"卫星资料应用"专题系列

# 卫星资料测量精度参数"NEDT"

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数值天气预报和气候变化研究不仅依赖于充分多的、高准确度的卫星资料，还依赖于这些资料在数值天气预报和气候模式中的有效同化。在这方面的应用上，观测资料的测量精度是一个关键参数。

假定对一个地球目标的辐射在$\lambda$波长上进行了$N$次观测，并假定这些观测是独立进行的且观测误差为正态分布的。我们把这$N$次观测的测量值记为$\left\{y_{i,\lambda}^{obs}, i=1,2,\cdots,N\right\}$，测量精度（$\sigma_\lambda$）可以用这些样本值的标准差来进行统计估计，即

$$\sigma_\lambda=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(y_{i,\lambda}^{obs}-\overline{y_\lambda^{obs}}\right)^2} \quad (1)$$

其中，$\overline{y_\lambda^{obs}}=\frac{1}{N}\sum_{i=1}^{N}y_{i,\lambda}^{obs}$是对平均值的统计估计。

在资料同化中，不同通道卫星资料的测量精度值是必须提供的。例如，在变分同化系统中，代价函数的极小化可以用下式进行求解：

$$J(\mathbf{x})=\frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b)+\frac{1}{2}(H(\mathbf{x})-\mathbf{y}^{obs})^T(\mathbf{O}+\mathbf{F})^{-1}(H(\mathbf{x})-\mathbf{y}^{obs}) \quad (2)$$

其中$\mathbf{x}_b$是背景场；$\mathbf{B}$是背景误差协方差矩阵；$\mathbf{y}^{obs}$代表不同通道卫星资料观测值；$\mathbf{O}$代表观测误差协方差矩阵，其对角线元素即测量精度 $\sigma_\lambda^2$；$H(\mathbf{x})$代表辐射传输模式（RTM），该模式依据给定的输入参数包括大气状态变量$\mathbf{x}$来计算大气顶层的辐射；$\mathbf{F}$是RTM的误差协方差矩阵。

公式（2）中代价函数的极小值$\mathbf{x}^{ana}$可以通过一种选定的迭代过程求解[1]。得到的极小值$\mathbf{x}^{ana}$满足下列不等式：$J(\mathbf{x}^{ana})\leqslant J(\mathbf{x})$，$\forall\mathbf{x}_b$附近的邻近值$\mathbf{x}$。 （3）

因此，准确确定观测资料的测量精度（$\sigma_\lambda^2$）对卫星资料同化结果（即分析场$\mathbf{x}^{ana}$）的精确度有直接影响。换句话说，测量精度的确定直接影响到分析卫星资料在数值天气预报和气候模式预报中的应用效果。

卫星仪器的测量精度通常是由参数"NEDT"提供的，它代表噪声等效温差（Noise Equivalent Delta Temperature）。例如，美国国家海洋和大气管理局（NOAA, National Oceanic and Atmospheric Administration）系列极轨环境卫星（POES，polar-orbiting environmental satellites）携带的高级微波温度探测仪（AMSU-A，Advanced Microwave Sounding Unit-A）提供共15个不同频率（即不同通道）的辐射观测量。AMSU-A1模块有2套天线辐射系统 （A1-1和A1-2），他们共提供分布在50～60 GHz氧气带上的12个不同频率的通道和分布在低频（23.8GHz和31.4GHz）和高频（89.5GHz）上的另外3个通道。氧气带通道主要用于得到从地表到42km（2hPa）的温度信息，另外3个低频和高频通道用来得到与地表发射率、大气中的云和水汽有关的信息。当NOAA把AMSU-A测量数据提供给用户的时候，依赖于通道的NEDT值也一并提供给了用户（见表1 [2]）。那么，什么是NEDT? NEDT值又是如果得到的呢？

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**表 1 AMSU-A给定的NEDT值**

| 通道 | 1-2 | 3 | 4-9 | 10-11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|
| NEDT (K) | 0.30 | 0.40 | 0.25 | 0.40 | 0.60 | 1.20 | 0.50 |

实际上，NEDT是描述卫星仪器观测精度的一个参数。NEDT的计算步骤可以描述如下。首先，当卫星每完成一次扫描线，铂金电阻温度计（PRT, Platinum Resistant Temperature）测量一个黑体校准温度，同时，卫星观测仪器记录指定波长（$\lambda$）来自地球场景不同观测像元的的原始辐射计数值，即所谓的观测计数值（observation count），记为$c_{j,i,\lambda}^{raw}$，其中下标$i$表示第$i$根扫描线，$j$表示第$j$轨。在每一个轨道上，卫星天线对地球场景进行$N$次扫描得到$N$条扫描线（即$c_{j,i,\lambda}^{raw}$，$i$=1, 2, ⋯, $N$）。通常情况下，将每5根邻近扫描线上的计数值平均可以得到一个平滑的量值（$c_{j,i,\lambda}=\sum_{k=5\times(i-1)+1}^{5(i-1)+5}c_{j,k,\lambda}^{raw}$，$i$=1, 2, ⋯, $N$/5）。计数值$\left\{c_{j,i,\lambda}\right\}$的样本标准差记为$\sigma_{c,\lambda}$（为简单起见，省略下标$j$）。利用两点校准方程，我们可以将观测计数值标准差（$\sigma_{c,\lambda}$）转换成卫星观测辐射量的标准差（$\sigma_\lambda$）。具体来说，两点校准方程可以写为：

$$R_{j,i,\lambda}=\overline{R_{c,\lambda}}+\frac{c_{j,i,\lambda}-\overline{c_{c,\lambda}}}{\overline{c_{w,\lambda}}-\overline{c_{c,\lambda}}}\left(\overline{R_{w,\lambda}}-\overline{R_{c,\lambda}}\right) \quad (4)$$

其中$R_{c,\lambda}$和$R_{w,\lambda}$分别表示波长为$\lambda$的对应于宇宙背景温度和黑体温度$T_w$的辐射量。$c_{w,\lambda}$表示黑体计数值，$c_{c,\lambda}$代表宇宙背景（冷空）计数值，$c_{j,i,\lambda}$是地球场景计数值。上划线表示相应量的多根扫描线的平均值。利用公式（4），我们可以得到：

$$\sigma_\lambda = \frac{\overline{R_{w,\lambda}} - \overline{R_{c,\lambda}}}{\overline{c_{w,\lambda}} - \overline{c_{c,\lambda}}}\sigma_{c,\lambda} \qquad (5)$$

$NEDT_\lambda$被定义成黑体在波长$\lambda$上发射辐射强度为$\sigma_\lambda$的辐射量所必须具有的温度。换句话说，$NEDT_\lambda$就是对应于辐射强度为$\sigma_\lambda$的亮温，其值的大小可以用下面的普朗克方程[3]计算所得:

$$\sigma_\lambda = \frac{2hc^2}{\lambda^5(e^{hc/(\kappa_B\lambda NEDT_\lambda)} - 1)} \qquad (6)$$

其中$c$=2.998×$10^8$是光速；$h$=6.626×$10^{-34}$（单位：J•s）是普朗克常数；$\kappa_B$=1.381×$10^{-23}$（单位：J•$K^{-1}$）是波尔兹曼常数。

$NEDT_\lambda$的大小是由该卫星仪器发射前的测试数据决定的。从理论上讲，$NEDT$会随着观测场景的温度变化而变化，随波长的变化而变化。当给出的不同通道的卫星资料的$NEDT$值相同时，如NOAA极轨卫星携带的微波温度探测仪（MSU, Microwave Sounding Unit），表明各个卫星通道间的$NEDT$值差异很小。

对用户来说，观测精度的重要性怎么强调都不为过分。Tarantola[4] 在他的《资料反演理论》一书中写道："理想情况下，仪器供应商应该提供经过详细统计分析得到的仪器误差（如果他不那样做，我们不应该付费）。"然而，当前存在的问题是资料提供者可能会提供免费数据，而用户在使用该数据的时候并不关注观测误差，或者用户愿意付费得到并没有提供资料的统计误差的数据。随着卫星观测技术的迅速发展，从事数值预报和气候研究的科研和业务人员在应用卫星资料时要特别重视所用资料的观测精度。

Serial of Applications of Satellite Observations

# Satellite Measurement Precision Parameter "NEDT"

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Numerical forecasts of weather and climate changes depend on the availability of highly accurate satellite observations and the effectiveness of assimilation of these observations into numerical weather prediction (NWP) and climate prediction models. Measurement precision is a key parameter associated with observations and their applications in NWP and climate studies.

Assuming that an Earth view was independently measured $N$ times at the wavelength $\lambda$ and the measured values are denoted as $\{y^{obs}_{i,\lambda}, i = 1,2,\ldots,N\}$, the measurement precision ($\sigma_\lambda$) is defined as the standard deviation of sampled values, i.e.,

$$\sigma_\lambda = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(y^{obs}_{i,\lambda} - \overline{y^{obs}_\lambda}\right)^2} \qquad (1)$$

where $\overline{y^{obs}_\lambda} = \frac{1}{N}\sum_{i=1}^{N} y^{obs}_{i,\lambda}$ is the mean.

The values of measurement precision for different channels are required input for satellite data assimilation. For example, in a variational satellite data assimilation system, the minimum solution ($\mathbf{x}^{ana}$) of the following cost function is sought:

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}_b) + \frac{1}{2}(H(\mathbf{x}) - \mathbf{y}^{obs})^T(\mathbf{O} + \mathbf{F})^{-1}(H(\mathbf{x}) - \mathbf{y}^{obs}) \qquad (2)$$

where $\mathbf{x}_b$ is the background state variable vector; $\mathbf{B}$ is the background error covariance matrix; $\mathbf{y}^{obs}$ includes satellite observations from various channels; $\mathbf{O}$ is the observation error covariance matrix with the measurement precisions $\sigma^2_\lambda$ as its diagonal elements; $H(\mathbf{x})$ represents a forward radiative transfer model (RTM) which calculates the radiance at the top of the atmosphere for a given set of input parameters which include the atmospheric state variables $\mathbf{x}$; and $\mathbf{F}$ is the RTM error covariance matrix.

The minimum solution $\mathbf{x}^{ana}$ in (2) is obtained through an iterative procedure [1] and satisfies the following inequality:

$$J(\mathbf{x}^{ana}) \leqslant J(\mathbf{x}), \quad \forall \mathbf{x} \text{ in the neighborhood of } \mathbf{x}_b. \qquad (3)$$

Therefore, the accurate quantification of measurement precision directly affects the accuracy of the analysis ($\mathbf{x}^{ana}$).

The measurement precision of any satellite instrument is often provided by the so-called "NEDT", which stands for Noise Equivalent Delta Temperature. For example, the Advanced Microwave Sounding Unit-A (AMSU-A) on the NOAA series of polar-orbiting environmental satellites (POES) provides 15-channels radiance measurements. AMSU-A1 module uses two antenna-radiometer systems (A1-1 and A1-2) and provides twelve channels in the 50 to 60GHz oxygen band for profiling the atmospheric temperature information from the Earth's surface to about 42km (or 2hPa), three channels at 23.8GHz, 31.4GHz and 89.5GHz for characterizing the surface and atmospheric features such as surface emissivity, atmospheric cloud and water vapor. When NOAA AMSU-A radiance data is delivered to users, a set of channel-dependent *NEDT* values is also provided to users (see Table 1[2]). Then what is *NEDT*? How is the value of *NEDT* determined?

Table 1 Specified NEDT of AMSU-A

| Channel | 1-2 | 3 | 4-9 | 10-11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|
| NEDT (K) | 0.30 | 0.40 | 0.25 | 0.40 | 0.60 | 1.20 | 0.50 |

In fact, *NEDT* describes the precision of measured radiances by satellite instruments. Its value is determined as follows: First, at the end of each scan line, a Platinum Resistant Temperature (PRT) thermometer measures a temperature of calibration target (e.g. blackbody) and the satellite antenna simultaneously records a raw radiometric count at a specified wavelength $\lambda$ from the measuring target or simply called field-of-view (FOV) count, $c_{j,i,\lambda}^{raw}$, where the subscript $i$ represents the $i^{th}$ scan line, and the subscript $j$ represents the $j^{th}$ swath. In each orbit, satellite antenna scans through the FOV target many times, say a total of $N$ scan lines (i.e., $c_{j,i,\lambda}^{raw}$, $i$ =1, 2, ⋯, $N$). Typically, the FOV target counts over every five scan lines are averaged to obtain a stable (smooth) count $c_{j,i,\lambda} = \sum_{k=5\times(i-1)+1}^{5(i-1)+5} c_{j,k,\lambda}^{raw}$ $i$ =1, 2, ⋯, $N$/5). The standard deviation of the count sample $\{c_{j,i,\lambda}\}$, $\sigma_{c,\lambda}$, is then calculated (the subscript "$j$" is omitted in $\sigma_{c,\lambda}$ for simplicity). Using a two-point calibration equation, the standard deviation of count ($\sigma_{c,\lambda}$) is then converted into the standard deviation of satellite-measured radiance ($\sigma_\lambda$). Specifically, the two-point calibration equation can be written as

$$R_{j,i,\lambda} = \overline{R_{c,\lambda}} + \frac{c_{j,i,\lambda} - \overline{c_{c,\lambda}}}{\overline{c_{w,\lambda}} - \overline{c_{c,\lambda}}}\left(\overline{R_{w,\lambda}} - \overline{R_{c,\lambda}}\right) \tag{4}$$

where $R_{c,\lambda}$ is the radiance at wavelength $\lambda$ corresponding to cosmic background temperature, $R_{w,\lambda}$ is the radiance at wavelength $\lambda$ corresponding to the blackbody target of temperature $T_w$, $c_{w,\lambda}$ is the blackbody warm count, $c_{c,\lambda}$ is the cosmic background count, $c_{j,i,\lambda}$ is the earth scene count, and the over-bar represents average of the corresponding variable over scan lines on which the standard deviation is being calculated. Based on (4), one obtains

$$\sigma_\lambda = \frac{\overline{R_{w,\lambda}} - \overline{R_{c,\lambda}}}{\overline{c_{w,\lambda}} - \overline{c_{c,\lambda}}}\sigma_{c,\lambda} \tag{5}$$

$NEDT_\lambda$ is defined as the temperature at which a blackbody in thermal equilibrium with its surroundings would have to emit at the intensity of radiation $\sigma_\lambda$ at wavelength $\lambda$. In other words, $NEDT_\lambda$ is the brightness temperature corresponding to radiance $\sigma_\lambda$ and its value can finally be derived using Planck's function [3]:

$$\sigma_\lambda = \frac{2hc^2}{\lambda^5\left(e^{hc/(\kappa_B \lambda NEDT_\lambda)} - 1\right)} \tag{6}$$

where $c$=2.998×10$^8$ (unit: m•s$^{-1}$) is the speed of light, $h$=6.626×10$^{-34}$ (unit: J•s) is Plank's constant, and $\kappa_B$=1.381×10$^{-23}$ (unit: J•K$^{-1}$) is Boltzmann's constant.

The value of $NEDT_\lambda$ for each satellite instrument is determined based on the data from the prelaunch tests for that instrument. Theoretically speaking, *NEDT* would vary with the temperature of the scene being observed and would be different for different channels. When a single value of *NEDT* is provided, such as Microwave Sounding Unit (MSU) on early NOAA polar-orbiting satellites, it means that such differences are rather small.

The importance of obtaining measurement precision for data users can never be emphasized enough. Tarantola [4] wrote in his book the following: "Ideally, the supplier of the apparatus should provide a statistical analysis of the errors of the instrument (if he does not, we should not pay for it!)." However, the data suppliers may deliver free data, the users may use the data with no concern of its errors, or the users are willing to pay for the data that do not come with error statistics. With the rapid advances in satellite observations, it is hoped that all data users be concerned with data errors and have a quantitative knowledge of measurement precision.

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