BASELINE REDUNDANCY AND RADIOMETRTIC SENSITIVITY: A CRITICAL REVIEW

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ABSTRACT

When computing the radiometric resolution of an interferometric radiometer the correlation among the errors of different baselines is usually assumed negligible. In this way: a) the radiometric sensitivity turns out to be pixel independent (except for antenna pattern effects), and b) the error of the average of P redundant baselines is reduced by a factor of $(P)^{1/2}$. While this may be the case in radioastronomy applications, for an on-board instrument where all the baselines are measured at the same time interval the errors will actually be correlated. This has two effects: a) The radiometric resolution changes from pixel to pixel and b) the radiometric resolution improvement introduced by redundance is reduced as compared with the case of independent errors. In this paper this correlation is computed and the results obtained are applied, first, to a fully redundant (all possible baselines are actually measured) filled linear array to analyze the actual radiometric improvement, and, next, to the same array without redundance to investigate the dependence of sensitivity on pixel information.

1. INTRODUCTION

The starting point is the equation relating the **mutual coherence function** $V(u,v;\tau)$ of the outputs of two antennas, $s_i(t)$, $s_j(t)$, to the brightness temperature T_B in a nearly ideal interferometer formed by identical antennas, identical transmission channels and ideal correlators [1], [2], [3]:

$$V(u,v;\tau) = \langle s_i(t+\tau)\, s_j^*(t) \rangle = K \iint \frac{T_B(\xi,\eta)}{\sqrt{1-\xi^2-\eta^2}} |F_n(\xi,\eta)|^2 \tilde{r}\left(\tau - \frac{u\xi+v\eta}{f_o}\right) e^{-j2\pi(u\xi+v\eta)}\, d\xi\, d\eta$$

$$= K \iint \mathrm{T}(\xi,\eta)\, \tilde{r}\left(\tau - \frac{u\xi+v\eta}{f_o}\right) e^{-j2\pi(u\xi+v\eta)}\, d\xi\, d\eta \qquad (1)$$

where K is a constant, F_n is the normalized voltage antenna pattern, (ξ,η) are the directing cosines (referred to boresight),

$$\tilde{r}(t) = e^{-j2\pi f_o t} \int_0^\infty |H_n(f)|^2 e^{j2\pi f t}\, df \qquad (2)$$

$H_n(f)$ is the channel band-pass normalized transfer function and we have introduced, for notation simplicity, the **modified temperature** T. Since fringe-washing affects the spatial resolution in directions off-boresight and is irrelevant for this paper's subject, we will ignore its effects in (1) and write:

$$V(u,v;\tau) = V(u,v;0)\,\tilde{r}(\tau) \triangleq V(u,v)\,\tilde{r}(\tau) \qquad (3)$$

$V(u,v)$ is most often called the 'visibility function'.

In the presence of noise $n_i(t)$ in the transmission channels (additive Gaussian noise) these expressions do not change, except the baseline u=v=0:

$$V^n(u,v) = \langle (s_i+n_i)(s_j^*+n_j^*) \rangle = V(u,v) \qquad (4)$$

$$V^n(0,0) = \langle |s_i|^2 \rangle + \langle |n_i|^2 \rangle = V(0,0) + \langle |n|^2 \rangle$$

Note that for an ideal band-pass filter of pass-band B:

$$\tilde{r}(\tau) = \mathrm{sinc}(B\tau) \qquad (5)$$

With **M visibility samples** equispaced over a rectangle we compute the following estimation of the modified temperature (rectangular window):

$$K\hat{\mathrm{T}}(\xi_m,\eta_n) = \sum_i \sum_k V(u_i,v_k)\, e^{j2\pi(u_i\xi_m+v_k\eta_n)} \Delta u \Delta v$$

$$\Rightarrow \sqrt{M}\, F^{-1} V \Delta u \Delta v \qquad (6)$$

where F^{-1} is the inverse 2-D discrete Fourier transform matrix (DFT).

2. IMAGE SENSITIVITY

Since the visibility samples have errors we actually measure:

$$\hat{V}(u_i,v_k) = V(u_i,v_k) + \Delta V(u_i,v_k) \qquad (7)$$

The errors $\Delta V(u_i, v_k)$ in turn produce errors on the estimated temperature given by the matrix equation:

$$K\Delta\hat{\mathrm{T}} = \sqrt{M}\, F^{-1} \Delta V\, \Delta u \Delta v \qquad (8)$$

If we define the **average** temperature error by:

$$e^2(\mathrm{T}) = \frac{1}{M} \langle \|\Delta \mathrm{T}\|^2 \rangle = \left(\frac{\Delta u \Delta v}{K}\right)^2 \langle \|\Delta V\|^2 \rangle = \left(\frac{\Delta u \Delta v}{K}\right)^2 \sum_i \sum_k \langle |\Delta V(u_i,v_k)|^2 \rangle \qquad (9)$$

then, when considering only the errors produced by the finite integration time T_{int} we have:

$$<|\Delta V(u_i, v_k)|^2> = \frac{1}{BT_{int}} V^{n2}(0,0), \qquad e(T) = \frac{V^n(0,0)\Delta u \Delta v}{K}\sqrt{\frac{M}{BT_{int}}} \quad (10)$$

where:

$$V^n(0,0) = K T_{avg} = K T_{sys}\Omega_p \quad (11)$$

with Ω_p the antenna pattern solid angle and T_{sys} the system equivalent temperature defined as the scene's average brightness temperature plus the channel's equivalent noise temperature:

$$T_{sys} = \overline{T}_B + T_n \quad (12)$$

Therefore:

$$\frac{e(T)}{T_{avg}} = \Delta u \Delta v \sqrt{\frac{M}{BT_{int}}} \quad (13)$$

For a radiometer with Nyquist sampling in the (u,v) plane, Δu=Δv=0.5, and ΔuΔv=0.25.

3. BASELINE REDUNDANCY

If a (u,v)-point visibility is measured by P baselines (that is, if is P-fold redundant), each yielding a value $\hat{V}_k$, we can take its average and then:

$$\Delta V = \frac{1}{P}\sum_1^P \Delta V_i, \quad <|\Delta V|^2> = \frac{1}{P^2}\sum_i \sum_k <\Delta V_i \Delta V_k^*> \quad (15)$$

At this point it is usually assumed that the errors of different baselines are uncorrelated, while the errors of each baseline are easily computed [2]:

$$<|\Delta V_i|^2> = \frac{V^{n2}(0,0)}{BT_{int}} \rightarrow <|\Delta V|^2> = \frac{1}{P}\frac{V^{n2}(0,0)}{BT_{int}} \quad (16)$$

It turns out that, when the baselines are measured over the same time interval, these errors can be strongly correlated, and its computation is this paper's main result.

Let us consider (fig. 1) four antennas labelled (1,2,3,4). Antennas (3,4) produce the following visibility sample by integration in the time interval (t, t+T_{int}):

$$\hat{V}_{34}(t) = \int a(t-\rho)\,[s_3(\rho)+n_3(\rho)]\,[s_4^*(\rho)+n_4^*(\rho)]\,d\rho \quad (17)$$

where s_i refers to the signal captured by the antenna and n_i to the noise introduced by the amplifying/down-converting chain, a(t) is the correlator's low-pass filter impulse response and the integrals extend to the interval (-∞, ∞) whenever not explicitly stated. Similarly, antennas (1,2) produce, in the delayed time interval (t+τ, t+τ+T_{int}):

$$\hat{V}_{12}(t+\tau) = \int a(t+\tau-\sigma)\,[s_1(\sigma)+n_1(\sigma)]\,[s_2^*(\sigma)+n_2^*(\sigma)]\,d\sigma \quad (18)$$

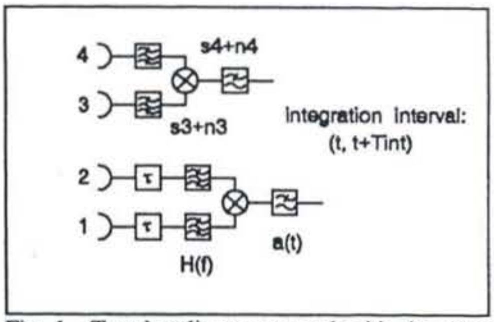

Fig. 1.- Two baselines measured with the same integration time T_{int}, one of them delayed τ.

Let us compute their correlation:

$$R_{\hat{V}(12)\hat{V}(34)}(\tau) = <\hat{V}_{12}(t+\tau)\hat{V}_{34}^*(t)> = \iint a(t-\rho)\, a(t+\tau-\sigma) <[s_1+n_1][s_2^*+n_2^*][s_3^*+n_3^*][s_4+n_4]> d\rho\, d\sigma \quad (19)$$

(the arguments on the s_i, n_i have been omitted for brevity). Since both the s_i and the n_i are complex zero mean Gaussian random processes with circular joint Gaussian statistics [1]:

$$<s_1 s_2^* s_3^* s_4> = <s_1 s_2^*><s_3^* s_4> + <s_1 s_3^*><s_2^* s_4> \quad (20)$$

and, furthermore, each n_i is uncorrelated with the remaining processes, (19) becomes:

$$R_{\hat{V}(12)\hat{V}(34)} = \iint a(t-\rho)\, a(t+\tau-\sigma)\,[V_{12}V_{34}^* + V_{13}V_{24}^*|r(\rho-\sigma)|^2]\, d\sigma\, d\rho \quad (21)$$

Note that the low-pass filter has an integration time of the order of 1s, while if B≈20 MHz, 1/B≈5x10^{-8}s; therefore, in (21) a(t-ρ) a(t+τ-σ) vary very slowly as compared to |r(ρ-τ)| and we can approximate:

$$r(\tau) = sinc(B\tau) \approx \frac{1}{B}\delta(\tau) \quad (22)$$

If for the low-pass filter we assume:

$$|A(f)|^2 = \begin{cases} 1 & if \ |f| < \frac{T_{int}}{2} \\ 0 & if \ |f| > \frac{T_{int}}{2} \end{cases} \quad (23)$$

then:

$$R_{\hat{V}(12)\hat{V}(34)} = V_{12}V_{34}^* + \frac{V_{13}V_{24}^*}{BT_{int}} sinc\left(\frac{\tau}{T_{int}}\right) \quad (24)$$

We finally find for the cross-correlation of the errors:

$$R_{\Delta V(12)\Delta V(34)}(\tau) = R_{\varrho(12)\varrho(34)}(\tau) - V_{12}V_{34}^{*} = \frac{V_{13}V_{24}^{*}}{BT_{int}}\, sinc\left(\frac{\tau}{T_{int}}\right) \tag{25}$$

This expression is still valid if the two baselines share an antenna, or even both of them (in this latter case we recover the expresión for the baseline noise) if whenever in the expression it appears V(0,0) its value is replaced by $V^{n}(0,0)$ as given by (4).

In an actual on-board interferometer like MIRAS all baselines are measured in the same time interval and $\tau=0$.

4. EXAMPLE: ONE-DIMENSIONAL FULLY REDUNDANT ARRAY

By this we will understand a linear array formed by N+1 equispaced antennas (numbered from 0 to N) where all possible baselines are measured. The available visibility samples are $V(m\Delta u)$, $m=0,\pm1,\pm2,...\pm N$, but since $V(-m\Delta u) = V^{*}(m\Delta u)$ we will examine only those with $m\geq0$. For simplicity ideal (noise-free) channels will be assumed.

Let us call $V_k(m\Delta u)$ the visibility sample measured by the baseline formed by the pair of antennas (k, k+m). Since $k+m\leq N$ the range of k is given by $k=0,1,2,...N-m$, and the sample redundancy is $N-m+1$. Therefore, if we define the average value:

$$V(m\Delta u) = \frac{1}{N-m+1}\sum_{k=0}^{N-m} V_k(m\Delta u) \tag{26}$$

its error comes given by:

$$\langle|\Delta V(m\Delta u)|^2\rangle = \frac{1}{(N-m+1)^2}\sum_{k=0}^{N-m}\sum_{l=0}^{N-m}\langle\Delta V_k \Delta V_l^{*}\rangle = \frac{A}{(N-m+1)^2}\sum_{k=0}^{N-m}\sum_{l=0}^{N-m}|V(k-l)|^2, \quad \left(A=\frac{1}{BT_{int}}\right) \tag{27}$$

In the last sum the term V(k-l) with $k-l=p\geq0$ appears $N-m+1-p$ times and since $|V(-p)| = |V(p)|$ we can write:

$$\langle|\Delta V(m\Delta u)|^2\rangle = \frac{A}{(N-m+1)^2}\left[(N-m+1)\,V^2(0) + 2\sum_{k=1}^{N-m}(N-m+1-k)\,|V(k\Delta u)|^2\right] \tag{28}$$

This expression's first term corresponds to its value when the errors are assumed uncorrelated; also, it corresponds to a scene where all $V(m\Delta u)$ but V(0) would vanish, that is, a **constant modified temperature scene**. We can then affirm that this latter scene minimizes the average error, which is the one obtained when the correlation among errors is neglected.

On the other hand, (28) attains its maximum value (worst case) when all $|V(m\Delta u)| = V(0)$; that is, when the scene is formed by a delta function (a highly improbable scene indeed).

The expected error vector is then:

$$\langle\|\Delta V\|^2\rangle = \sum_{m=-N}^{N}\langle|\Delta V(m\Delta u)|^2\rangle = \langle|\Delta V(0)|^2\rangle + 2\sum_{m=1}^{N}\langle|\Delta V(m\Delta u)|^2\rangle \tag{29}$$

By substitution of (28) and after some mathematical manipulations this transforms into:

$$\langle\|\Delta V\|^2\rangle = A\sum_{0}^{N} a_k|V(k\Delta u)|^2, \quad a_0 = \frac{1}{N+1} + \sum_{m=1}^{N}\frac{2}{N-m+1}$$

$$a_k = 2\frac{N+1-k}{(N+1)^2} + 4\sum_{m=1}^{N-k}\frac{N-m+1-k}{(N-m+1)^2}, \quad k=1,2,...N \tag{30}$$

For example, if we consider the case N=43, the following values are obtained:

TABLE 1. COEFFICIENTS a_k FOR A FULLY REDUNDANT LINEAR ARRAY WITH 44 ANTENNAS

8.7227245e+000	1.0956630e+001	8.4678103e+000
6.9789910e+000	5.9346161e+000	5.1402412e+000
4.5058663e+000	3.9826025e+000	3.5409713e+000
3.1618402e+000	2.8320917e+000	2.5423433e+000
2.2856527e+000	2.0567399e+000	1.8514958e+000
1.6666598e+000	1.4996016e+000	1.3481684e+000
1.2105760e+000	1.0853293e+000	9.7116289e-001
8.6699651e-001	7.7190043e-001	6.8506882e-001
6.0579864e-001	5.3347290e-001	4.6754716e-001
4.0753858e-001	3.5301698e-001	3.0359741e-001
2.5893408e-001	2.1871520e-001	1.8265865e-001
1.5050835e-001	1.2203115e-001	9.7014150e-002
7.5262459e-002	5.6597187e-002	4.0853756e-002
2.7880408e-002	1.7536909e-002	9.6934103e-003
4.2294472e-003	1.0330579e-003	

It can be shown that:

$$\sum_{0}^{N} a_k = 2N+1 \tag{31}$$

We can now establish the following for the example above:

-In the absence of redundance:

$$\langle\|\Delta V\|^2\rangle^{1/2} = \sqrt{\frac{2N+1}{BT_{int}}}\,V(0,0) = \frac{9.327}{\sqrt{BT_{int}}}\,V(0,0) \tag{32}$$

-Fully redundant array, constant modified temperature scene (uncorrelated errors):

$$<\|\Delta V\|^2>^{1/2} = \sqrt{\frac{a_o}{BT_{int}}}V(0,0) = \frac{2.95}{\sqrt{BT_{int}}}V(0,0) \qquad (33)$$

That is, a 30% of the value without redundance.

-Fully redundant array, delta-function scene (fully correlated errors, worst case):

$$<\|\Delta V\|^2>^{1/2} = \sqrt{\frac{\Sigma a_k}{BT_{int}}}V(0,0) = \sqrt{\frac{2N+1}{BT_{int}}}V(0,0) = \frac{9.327}{\sqrt{BT_{int}}}V(0,0) \qquad (34)$$

Note that in this case, in view of (31), we have recovered the value of the non-redundant array; a logical conclusion since, if all the errors are completely correlated, redundance does not add any information.

For a more realistic scene, intermediate values between those of (33) and (34) are to be expected. As an example, we constructed the brightness temperature distribution of fig. 2, wich shows a sharp transition to 0 K (cold sky) and other jumps ranging from 40 to 100 K, together with some rapid fluctuations to introduce higher frequency components. With this distribution and an antenna pattern given by:

$$F_n(\theta) = (\cos\theta)^{1.5} = (1-\xi^2)^{0.75}, \quad -\pi/2 \le \theta \le \pi/2 \qquad (35)$$

it is found that the actual average temperature error is a 16% higher than that computed assuming uncorrelated errors.

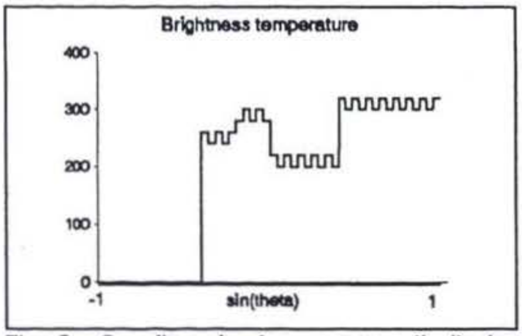

Fig. 2.- One-dimensional temperature distribution used as example.

5. GLOBAL vs. LOCAL SENSITIVITY

In section 2 we defined the average temperature error with help of the norm-preserving property of Fourier transform (Parseval's), eqn. (9). If we are interested in the expected error of an specific pixel we have to compute (a square grid is assumed for simplicity):

$$K\Delta\hat{T}(\xi_m,\eta_n) = \Delta u \Delta v \sum_l \sum_k V(u_l,v_k)\, w^{ml+nk}, \qquad (36)$$

$$w = e^{j\frac{2\pi}{\sqrt{R}}}$$

$$K^2 <|\Delta\hat{T}(\xi_m,\eta_n)|^2> = (\Delta u \Delta v)^2 \sum_l \sum_k \sum_r \sum_s \qquad (37)$$

$$<\Delta V(u_l,v_k)\,\Delta V^*(u_r,v_s)>w^{m(l-r)+n(k-s)}$$

and the correlations among errors appear again. If we neglect them eqn. (9) is recovered; that is, the approximation of uncorrelation gives for each pixel a temperature error which is constant and equal to the correct average value.

Note that computation of (37) requires, in view of (25), a knowledge of the spatial position of the antennas forming each baseline, that is, a knowledge of the specific radiometer configuration, what makes it impossible to proceed with a general analysis. We return therefore to a linear array with N+1 antennas and arbitrarily agree that baseline $V(m\Delta u)$, m>0, is measured only once with antennas (0,m) (zero redundance array). This will be denoted with subindexes referring to the antennas:

$$V(m\Delta u) = <s_0 s_m^*> = V_{om}, \quad V(-m\Delta u) = V_{om}^* \qquad (38)$$

We can now write:

$$\frac{K}{\Delta u}\Delta\hat{T}(m\Delta\xi) = \sum_{-N}^{N}\Delta V(n\Delta u)\, w^{mn} =$$

$$\sum_0^N e_n \Delta V_{on} w^{mn} + \sum_0^N e_n \Delta V_{on}^* w^{-mn}, \quad e_o = \frac{1}{2}, \quad e_{n\neq o} = 1 \qquad (39)$$

Now $<|\Delta T(m\Delta\xi)|^2>$ can be computed if, in view of (25), we note that:

$$<\Delta V_{op}\Delta V_{oq}^*> = A\,V(0)\,V^*[(q-p)\Delta u], \qquad (40)$$
$$<\Delta V_{op}\Delta V_{oq}> = A\,V(q\Delta u)\,V(p\Delta u)$$

(constant A as in (27)). The following expression is obtained:

$$e^2(T_m) = <|\Delta\hat{T}(m\Delta\xi)|^2> = \sum_0^N \sum_0^N e_p e_q V(0) \qquad (41)$$

$$V[(p-q)\Delta u]\, w^{m(p-q)} + real\left[\sum_0^N e_p V(p\Delta u)\, w^{mp}\right]^2$$

with D a constant. This expression is computed for the temperature distribution of fig. 2, again assuming noise free channels, and the results are shown in figs. 3 and 4. Note in fig. 3 that the errors of the modified temperature (lower line, arbitrary scale) seem to follow the profile of the recovered values of this latter (upper line). This result is not accidental; for the linear array under consideration it can be shown that:

$$e^2(T_m) = A(2N+1)\,T_{avg}T(m\Delta\xi)\,(\Delta u)^2 + f_m \qquad (42)$$

where f_m contains a constant part and another part dependent on the derivative of the modified temperature. In the examples worked out f_m turned out to be much smaller than the other term.

In fig. 4 the error of the brightness temperature, along with the recovered value of this latter, is represented. It can be seen that this increases sharply when approaching the field of view limits, $|\xi|=1$. In fact, according to (42):

$$\epsilon(T_{Bm}) = \epsilon(T_m)\frac{\sqrt{1-(m\Delta\xi)^2}}{|F_n(\xi)|^2} = \left[\frac{(2N+1)}{BT_{int}}\frac{\overline{T}_{avg}T_B(m\Delta\xi)}{1-(m\Delta\xi)^2}\right]^{1/2}\Delta u \quad (43)$$

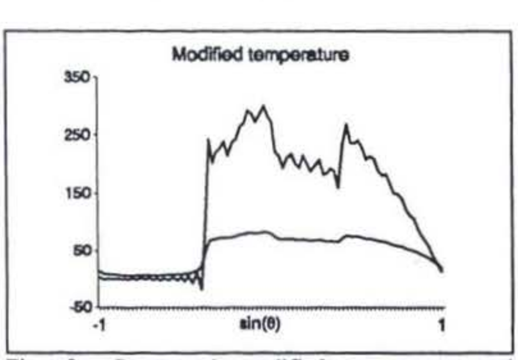

Fig. 3.- Recovered modified temperature and associated error (lower curve, arbitrary scale).

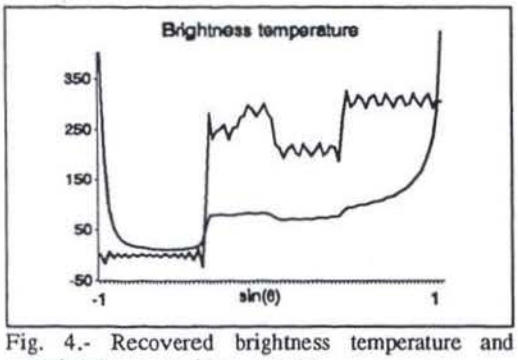

Fig. 4.- Recovered brightness temperature and associated error (arbitrary scale).

6. REDUNDANCY ON MIRAS AND ITS EFFECTS ON RADIOMETRIC RESOLUTION

MIRAS has a very low degree of redundancy [4]. If we disregard the three central elements introduced for the purpose of phase calibration, only baselines between antennas on the same arm can be redundant. By the zero baseline we will understand that corresponding to u=v=0, which in Miras is non-redundant.

Since we are considering a structure with 3 arms, each with N=43 elements, plus a central element, we will have:

-Total number of baselines: $3N(3N+1)/2+1 = 8386$

-Non-redundant baselines = non-redundant (u,v)-points: $3N^2+3+1 = 5551$ (three are formed by the central antenna and those at the ends of the arms and one is the zero baseline)

-Redundant (u,v)-points: $3(N-1) = 126$, with different degrees of redundancy.

-Total number of (u,v)-points: $3N^2+4+3(N-1) = 3N^2+3N+1 = 5677$

When we consider the Hermitian property every (u,v)-point is actually duplicated, but we stick to the previous figures which are more meaningful in terms of number of correlators.

If all (u,v)-points are measured only once, the norm of the visibility error vector is:

$$\langle|\Delta V|^2\rangle = \sum\sum\langle|\Delta V(u_m, v_n)|^2\rangle = \frac{5677}{BT_{int}}V^{n2}(0,0) \quad (44)$$

Let us now consider redundance. For each arm let $V(m\Delta u)$ be the visibility function corresponding to the baseline formed by two antennas separated by m basic spacings (0.89λ). If all possible baselines produce a visibility sample, $V(m\Delta u)$ has a redundacy (N-m+1). Therefore, the errors of the 126 previously non-redundant (u,v)-points:

$$\frac{126}{BT_{int}}V^{n2}(0,0) \quad (45)$$

have to be replaced by (assuming uncorrelated errors):

$$\frac{3V^{n2}(0,0)}{BT_{int}}\sum_{m=1}^{N-1}\frac{1}{N-m+1} = 3[C-1+\ln(N)]\frac{V^{n2}(0,0)}{BT_{int}} = \frac{10.015}{BT_{int}}V^{n2}(0,0) \quad (46)$$

where C=Euler's constant=0.5772. That is, with full redundancy in the arms of the interferometer the norm of the error vector becomes:

$$\langle|\Delta V|^2_{red}\rangle = \sum\sum\langle|\Delta V(u_m, v_n)|^2\rangle = \frac{5561}{BT_{int}}V^{n2}(0,0) \quad (47)$$

and therefore, the resolution improvement is given by:

$$\frac{e(T)-e(T)_{red}}{e(T)} = 1-\left(\frac{\langle|V|^2_{red}\rangle}{\langle|V|^2\rangle}\right)^{1/2} = 0.0103 = 1.03\% \quad (48)$$

That is, the average temperature resolution improvement contributed by the 2709 redundant complex correlators (from a total of 8386) is just a 1.0%.

(Recall that in the above computations the presence of three extra antennas at the center of the interferometers introduced for phase calibration has not been considered).

7. CONCLUSIONS

It has been shown that the correlation among the errors of the visibility samples taken in the same time interval modifies the resolution improvement obtained through baseline redundance and makes the temperature resolution pixel-dependent. In the first case the effect is moderate; according to the one dimensional simulations performed, in actual earth remote sensing scenes the correction will probably not exceed a 20%. In the case of radiometric resolution, the expressions derived for the error's correlation allow the computation of the errors of each pixel of a given scene. It has been shown that these errors are aproximately proportional to the square root of the pixel modified temperature, and, when considering the brightness temperature, the errors increase sharply towards the borders of the field of view.

At present, computation of the local radiometric sensitivity of two-dimensional arrays (in particular, MIRAS) is being performed.

ACKNOWLEDGMENTS

This work has been supported by ESA-ESTEC on its MIRAS project activities.

REFERENCES

1.- J.W. Goodman, "Statistical Optics", Wiley-Interscience, 1985.

2.- C.S. Ruf, C.T. Swift, A.B. Tanner, D.M. Le Vine, "Interferometric Synthetic Aperture Microwave Radiometry for the Remote Sensing of the Earth", Trans. on Geos. and Rem. Sens., Vol. 26, No. 5, Sept. 1988.

3.- J. Bará, A. Broquetas, A. Camps, I. Corbella, E. Daviu, S. Vilar, "Feasibility Study of a Dual Interferometer Radiometer", P.O. 132255 Final Rept. ESA-ESTEC, May 1994.

4.- Matra Marconi Space, "MIRAS: Microwave Imaging Radiometer with Aperture Synthesis. Microwave Radiometry Critical Technical Development", ESA-ESTEC, Mid Term Rept., JAN 1995.