An Improved Fast SPIHT Image Compression Algorithm for Aerial Applications

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***Abstract*—In this paper, an improved fast SPIHT algorithm has been presented. SPIHT and NLS (Not List SPIHT) are efficient compression algorithms, but the algorithms application is limited by the shortcomings of the poor error resistance and slow compression speed in the aviation areas. In this paper, the error resilience and the compression speed are improved. The remote sensing images are decomposed by Le Gall5/3 wavelet, and wavelet coefficients are indexed, scanned and allocated by the means of family blocks. The bit-plane importance is predicted by bitwise OR, so the N bit-planes can be encoded at the same time. Compared with the SPIHT algorithm, this improved algorithm is easy implemented by hardware, and the compression speed is improved. The PSNR of reconstructed images encoded by fast SPIHT is higher than SPIHT and CCSDS from 0.3 to 0.9db, and the speed is 4-6 times faster than SPIHT encoding process. The algorithm meets the high speed and reliability requirements of aerial applications.**

***Index Terms*—image compression, fast SPIHT coding, error resistance, bit-plane parallel**

I. Introduction

With the development of high-resolution remote sensing technology at home and abroad, the space camera sampling rate and the remote sensing image resolution are higher and higher. Therefore, a high error resistance and compression speed algorithm has become the research focus in the field of remote sensing image compression in the communication channel limited. There are some compression chips on the market, such as ADI's ADV202 and ADV212. But the largest input speed is only 65Mpixel/s, and the pixel depth can't meet all requirements. Therefore, to meet the engineering requirements, the reliable and efficient compression system must be studied.

1996, SPIHT (set partitioning in hierarchical trees) algorithm [1] was proposed by Said and Pearlman, which adopts spatial orientation tree structure, and can effectively extract the significant coefficients in wavelet domain. SPIHT has less extremely flexible features of bit stream than JPEG2000, but SPIHT has low structure and algorithm complexity relatively, and supports multi-rate, has high signal-to-noise ratio (SNR) and good image restoration quality, so it is suitable for encoding occasions with a high real-time requirement. Wavelet domain coefficients are scanned by three lists of SPIHT, which named: the list of insignificant pixels (LIP), the list of significant pixels (LSP) and the list of insignificant pixels sets (LIS). Each scan is from the highest bit-plane to the lowest bit-plane. The encoding speed is limited via the repetitive scans and dynamic update of three lists, and it isn't conducive to hardware implementation.

Subsequently, F.W.Wheeler and W.A.Pearlman proposed a variant of the original SPIHT algorithm can be achieved with hardware, named NLS (Not List SPIHT)[2]. The process of scans, the sets, and the compression ratio of NLS are the same with SPIHT. The IP, IS, REF of NLS are corresponding to LIP, LIS, LSP three lists of SPIHT. NLS solves the problem of hardware implementation, but does not improve the encoding speed.

In the aerial space, there are a lot of charged particles and cosmic rays, so the bits stream in storage devices may be disturbed by radiation effects, and then errors will be caused. The output bits stream of SPIHT and NLS are in accordance with the order of scans, so the whole image

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reconstruction will be influenced when an error generated.

Based on the above discussions, SPIHT and NLS are not conducive to hardware implementation. Actually, SPIHT and NLS are not used widely by virtue of the slow scanning speed and the poor error resistance factors. In this paper, the scanning process is simplified, and wavelet domain coefficients are stored by family blocks. The error resilience and encoding speed are improved, so the compression algorithm can be used in the aerial camera image compression system.

II. THE IMPROVEMENTS AND DEFICIENCIES OF NLS

A. *The improvements of NLS*

The spatial orientation tree structure is still adopted in NLS. The wavelet domain coefficients are separated into fathers, children, and grandchildren, as shown in the Fig. 1. Compared with SPIHT, NLS is improved at the aspect of hardware implementation, as follows:

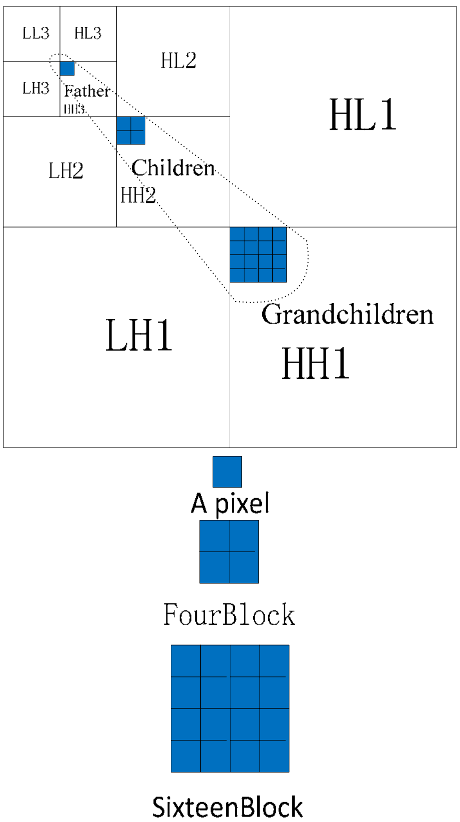

Figure 1. Spatial orientation tree structure of wavelet coefficients

The linear index technology is introduced. Linear index uses one number instead of the two-dimensional index. R = C = 2^N, R, C are the number of rows and columns of the image. (r, c) is the coordinates of coefficients, and r, c, can be wrote as binary numbers:

$$r = [r_{N-1}, r_{N-2}, \cdots, r_1, r_0] \quad c = [c_{N-1}, c_{N-2}, \cdots, c_1, c_0] \qquad (1)$$

Where r_n, c_n (n = 1,2, ... N-1) is a binary number. The linear index can be defined as:

$$i = [r_{N-1}, c_{N-1}, r_{N-2}, c_{N-2}, \cdots, r_1, c_1, r_0, c_0] \qquad (2)$$

Coordinates of a 8*8 image coefficients are arranged by the linear index, as shown Table I.

TABLE I. THE LINEAR INDEX

0	1	4	5	16	17	20	21
2	3	6	7	18	19	22	23
8	9	12	13	24	25	28	29
10	11	14	15	26	27	30	31
32	33	36	37	48	49	52	53
34	35	38	39	50	51	54	55
40	41	44	45	56	57	60	61
42	43	46	47	58	59	62	63

A state table Mark is used to show the state of each wavelet coefficient instead of three lists of SPIHT. Mark is updated by the results of each scan process. Val is used to store the coefficients arranged by the linear index. Two maximum arrays, dmax [i] and gmax [i], are introduced, so that it is not computing the maximum value of descendant sub-bands coefficients repeatedly. They are the maximum magnitude of the descendant (dmax) and the maximum magnitude of the grand descendant (gmax), and can be computed by (3) and (4), separately. They are no longer updated during the encoding process.

$$g\max(i) = \max(d\max(4i), d\max(4i+1), d\max(4i+2), d\max(4i+3)) \qquad (3)$$

$$d\max(i) = \max(val(4i), val(4i+1), val(4i+2), val(4i+3), g\max(i)) \qquad (4)$$

NLS uses one-dimensional linear index instead of the two-dimensional index, and adopts the SKIP function to skip the unimportant pixels blocks. The state table Mark can be implemented by hardware easily.

B. *Time consumption and error resistance of NLS*

Wavelet transform coefficients are rearranged by the linear index module. The address of high frequency sub-bands of coefficients is fragmented in the linear index lookup table. A standard image Lena of 512 * 512* 8 bits is done the 3-level DWT, as shown in the Figure 1. In the last row of the sub-band HH1, the coefficients (511, 256), (511,511) can be wrote as the binary number (11111,1111, 10000,0000), (11111,1111,11111,1111), corresponding the index value 240298, 262143 on the linear index lookup table, respectively. The linear index value of each coefficient must be corresponding with the storage RAM address by the means of address mapping. The lookup table need a lot of memory space to be stored, and the computing process is more and more complicated with the increasing rows and columns. NLS can properly encode or not, depends on whether the wavelet domain coefficients are arranged properly. Therefore, the linear index process must be simplified.

The scanning process of IP, IS, REF adopt the serial processing approach, a bit-plane by a bit-plane, from MSB to LSB._So the processing of a bit-plane needs scan the image 3times, and 24 times for a 8 bit-planes image.

The output message of the scanning process of each bit-plane includes the information for decoder and the scanning process of next bit-plane. If some errors in the code stream, the next scanning and decoding process would be wrong, and disastrous consequences would happen in the image reconstruction process. The cost time of the scanning process is the bottleneck of the time requirement of the whole compression system. The image could be correct reconstructed or not, demands on whether the output codes stream is right. Therefore, the scanning process need be improved.

III. Improved initialization of SPIHT

In this paper, wavelet domain coefficients are arranged by the linear index module, and dmax, gmax value arrays are computed at the same time. Wavelet domain coefficients are divided into many family blocks. A family is composed of one coefficient of the HL3, HH3, LH3 sub-bands (a pixel), four coefficients of HL2, HH2, LH2 sub-bands (FourBlock), and sixteen coefficients of HL1, HH1, LH1 sub-bands (SixteenBlocks), as shown in the Fig.1. 32*32 families form a family block, which is stored in a RAM.

Wavelet domain coefficients at all levels (except LL3 sub-band) are stored in the family blocks RAM by the mapping address module directly, as shown in Fig.2. There are 12 family blocks totally. Coefficients in the LL3 sub-band are stored separately. Compared to the whole image coefficients, the number of coefficients in each family block is small, so the computational complexity of the linear index process is greatly reduced. All family blocks share the linear index module, which also reduces the memory space requirements. The size of the family block can be adjusted according to the hardware resources, such as 16*16, 64*64 and so on. The output code streams are stored in blocks separately. If an error generated in a scanning process, the wrong codes would be constrained in the only block, and not disturb other family blocks. The error resistance has been improved. Each family block is encoded by the same scanning process, and the encoding module can be easy generated by the means of citing the module in Verilog HDL or VHDL. Therefore, the encoding efficiency has been improved. The improved initialization process is shown in the Fig.2.

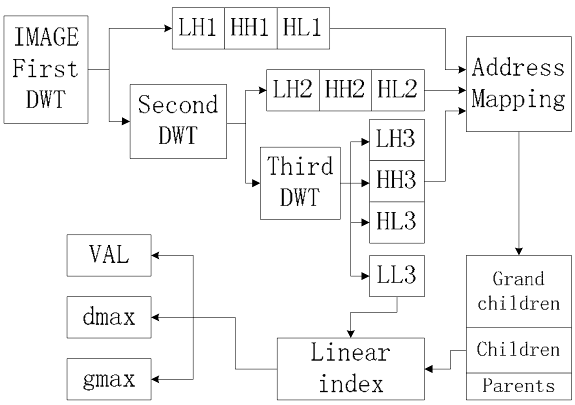

Figure 2. Improved initialization of SPIHT

IV. Parallel SPIHT

SPIHT and NLS adopts the serial processing approach, form MSB to LSB, because the processing for a bit-plane needs the results of the previous bit-plane's processing. The parallel SPIHT algorithm in this paper can deal with all bit-planes simultaneously. It also adopts three lists (LSP, LIP, LIS) instead of the state Mark, but the scanning results of all bit-planes can be obtained at the same time. The proposed algorithm predicts each pixel's state by the bitwise OR operation. The bitwise OR results of the first n-1 bits of the val, dmax and gmax value are computed in the scanning process. In addition, 3 times' image scanning is need for a bit-plane in NLS. While the fast SPIHT handles three processes in NLS through one scan. Therefore, the scanning speed is only relative to the image resolution. Bitwise OR is easy implemented by hardware, so it is a real-time process.

Define: PixelOR is the bitwise OR result of the first n-1 bits of val for each pixel, and PixelOR is 0 for the first bit-plane. DmaxOR is the bitwise OR result of the first n-1bits of dmax for each FourBlock, and DmaxOR is 0 for the first bit-plane. GmaxOR is the bitwise OR result of the first n-1bits of gmax for each SixteenBlock, and GmaxOR is 0 for the first bit-plane. PxielBit,DmaxBit and GmaxBit is the nth bit of val , dmax and gmax respectively.

PixelOR, DmaxOR and GmaxOR modules can be used to determine whether the pixel, the FourBlock and the SixteenBlock have been an important element respectively. When 1, it indicates that there is at least one bit 1 in the first n-1 bit-planes. When 0, it indicates that the first n-1 bits are all 0, and the pixel is unimportant.

MGpredict is the bitwise OR result of the first n bits of FourBlock's dmax in the HL2, HH2 and LH2 sub-bands for each SixteenBlock. MGpredict can be used to determine whether the SixteenBlock has been flagged as MG (a kind of state of the pixel in NLS, as the L-type entry in SPIHT).

Sign is the sign for each pixel. LIP, LIS, and LSP are three lists, which correspond to the output stream of the IP, IS and REF process of NLS. LIP, LIS and LSP correspond to the output stream of the IPP, ISP and RP process of NLS respectively.

Specific description of the parallel SPIHT algorithm:

- The 3rd level DWTcoefficients(LL3,LH3,HL3,HH3):

```
if (PixelOR==1) output PixelBit to the lsp
else
    output PixelBit to the lip
  if(PixelBit ==1) output sign to the lip
```

- The 2nd level DWT coefficients (LH2,HL2,HH2):

```
if(DmaxOR==1)
    for each pixel∈FourBlock
       if(PixelOR==1)output PixelBit to the lsp
       else
    output PixelBit to the lip
    if(PixelBit==1)output sign to the lip
 else
  output DmaxBit to the lis
```

```
      if(DmaxBit ==1)
          for each pixel∈FourBlock
        output DmaxBit to the lis
        if(DmaxBit ==1) output sign to the lis
```

● The 1st level DWT coefficients(LH1,HL1,HH1):

```
if(MGpredict==1)
   if(GmaxOR==1)
      for each FourBlock∈SixteenBlock
       if(DmaxOR ==1)
          for each pixel∈FourBlock
         if(PixelOR==1)output PixelBit to the lsp
         else
             output PixelBit to the lip
             if(PixelBit ==1)output sign to the lip
       else
          output DmaxBit to the lis
          if(DmaxBit ==1)
        for each pixel∈FourBlock
           output PixelBit to the lis
           if(PixelBit ==1)output sign to the lis
    else
    output GmaxBit to the lis
    if(GmaxBit ==1)
   for each FourBlock∈SixteenBlock
       output GmaxBit to the lis
       if(DmaxBit ==1)
          for each pixel∈FourBlock
       output PixelBit to the lis
       if(PixelBit ==1)output sign to the lis
```

The flowchart of the parallel SPIHT algorithm is shown in the Fig.3 [3].

V. BIT-RATE CONTROL

Bit-Rate control is a process by which the bitrates are allocated in each code-block in each sub-band in order to achieve the overall target encoding bit-rate for the whole image while minimizing the distortion (errors) introduced in the reconstructed image due to quantization and truncation of codes to achieve the desired code rate.

The scanning processes of SPIHT and NLS are from the MSP to the LSP, and it is truncated at a bit-plane when the communication channel bandwidth is limited. All wavelet domain coefficients are quantified at the same step size, and it is bigger when the bit-rate is lower. The serious distortion and false contour may be introduced.

In this paper, the entropy of each sub-band family is estimated according to LOCO-I MED prediction algorithm in [5] when coefficients are indexed, as shown in Fig. 2. The number of output codes of each sub-band family is allocated according to compression rate requirements, and codes are truncated from high to low bit-planes to achieve rate control.

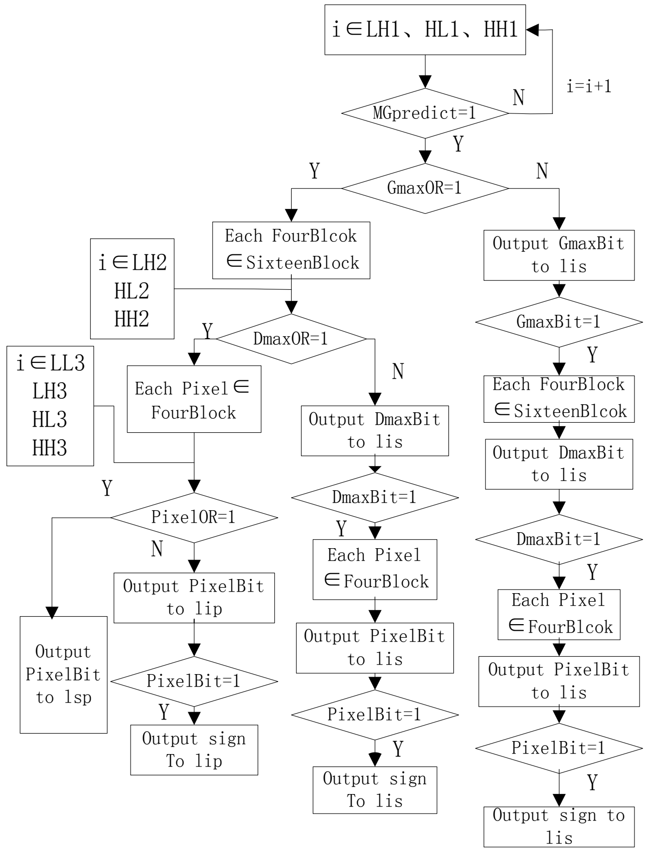

Figure 3. The flowchart of the scanning process

The forecast template is shown in Fig. 4:

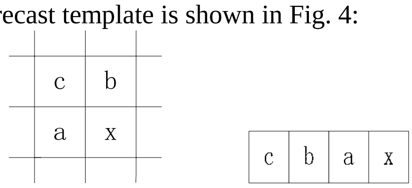

Figure 4. The forecast template and linear index order

The prediction coefficients:

$$\hat{x} = \begin{cases} \min(a,b), c \geq \max(a,b) \\ \max(a,b), c \leq \min(a,b) \\ a+b-c, otherwise \end{cases} \quad (5)$$

The forecast expression is shown in figure 5. The coefficient at the boundary is predicted by the former one. The FamilyBlock is composed of three SubBands, and H_s is the prediction entropy of a SubBand.

$$H_s = \sum_i |\hat{x}_i - x_i| \quad (6)$$

$i \in SubBand$,s=1、2、3. x_i and $\hat{x}_i$ are the reality value and the prediction value respectively. Similarly H_f , $H_f = \sum_s H_s$, is the prediction entropy of a FamilyBlock, and H_{LL3} is the prediction entropy of LL3.

The prediction entropy of the whole coefficients can be defined as follows:

$$H = H_{LL3} + \sum_{f} H_f \qquad (7)$$

f is the number of the FamilyBlocks, $f=1$、2、…、12.

W_f is the pre-allocated weight of each FamilyBlock, which is defined as $W_f = H_f / H$. W_{fs} is the pre-allocated weight of the s SubBand of the f FamilyBlock, which is defined as :

$$W_{fs} = H_{fs} / H \qquad (8)$$

H_{fs} is the prediction entropy of the s SubBand of the f FamilyBlock. Similarly, W_{LL3} is the pre-allocated weight of the LL3 sub-band, which is defined as :

$$W_{LL3} = H_{LL3} / H \qquad (9)$$

The sum of all weights is equal to 1, as $W_{LL3} + \sum_{f} W_f = 1$.

Rate is the compressed bit-rate, and the size of the image is $R \times C$ .Then the pre-allocated code streams of each SubBand can be defined as :

$$\begin{aligned} Bit_{fs} &= Rate \times R \times C \times W_{fs} \\ Bit_{LL3} &= Rate \times R \times C \times W_{LL3} \end{aligned} \qquad (10)$$

Bit-rate of each SubBand is controlled by (10), according to the channel bandwidth.

VI. Experimental Results

The standard images of Lena, Goldhill, Aerial, and Fukushima nuclear plant (before and after disaster) are chose as experimental images. The size of images is 512 *512*8bits. Images are done the 3-level DWT with matlabR2008. The computer CPU is Intel Pentium Dual E2160 1.8GHz, and the memory size is 1G. The PSNR of Goldhill reconstruction compressed by fast SPIHT, SPIHT, NLS and CCSDS are shown in the Fig.5, and the PSNR of reconstruction images compressed by fast SPIHT at different bit-rate are shown in the Fig. 6.

Fast SPIHT processes 8 bit-planes at the same time containing three lists, so the code-stream must be reordered. The output streams are adjusted by the order process in accordance with the sequence of SPIHT, so the decompressed process is the same with SPIHT, and the compression ratio can be controlled. The time cost of SPIHT encoding at different bit-rate are shown in the Fig.7, also the time cost and PSNR of fast SPIHT encoding at bit-rate 1bpp are shown in the table II.

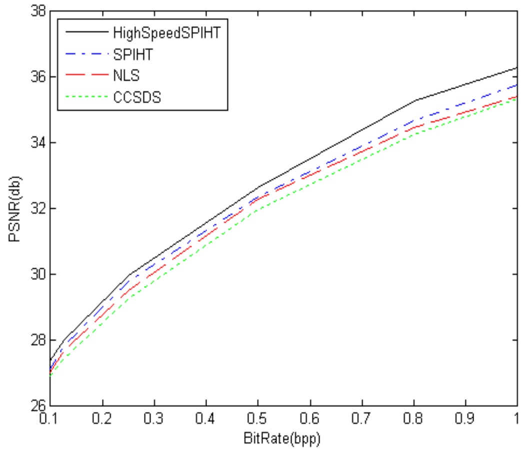

Figure 5. PSNR of Goldhill reconstruction compressed by diffeient methods

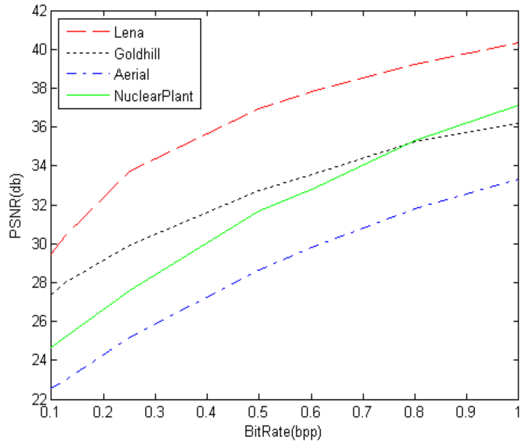

Figure 6. PSNR of reconstruction images compressed by fast SPIHT at different bit-rate

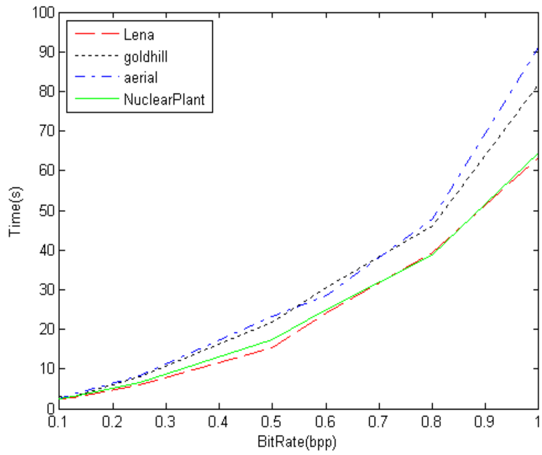

Figure 7. Time cost of SPIHT encoding at different bit-rate

TABLE II. CONSEQUENCES OF FAST SPIHT ALGORITHM

Image	Fast SPIHT rate=1bpp		SPIHT rate=1bpp	
——	Time(s)	PSNR(db)	Time(s)	PSNR(db)
Lena	14.1853	40.38	63.2569	39.85
Goldhill	14.5472	36.21	81.8279	35.73
Aerial	15.3227	33.02	91.0756	32.17
Nuclear Plant	12.3271	37.24	64.3354	36.69

Goldhill reconstruction images PSNR=32.83 db

Aerial reconstruction images PSNR=28.65 db

Fukushima nuclear plant (before disaster) reconstruction images PSNR=30.59 db

Fukushima nuclear plant (after disaster) reconstruction images PSNR=31.84 db

Figure 8. Reconstruction Images compressed by fast SPIHT, Bit-Rate=0.5bpp

Goldhill, Aerial and Fukushima nuclear plant (before and after disaster) reconstruction images at bit-rate 0.5bpp are displayed in the Fig.8. By comparing images of the nuclear plant before and after disaster, the situation of plant damaged can be seen clearly. The image of nuclear plant after disaster is smoother than the image before, so the PSNR is higher at the same bit-rate.

The experiments results show that the PSNR of reconstruction images encoded by fast SPIHT are increased 0.3 to 0.9db, and the time are only 1/4-1/6 of SPIHT encoding process. Implemented by hardware, the speed can be further improved via virtue of parallelism and pipelining.

VII. CONCLUSIONS

In this paper, the error resilience and compression speed are improved. The compression algorithm based on set partitioning in hierarchical scans coefficients by the serial processing approach. The encoding speed is limited by repeatedly scans. A new fast SPIHT algorithm is proposed, which can deal with all bit-planes simultaneously, and the speed is only relative to the image resolution. The coefficients are divided into many family blocks, stored in block RAMs separately. The algorithm is suitable for a fast, simple hardware implementation, and can be used in the field of aerial image compression system, which requiring the high speed and high error resilience.

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