接收机的非理想性对复相关值测量的影响

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摘 要：分析了矩形模型接收机频率响应的非理想性对综合孔径微波辐射计复相关值测量的影响.频率响应非理想性包括中心频率不一致、带宽不一致、群延迟不一致、本振相位不一致及带内波动，它们通过条纹洗涤函数产生复相关值测量误差.分析结果表明，群延迟不一致与本振相位不一致是产生复相关值相位误差的主要原因，中心频率不一致、带宽不一致、群延迟不一致及带内波动是产生复相关值幅度误差的主要原因，通过噪声注入法可校正这些幅度和相位误差，并用以上理论对北航二维综合孔径微波辐射计(BHU-2D)校正前后的误差进行了估计.

关 键 词：综合孔径微波辐射计；接收机频率响应；条纹洗涤函数；微波成像

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Impacts of imperfect receivers on complex correlation of 2D aperture synthesis microwave radiometer

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Abstract: The impacts of receivers' rectangular frequency response imperfections on the complex correlation measurement of 2D aperture synthesis microwave radiometer were presented. These imperfections include center frequency imbalance, bandwidth imbalance, group delay imbalance, phase imbalance of local oscillator and in-band ripple. The analytical results show that the phase error of complex correlation mainly comes from group delay imbalance, phase imbalance of local oscillator, and that the amplitude error of complex correlation mainly comes from center frequency imbalance, bandwidth imbalance, group delay imbalance and in-band ripple. These amplitude errors and phase errors can be corrected by correlated noise injection. The complex correlation errors of Beihang university, 2-dimensional(BHU-2D) aperture synthesis microwave radiometer before and after system correction were estimated.

Key words: aperture synthesis microwave radiometers; frequency response; fringe-washing function; microwave imaging

1 条纹洗涤函数及归一化增益因子

综合孔径微波辐射计通过不同基线干涉测量的复相关值进行处理从而反演被观察区域的亮温分布，这些干涉测量的复相关值就是所谓的可视度函数.北航电磁工程实验室已经研制出的一套工作于8 mm波段的10天线二维综合孔径微波辐射计成像系统BHU-2D，满足中心频率不一致小于1MHz($|f_m-f_0|\leqslant 1$ MHz)；带宽不一致小于1 MHz($|B_m-B_n|\leqslant 1$ MHz)；群延迟不一致小于0.2 ns($|\tau_m-\tau_n|<0.2$ ns)；本振相位不一致大于2π弧度(因此相位误差可能是周期内任何数

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值);,带内波动常数项、一次项与二次项误差均小于 1%.本文分析了接收机频率响应的不理想性对复相关值测量值的影响,同时估计了 BHU-2D 系统校正前后这些不理想性产生的幅度误差与相位误差.

在远场条件下,可视度函数为[1-3]

$$V(u_{mn},v_{mn})=\frac{\langle b_m,b_n\rangle}{k_B\alpha_m\alpha_n\sqrt{B_mB_n}}=$$
$$1\Big/\sqrt{\Omega_m\Omega_n}\iint\limits_{\xi^2+\eta^2\leqslant 1}\frac{T(\xi,\eta)}{\sqrt{1-\xi^2-\eta^2}}F_m(\xi,\eta)F_n^*(\xi,\eta)\cdot$$
$$r\left(-\frac{u_{mn}\xi+v_{mn}\eta}{f_0}\right)e^{-j2\pi(u_{mn}\xi+v_{mn}\eta)}\,d\xi d\eta \qquad (1)$$

其中,b_m,b_n 分别是 m 通道与 n 通道输出信号;$\langle\ \rangle$为对时间序列做复相关运算;k_B 是玻尔兹曼常数;α_m,α_n 为 m 通道与 n 通道增益;$(\xi,\eta)=(\sin\theta\cos\varphi,\sin\theta\sin\varphi)$ 为方向余弦坐标;$(u_{mn},v_{mn})=(x_m-x_n,y_m-y_n)/\lambda$ 是归一化的基线;Ω_m,Ω_n 是 m 天线与 n 天线的立体角;$F_{m,n}(\xi,\eta)$是 m 通道与 n 通道的归一化天线方向图;$T(\xi,\eta)$是场景亮温分布;$\hat{T}(\xi,\eta)=T(\xi,\eta)F_m(\xi,\eta)F_n^*(\xi,\eta)/\sqrt{1-\xi^2-\eta^2}$ 为修正亮温;

$$r_{mn}(\tau)=\frac{e^{-j2\pi f_0\tau}\int_0^\infty H_m(f)H_n^*(f)e^{j2\pi f\tau}\,df}{\sqrt{\int_0^\infty H_m(f)H_m^*(f)\,df}\sqrt{\int_0^\infty H_n(f)H_n^*(f)\,df}} \qquad (2)$$

是条纹洗涤函数[4-5];$H_m(f)$是 m 通道的频率响应;$H_n(f)$是 n 通道的频率响应;f 为射频频率;f_0 为窄带中心频率(零中频时为接收机本振频率).

从式(1)不能直接反解出 $T(\xi,\eta)$,若 $r_{mn}(\tau)=r_{mn}(0)\gamma_{mn}(\tau)$,在忽略相对条纹洗涤函数 $\gamma_{mn}(\tau)$ 的影响时(即 $\gamma_{mn}(\tau)\approx 1$),可解出 $T(\xi,\eta)$.因为 $r_{mn}(0)$是可校正的条纹洗涤函数部分,记为 G_{mn},定义为归一化增益因子.

$$G_{mn}=\frac{\int_0^\infty H_m(f)H_n^*(f)\,df}{\sqrt{\int_0^\infty H_m(F)H_m^*(f)\,df}\sqrt{\int_0^\infty H_n(f)H_n^*(f)\,df}} \qquad (3)$$

2　理想矩形频率响应

综合孔径微波成像辐射计系统的理想接收机频率响是矩形,通带内幅度相等,相位线性变化,即

$$H(f)=\begin{cases}\alpha e^{-j2\pi f\tau_0} & |f-f_0|<\dfrac{B}{2}\\ 0 & \text{其它}\end{cases}$$

其中,α 为通道总增益;f_0 为接收机本振频率,也是接收机的中心频率;τ_0 为群延迟;B 为带宽.代入式(2)得

$$r_{mn}^{(0)}(\tau)=\mathrm{sinc}(B\tau)$$

则 $G_{mn}^{(0)}=r_{mn}^{(0)}(0)=1$,上标 0 表示理想接收机,当相对带宽 $\dfrac{B}{f_0}\ll 1$ 时有

$$r\left(-\frac{u_{mn}\xi+v_{mn}\eta}{f_0}\right)=\gamma\left(-\frac{u_{mn}\xi+v_{mn}\eta}{f_0}\right)\approx 1$$

则 $\hat{T}(\xi,\eta)\overset{\text{FFT}}{\Longleftrightarrow}V(u,v)$,因而对于窄带理想接收机,修正亮温与可视度函数成傅里叶变换关系.对于 BHU-2D 系统,$f_0=34.07$ GHz,$B=50$ MHz,视场为全视角,最大基线为 0.5 m,30°视场角,则

$$\tau=\frac{u_{mn}\xi+v_{mn}\eta}{f_0}\leqslant\sqrt{2}\,|\,u_{mn}\xi/f_0\,|\leqslant$$
$$\sqrt{2}\times\frac{0.5}{c}\times\sin\left(\frac{30}{2\times 180}\pi\right)=0.61\ \text{ns}$$
$$\gamma(-\tau)=\frac{r(-\tau)}{r(0)}=\frac{\mathrm{sinc}(-B\tau)}{r(0)}\geqslant 0.998 \qquad (4)$$

与 1 的误差小于 0.2%,即理想接收机的归一化增益因子不产生可视度函数误差($G_{mn}=1$),相对条纹洗涤函数 $\gamma_{mn}(\tau)$不产生可视度函数相位误差,产生的可视度函数幅度误差不大于 0.2%.

3　非理想矩形频率响应

实际接收机频率响应的非理想性包括:中心频率的不一致性、带宽的不一致性、群延迟不一致、本振相位不一致、带内波动.

通带内频率响应在 f'_0 处泰勒展开,幅度只保留头 3 项,则接收机频率响应为

$$H_m=\begin{cases}\alpha(1+A_{m0}+A_{m1}(f-f'_0)/B_m+\\ A_{m2}(f-f'_0)^2/B_m^2)e^{j(E_m+2\pi(f-f'_0)D_m)}\\ \qquad |f-f_m|<\dfrac{B_m}{2}\\ 0 \qquad \text{其它}\end{cases}$$

其中,f'_0 为 $H_m(f)H_n^*(f)$的中心频率;f_m 为第 m 个接收机中心频率;B_m 为第 m 个接收机带宽;E_m,D_m 是相位误差的常数项与线性项系数,即常数项相位误差为 $E_m=-2\pi f'_0\tau_m-\phi_m$;一次项相位误差为 $D_m=-\tau_m$,τ_m 为 m 通道的群延迟,ϕ_m 为 m 通道本振信号混频时相位;A_{m0},A_{m1} 与 A_{m2} 是 m 带内波动的常数项、线性项系数与二次项系

数.

不妨设 $f_m \geqslant f_n$,分以下几种情况讨论:

1) 当 $|B_m - B_n| < f_m - f_n$ 时,有:

$$B_{mn} = (B_m + B_n)/2 - (f_m - f_n)$$

$$f'_0 = \frac{f_m + f_n}{2} - \frac{B_m - B_n}{4}$$

2) 当 $B_m - B_n \geqslant f_m - f_n$ 时,有:$B_{mn} = B_n$,$f'_0 = f_n$

3) 当 $B_n - B_m \geqslant f_m - f_n$ 时,有:$B_{mn} = B_m$,$f'_0 = f_m$

以下讨论情况 1),其它情况类似.

忽略大于二次的项,$H_m(f)H_n^*(f)$有如下形式:

$$H_m(f)H_n^*(f) = \begin{cases} \alpha^2(A_0 + 2\pi A_1(f - f'_0) + \\ \quad A_2(2\pi)^2(f - f'_0)^2)\mathrm{e}^{\mathrm{j}(E - 2\pi(f - f_0^3)D)} \\ \quad |f - f'_0| < \dfrac{B_{mn}}{2} \\ 0 \qquad \text{其它} \end{cases} \tag{5}$$

其中 $A_0 = (1 + A_{m0})(1 + A_{n0})$

$$A_1 = \frac{1}{2\pi B_{mn}}(A_{m1}(1 + A_{n0}) + (1 + A_{m0})A_{n1})$$

$$A_2 = \frac{1}{(2\pi)^2 B_{mn}^2}(A_{m2}(1 + A_{n0}) + (1 + A_{m0})A_{n2} + 2A_{m1}A_{n1})$$

$$E = 2\pi f'_0(\tau_n - \tau_m) + (\phi_n - \phi_m)$$

$$D = \tau_m - \tau_n$$

$$B_{mn} = \frac{(B_m + B_n)}{2} - (f_m - f_n)$$

将式(5)代入式(2)得

$$\begin{aligned} r_{mn}^{(4)}(\tau) = {} & A_0 A\mathrm{sinc}(B_{mn}(\tau - D))\mathrm{e}^{\mathrm{j}(E + F\tau)} + \\ & A_1\left\{\frac{\pi A B_{mn}\cos(\pi B_{mn}(\tau - D))\mathrm{e}^{\mathrm{j}(E + F\tau)}}{\pi B_{mn}(\tau - D)} + \right. \\ & \frac{\mathrm{j}AF\sin[\pi B_{mn}(\tau - D)]\mathrm{e}^{\mathrm{j}(E + F\tau)}}{\pi B_{mn}(\tau - D)} - \\ & \left.\frac{\pi A B_{mn}\sin[\pi B_{mn}(\tau - D)]\mathrm{e}^{\mathrm{j}(E + F\tau)}}{(\pi B_{mn}(\tau - D))^2}\right\} + \\ & A_2\left\{\frac{\pi^2 A B_{mn}^2\sin(\pi B_{mn}(\tau - D))\mathrm{e}^{\mathrm{j}E + F\tau}}{\pi B_{mn}(\tau - D)} + \right. \\ & \frac{\mathrm{j}2\pi A B_{mn}F\cos(\pi B_{mn}(\tau - D))\mathrm{e}^{\mathrm{j}(E + F\tau)}}{\pi B_{mn}(\tau - D)} + \\ & \frac{-F^2 A\sin(\pi B_{mn}(\tau - D))\mathrm{e}^{\mathrm{j}(E + F\tau)}}{\pi B_{mn}(\tau - D)} + \\ & \frac{-2A\pi^2 B_{mn}^2\cos(\pi B_{mn}(\tau - D))\mathrm{e}^{\mathrm{j}(E + F\tau)}}{(\pi B_{mn}(\tau - D))^2} - \\ & \frac{\mathrm{j}2\pi B_{mn}AF\sin(\pi B_{mn}(\tau - D))\mathrm{e}^{\mathrm{j}(E + F\tau)}}{(\pi B_{mn}(\tau - D))^2} + \\ & \left.\frac{2A\pi^2 B_{mn}^2\sin(\pi B_{mn}(\tau - D))\mathrm{e}^{\mathrm{j}(E + F\tau)}}{(\pi B_{mn}(\tau - D))^3}\right\} \end{aligned} \tag{6}$$

则归一化增益因子为

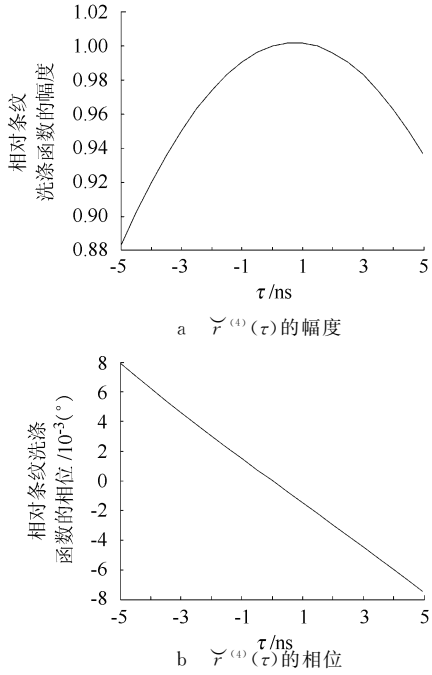
$$\begin{aligned} G_{mn}^{(4)} = {} & \left\{\left[A_0 A\mathrm{sinc}(B_{mn}D) + \right.\right. \\ & A_1 A\frac{\mathrm{sinc}(B_{mn}D) - \cos(\pi B_{mn}D)}{D} + \\ & A_2 A\left((\pi B_{mn})^2 - F^2 + \frac{2}{D^2}\right)\mathrm{sinc}(B_{mn}D) - \\ & \left.\frac{2A_2 A}{D^2}\cos(\pi B_{mn}D)\right] + \\ & \mathrm{j}\left[A_1 AF\mathrm{sinc}(B_{mn}D) + \right. \\ & \left.\left.\frac{2A_2 AF}{D}(\mathrm{sinc}(B_{mn}D) - \cos(\pi B_{mn}D))\right]\right\}\mathrm{e}^{\mathrm{j}E} \end{aligned} \tag{7}$$

对于 BHU-2D 系统,A_{m0},A_{m1},A_{m2}小于0.01,$B = 50$ MHz,$|f_m - f_0| \leqslant 1$ MHz,$|B_m - B_n| \leqslant 1$ MHz,$|\tau_m - \tau_n| < 0.2$ ns,$\tau_{m,n} \leqslant 10$ ns,$|\phi_m - \phi_n| > 2\pi$ 弧度,由式(7)得:幅度降至0.816,幅度误差不大于3.7%,相位误差大于 2π rad,采用噪声注入法可校正这些误差.

相对条纹洗涤函数为:

$$\breve{r}_{mn}^{(4)}(-\tau) = \frac{r_{mn}^{(4)}(-\tau)}{r^{(4)}(0)} = \frac{r_{mn}^{(4)}(-\tau)}{G_{mn}^{(4)}} \tag{8}$$

将式(6)与式(7)代入式(8),数值仿真结果见图1.



a $\breve{r}^{(4)}(\tau)$的幅度

b $\breve{r}^{(4)}(\tau)$的相位

图1 相对条纹洗涤函数仿真结果

对于 BHU-2D 系统,$f_0 = 34.07$ GHz,$B = 50$ MHz,视场为全视角,最大基线为 0.5 m,30°视场角,$\tau = 0.6$ ns,幅度误差小于 0.49 %,相位误差小于 0.01°.

因此,复相关值相位误差产生的主要原因是群延迟不一致与本振相位不一致;幅度误差产生

的主要原因是中心频率不一致、带宽不一致、群延迟不一致与带内波动不一致.

4　结　论

本文分析了接收机频率响应的非理想性对综合孔径微波辐射成像复相关值干涉测量的影响,这些不理想性包括:①中心频率不一致;②带宽不一致;③群延迟不一致;④本振相位不一致;⑤带内波动.接收机频率响应的非理想性是通过条纹洗涤函数对复相关值测量值产生误差,结果表明群延迟不一致与本振相位不一致是产生相位误差的主要原因,BHU-2D 系统校正之前的相位误差大于 2π rad;中心频率不一致、带宽不一致、群延迟不一致及带内波动均产生幅度误差,BHU-2D 系统校正之前的总幅度误差不大于 3.7%.

条纹洗涤函数的原点值相位误差及幅度误差可通过噪声注入法校正,相对于原点值的条纹洗涤函数作为残留误差保留下来.对于 BHU-2D 系统,校正条纹洗涤函数的原点值后,幅度残余误差小于 0.49 %,相位残余误差小于 0.01°,因此残余误差的影响可忽略.

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