MWTS, respectively. A schematic illustration of the 15 FOVs along a scan line of the cross-tracking MWTS on board FY-3A for the ascending node is provided in Fig.3. FY-3A satellite moves in a circular, near-polar orbit at an altitude of 836 km above the Earth. As the satellite FY-3A moves toward north (e.g., ascending node), the MWTS on board FY-3A observes the earth 15 times from left (west) to right (east). The beam position eight (i.e., the 8^{th} FOV) is the nadir direction of MWTS. The size of FOV varies greatly with scan angle and is determined solely by the beam width, the scan angle, as well as the altitude of the satellite. The larger the FOV is, the coarser the horizontal resolution of a radiance measurement is for that FOV.

The exact FOV distributions and sizes for MSU, AMSU-A and MWTS are shown in Fig.4. It is seen that the FOV at nadir is smallest, indicating that the highest horizontal resolution for measurements from a cross-scanning radiometer is at nadir. The across-track diameter of the FOV at nadir is 109, 48 and 62 km for MSU, AMSU-A and MWTS, respectively. The across-track diameter of the FOV increases significantly with scan angle. For example, the across-track diameter of the 1^{st} or 30^{th} FOV of AMSU-A is near 155 km, which is more than three times larger than that of the 15^{th} and 16^{th} FOV near the nadir. Differences in FOV sizes among MSU, AMSU-A and MWTS arise mostly from large differences of the beam width for MSU, AMSU-A and MWTS, which are 7.5°, 3.3° and 6.9°, respectively. A single MWTS FOV is about twice larger in diameter than the AMSU-A FOV in diameter. An MSU FOV is slightly larger than an MWTS FOV at a similar scan angle. There is no overlap between neighboring FOVs along the scan directions. FOV overlaps are found in along-track directions for AMSU-A and MWTS at large scan angles. The larger the scan angles are, the more the FOVs overlap between the neighboring scan lines. It is also reminded that the across-track FOV diameter increases with scan angle much more greatly than the along-track diameter. An example is provided for AMSU-A in Fig.5. The across-track FOV diameter is slightly smaller than the along-track diameter near the nadir, but the former is nearly twice as large as the latter at the largest scan angles.

The temporal resolution of observations is determined by the so-called integration time, which is the time a microwave radiometer stars at each FOV. The integration time for MSU, AMSU-A1, AMSU-A2 and MWTS is 1820, 165, 158 and 780 ms, respectively.

The resolution differences among three microwave temperature sounders MSU, AMSU-A and MWTS shall result in different impacts of these data on NWP and climate studies. Further research is needed to quantify such differences. Since the total channel number of MSU or MWTS is much smaller than that of AMSU-A, the vertical resolution of the AMSU-A temperature profile retrieval is higher than that of MSU or MWTS in the troposphere. In the stratosphere, useful temperature profile can be deduced from AMSU-A channels 8~14. Since there is only one channel of MSU or MWTS (e.g., channel 4) that contains stratospheric temperature information, it is difficult to retrieve useful stratospheric temperature information from MSU and MWTS data.

Although microwave sounding instruments can observe the atmosphere in all weather conditions except heavy precipitation, data assimilation of these measurements still faces the following two major challenges: cloudy radiance assimilation and surface-sensitive radiance assimilation. Challenges in cloudy radiance assimilation are associated with forward model cloud simulations and bias corrections, and those in surface-sensitive channels assimilation are mainly associated with surface emissivity. The values of microwave radiance measurements from polar-orbiting satellites for improving the numerical model forecast skill of any NWP system could be fully reached only when substantial improvements in cloudy radiance and surface-sensitive radiance simulation and assimilation were made.

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