In-flight Wavelength Calibration of Thermal Infrared Multispectral Scanner (TIMS) Data acquired from the ER-2

Sirnon J. Hook and Kinya Okada[1]

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract

In 199: one flightline of Thermal Infrared Multispectral Scanner (TIMS) data was acquired over Castaic Lake, California and in 1992 four flightlines of TIMS data were acquired over Death Valley, California, Both datasets were obtained from. an altitude of 20 km. The data were calibrated and corrected for atmospheric effects using LOWTRAN 7 to brightness temperature at the surface. The brightness temperatures for a spectrally flat area in the Castaic Lake data were then examined. Since the emissivity of the area was constant, the brightness temperatures in the six TIMS channels should also have been similar. However, this was not the case, the values in channel 4 were much higher and the values in channel 3 much lower than those in the other channels. This difference is explained by an in-flight shift in the system response functions of the TIMS channels. The amount of shift can be determined by incremental shifting of the pre-flight system response functions to longer wavelengths then re-calculating the surface brightness temperature using the above method until the temperatures for channels 3 and 4 agree. A shift of 113 nm was required to make the brightness temperatures of channels 3 and 4 agree with the Castaic Lake data. The same procedure was undertaken with the TIMS data from the four

[1] On study leave from the Japex Geoscience Institute, Tokyo, Japan

flightlines acquired at Death Valley that overlapped a spectrally flat target. The brightness temperatures for all the channels were found to be in good agreement after shifts of 75, 87, 90 and 103 nm. The amount of shift increased as a function of the time that TIMS was airborne. The Castaic Lake data were acquired after TIMS had been airborne for a similar amount of time to the Death Valley flightline which showed a shift of 90 nm.

The results from this study clearly demonstrate that the system response functions of the six TIMS channels shift to longer wavelengths compared to their pre-flight values with data acquired from the ER-2. A method is provided for determining the amount of shift permitting its correction. The method could also be used to verify the in-flight wavelength calibration of multispectral thermal infrared data acquired from other airborne or spaceborne scanners with a similar optical configuration to TIMS.

I. Introduction

The radiation emitted from a surface in the thermal infrared (8-12pm) is a function of its temperature and emissivity. Both of these parameters are useful for a wide variety of studies and several airborne and spaceborne instruments have been developed that measure the radiation from this wavelength region. One such instrument is the Thermal Infrared Multispectral Scanner (TIMS) (Kahle and Goetz, 1983). TIMS data have been acquired from the NASA Learjet at Stennis since 1982, the NASA C-130 at AMES since 1985, and the NASA ER-2 also at AMES since 1990. In order to derive surface temperature and emissivity the TIMS data must be calibrated and corrected for any atmospheric effects to radiance at the surface. An in-flight calibration experiment is undertaken each flight season to estimate the radiometric calibration of TIMS. In this experiment the radiant temperature of a target, typically water, is measured on the ground simultaneously with a TIMS overflight. Water is used since its surface temperature tends to be uniform over space and time due to its high heat capacity and also it is spectrally flat at the resolution of TIMS. In order to characterize the atmosphere, an atmospheric sounding balloon is released prior to the overflight. The TIMS data are then calibrated and corrected for atmospheric effects using the local atmospheric data and the temperature recovered for the target with TIMS is compared with the target temperature measured on the ground. This in-flight radiometric calibration methodology has been utilized with other spaceborne systems, e.g. the thermal channel of the LANDSAT Thematic Mapper (Schott and Volchok, 1985; Schott, 1989). These experiments confirm the radiometric calibration of TIMS but do not usually provide any indication of the accuracy of the in-flight wavelength calibration which is based on a pre-flight laboratory calibration. This study describes a method for determining the in-flight wavelength calibration of TIMS data. Two TIMS/ER-2 datasets were evaluated. The two datasets were acquired at Castaic Lake, California and Death Valley, California on November 22 nd, 1991 and May 31 st 1992 respectively. A single flightline of TIMS data was acquired at Castaic Lake and four flightlines of TIMS data were acquired at Death Valley (Figures 1A and 1B). The pre-flight calibration produces a set of system functions that describe the spectral response of the six TIMS channels with wavelength. Analysis of the Castaic Lake and Death Valley datasets indicates that the system response functions move to longer wavelengths with time when TIMS is operated from the ER-2. This paper describes the results that indicate a shift has taken place and a method for determining the amount of shift permitting its correction.

11. TIMS Instrument Description

TIMS has six channels between 8 and 12 pm, an instantaneous field of view (IFOV) of 2.5 mrad and a total field of view of 76.56° (Palluconi and Meeks, 1985). The wavelength calibration of the instrument is checked in the laboratory approximately annually at the Stennis Space Center. Figure 2 shows the central wavelength positions of the six TIMS channels derived from the laboratory calibrations over several years. The central wavelength positions of the TIMS channels tend to shift between calibrations due to small changes in the alignment of various components in the optical path. The optical path of the energy incident on the TIMS is shown in Figure 3. Cross track scanning is achieved through rotation of a 45° flat scan mirror that reflects incident energy to the parabolic primary mirror (Ml). The energy is then directed into the spectrometer section of the instrument by a flat secondary mirror (M2). At the entrance to the spectrometer section and focal plane of the primary mirror is an 0.8 mm field stop aperture which defines the instruments 2.5 mrad IFOV. The energy that passes through the field stop is collimated by an off-axis parabolic section mirror (M3) and directed to a replica grating (M4) which produces the spectral dispersion of the energy onto a germanium triplet lens (L1) which focuses the energy onto the detector array. If the alignment of any of the mirrors beyond M 1 changes all the channel positions shift to longer or shorter wavelengths by the same amount. This effect can be seen in the laboratory calibrations undertaken at different times (Figure 2).

The pre-flight laboratory wavelength calibration nearest the acquisition dates of these data was undertaken in December 1991 .The centı al wavelengths positions (in micrometers) of the TIMS channels for that calibration were 8.383, 8.785, 9.180, 9.892, 10.733 and 11.655.

The in-flight radiometric calibration of TIMS is accomplished with two blackbodies whose temperatures are set to bracket the anticipated ground temperatures. One of the blackbodies is observed by the TIMS scanner at the start and stop of each scanline. The blackbody temperatures and responses can then be used to derive a set of coefficients to convert the instrument digital numbers to radiance at the sensor with the method described by Palluconi and Mecks, (1985).

111. Data Processing and Results

Initially the TIMS data from Castaic Lake were calibrated to radiance at the sensor (Palluconi and Meeks, 1985). After calibration the radiance at the sensor can be written as:

$$L_\lambda = [\epsilon_\lambda L_{bb\lambda}(T) + (1 - \epsilon_\lambda) L_{sky\lambda}]\tau_\lambda + L_{atm\lambda} \tag{1}$$

where:

ϵ_λ = surface emissivity at wavelength λ.

$L_{bb\lambda}(T)$ = spectral radiance from a blackbody at surface temperature T.

$L_{sky\lambda}$ = spectral radiance incident upon the surface from the atmosphere.

τ_λ = spectral atmospheric transmission.

$L_{atm\,\lambda}$ = spectral radiance from atmospheric emission and scattering that reaches the sensor.

The radiance at sensor data were corrected for atmospheric effects to radiance at the surface ($\varepsilon_\lambda L_{bb\lambda}(T)$) using the LOWTRAN 7 radiative transfer model (Kneizys *et al.*, 1988). LOWTRAN 7 derives values for the atmospheric correction based on an input atmospheric profile which may be obtained from the default profiles in LOWTRAN 7, or the profile may be modified/replaced with local atmospheric data. In this study, local atmospheric data were acquired at Castaic Lake from an airsonde released approximately 10 minutes prior to the overflight. The airsonde provides atmospheric profiles of relative humidity, temperature and pressure. The relative humidity is derived from the wet and dry bulb thermometers on the airsonde. The wet bulb froze at 4.5 km and no useful data were provided by the airsonde above 4.5 km. Atmospheric data for the remainder of the profile were obtained from the default mid-latitude summer model of LOWTRAN 7. The default summer rather than winter profile was used because the temperature and pressure profiles derived from the atmospheric sounding balloon closely matched the default values in the summer rather than winter model. The radiance values were converted to brightness temperatures to facilitate comparison with ground temperature measurements.

In order to evaluate the atmospheric correction, the brightness temperatures from an area of water, considered to be spectrally flat with similar surface temperatures over large areas, were extracted from the Castaic Lake dataset. Since water has similar emissivity values in all six TIMS channels the brightness temperature values for all the channels should be similar after calibration and atmospheric correction.

Examination of the mean spectrum of the brightness temperatures from the spectrally flat area within the Castaic Lake dataset indicates that there is considerable variation in the brightness temperatures with a distinct maximum in channel 4 and minimum in channel 3 (Figure 4). High brightness temperature values in channel 4 relative to the other channels have also been observed with TIMS data acquired over spectrally flat targets with the C-130 at much lower altitudes. They were attributed to an excess of ozone in the default atmospheric profile used by LOWTRAN 7.

This effect was corrected by reducing the total ozone in the atmospheric profile (} look *et al.*, *1992)*. This approach was attempted with these data, and the values in channel 4 did fall however, the values in channel 3 remained lower than those in the other channels (Figure 5). An alternative hypothesis was then evaluated which assumed that the system response functions of the TIMS channels had shifted in-flight to longer wavelengths relative to their pre-flight positions. In the pre-flight system response functions the ozone band is almost entirely confined to channel 4 (Figure 6), therefore if the response functions had shifted to longer wavelengths, but the atmospheric correction factors were calculated based on the pre-flight values, the brightness temperatures would be over-corrected in channel 4 and not corrected in channel 3. To test this hypothesis the pre-flight system response functions were shifted in increments to longer wavelengths and the surface brightness temperatures of the six TIMS channels re-calculated after each shift (Figure 7C). As the shift increases, the brightness temperature values in channel 4 decrease and the values in channel 3 increase as the influence of the ozone band decreases in channel 4 and increases in channel 3 until there is a crossover at 113 nm. The brightness temperatures in the other TIMS channels are largely unaffected by the shifting. After a shift of 113 nm channels 3 and 4 have similar brightness temperatures that lie between the brightness temperatures of the other channels. Further shifting beyond 113 nm causes the values in channel 4 to decrease and the values in channel 3 to increase relative to the values in the other channels (Figure 7C).

In order to determine whether this shift was an isolated phenomenon a similar analysis was performed on the data acquired over Death Valley. Several flightlines of data were acquired over Death Valley and four of these went over the same spectrally flat target. An area of wet halite was used as the spectrally flat target since no areas of water were available. Halite is a salt which when wet is spectrally flat in the thermal infrared. No local atmospheric data were acquired for Death Valley and the default mid-latitude summer profile was used for the atmospheric correction. Figure 8 shows the brightness temperature spectra extracted from the area of halite after calibration and atmospheric correction with no wavelength shift applied for the four flightlines. The spectra show the same artifact with respect to channels 3 and 4 observed with the Castaic Lake data and in addition the values in channel 1 are higher than those from channels 2, 5 and 6. The high values in channel 1 are believed to result from the fact that the default mid latitude summer profile is far moister than would be expected for a desert area such as Death Valley in the summer, When the shifting procedure was applied to these data it was not possible to derive a flat spectrum (Figure 9). In order to bring channel 1 into agreement with the other channels the total water vapor was reduced by increments and the surface brightness temperatures in each channel re-calculated. After a reduction of 70% in the total column water vapor the brightness temperatures in channels 1 to 5 for the four flightlines were in good agreement (Figure 10). The slightly lower values in channel 6 are believed to be associated with a problem with the preamplifier circuits for channel 6 (Realmuto *pers. comm.* 1994). Therefore, the data in this channel was not used in any subsequent analysis.

IV. Discussion

In addition to shifting the system response functions there are several other factors that affect the wavelength position that the crossover in the temperatures of channels 3 and 4 occurs. These include the total ozone in the profile, the spectral character of the surface, the *NEAT* of the instrument and the accuracy of the laboratory calibration.

If the total ozone in the profile is increased or decreased the position of the crossover will shift, this effect is illustrated in Figure 7 A-E. The criterion used to determine if the amount of shift was valid with the default model was whether the temperatures of channels 3 and 4 were bracketed by those derived from the other channels (Figure 7C). If the total ozone in the model is increased or decreased then a different shift is valid (Figures 7 B and D respectively) If the crossover temperature is not bracketed by the temperatures in the other channels then the spectrum will not be flat (Figure 7 F).

If the emissivity of the surface used is different in channels 3 and 4, the amount of shift will be over- or under-estimated depending on whether the emissivity in channel 3 is lower or higher than the emissivity in channel 4.

The *NEAT* will also affect the crossover position since it limits the range in the position at which the crossover may occur. In order to examine this effect the ratio of the hot and cold blackbodies to their digital number (DN) values was calculated for channels 3 and 4 ($\Delta T/\Delta DN$). These were 0.2 and 0.25°C respectively. If the crossover occurred when channels 3 and 4 were at 16.31 ‘C and the *NEAT* of channels 3 and 4 were 0.2 and 0.25°C respectively. Then the crossover could occur anywhere between 16.06°C and 16.56 °C or 102 to 117 nm (Table 1). Lastly, the laboratory calibration affects the amount of shift since it forms the point of reference. The laboratory calibration is done approximately once a year and examination of the laboratory calibrations for several years (Figure 2) indicates that the fluctuation in the central wavelengths of the TIMS channels are approximately half the magnitude of the amount of shift obtained with the above method. <-

Figure 11 shows the crossover point for the Death Valley and Castaic Lake datasets as a function of time since launch. These data indicate an increasing linear trend in the amount of shift with time. 'I'he exact cause for this apparent shift is unknown at the present time, but a shift in any of the optics beyond Ml (Figure 3) would clearly cause this type of shift. Although the cause for the shift is unknown, since the amount of shift increases with time one or more components are probably becoming increasingly misaligned with time. Presumably the shift will increase until a threshold is reached when the instrument is in equilibrium with the environment. The Castaic Lake data were acquired when TIMS had been airborne for a similar amount of time to when the third TIMS Death valley flightline were acquired. The shifts for the two flightlines were 113 nm and 90 nm respectively. The similarity in the amount of shift is remarkable, the slight differences could arise in a variety of ways but one likely candidate would be if the center wavelength positions of the channels did not return to their pre-flight position at the end of the flight.

Lastly, the detection of the shift from the ER-2 is possible due to the strong ozone component *in* the atmospheric path at the ER-2 flight altitude of 20 km. However, this effect may well exist in TIMS data acquired from other platforms that operate from lower altitudes if the instrument is exposed in a similar environment.

V. Summary and Conclusions

In 1991 and 1992 TIMS data were acquired from the ER-2 at Castaic Lake and Death Valley, California respectively. Initially, the TIMS data from Castaic Lake were calibrated and corrected for atmospheric effects with LOWTRAN 7 to radiance at the surface. The surface radiances were converted to brightness temperature with the Planck function. The mean brightness temperature spectrum from a spectrally flat, homogeneous area was then extracted. Since the emissivity of the surface is similar in all six TIMS channels, the brightness temperatures should also be similar. However, the brightness temperatures for channel 4 were much higher and the brightness temperatures for channel 3 much lower than channels 1, 2, 5 and 6.

The difference between channel 3 and 4 was initially attributed to an excess of ozone in the atmospheric profile (ozone strongly affects "the values in channel 4 and has a lesser effect on the values in channel 3). In order to corr ect this affect the total ozone in the atmospheric profile was reduced. While this approach lowered the values in channel 4 the values in channel 3 remained lower than those in the other channels. An alternate hypothesis was then evaluated that assumed the cause for the channel 3/4 difference was a shift in the TIMS system response functions from their pre-flight positions to longer wavelengths. The system response functions were shifted in increments and after a shift of 113 nrn the values in channels 3 and 4 were similar and the values in channels 1 through 6 agreed within -2°C for the Castaic Lake data.

The above approach was then repeated with the four flightlines of data from Death Valley. The target spectra had a similar shape to those at Castaic Lake except that the values from channel 6 were much lower due to a problem with the instrument gain. Shifts of 75, 87, 90, 103 nm were determined for the four flightlines with the amount of shift increasing as a function of the time that TIMS was aloft in the ER-2.

In conclusion, the systems functions that describe the response of the TIMS channels show a shift to longer wavelengths with data acquired from the ER-2. The amount of shift appears to increase with the time TIMS is airborne in the ER-2. The shift is on the order of 100 nm and it is possible to determine the amount of shift from the data. The approach for determining the shift allows the in-flight wavelength calibration of multispectral thermal infrared data to be verified where two channels overlap an atmospheric absorption band, in this case ozone, and the instrument has a similar optical configuration to TIMS. However, in order to determine the shift a target is required in the scene that is either spectrally flat or has known emissivities in the six TIMS channels. Any unaccounted emissivity differences in the target will result in the amount of shift being over or under estimated. Other factors that affect the determination of the amount of shift include the *NEAT* of the instrument and the amount of ozone assumed in the model to determine the shift, as well as the accuracy of the pre-flight laboratory calibration.

Acknowledgements

The research described in this paper was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, K. Okada's study leave was supported by the Japan National Oil Corporation and Japan Petroleum Exploration Co. Ltd.

Reference herein to any specific commercial product, process, or service by trade names, trademark, manufacturer or otherwise does not imply endorsement by the United States or the Jet Propulsion Laboratory, California Institute of Technology.

Special thanks go to Frank Palluconi and Vince Realmuto also at the Jet Propulsion Laboratory for reviewing this manuscript and providing many helpful suggestions during the course of this work.

References

Hook, S. J., A. R. Gabell, A. A. Green, and P. S. Kealy, 1992. A Comparison of Techniques for

Extracting Emissivity Information from Thermal Infrared Data for Geologic Studies, *Remote Sens. Environ .*, 42, pp. 123-135, 1992.

Kahle, A. B., and A. F. H. Goetz, 1983. Mineralogic Information from a New Airborne Thermal Infrared Multispectral Scanner. *Science, 22,2,* pp. 24-27.

Kneizys, F, X., E. P. Shettle, L. W. Abreu, J. H. Chetwynd Jr., G. P. Andersen, W. O. Gallery, J. E. A. Selby, and S. A. Clough, 1988. Users guide to LOWTRAN 7, Environmental Research Paper 1010, *Tech. Rep. AFGL-TR-88-0177,* Air Force Geophys. Lab., Bedford, Mass.

Palluconi, F. D., and G. R. Meeks, 1985. Thermal infrared multispectral scanner (TIMS): An investigator's guide to TIMS data, *JPL Put)/., 85-32.*

Schott, J. R., and W. J. Volchok. Thematic Mapper Thermal Infrared Calibration. *Photogrammetric Engineering and Remote Sensing, 51,* pp. 1351-1357.

Schott, J. R., 1989. Image Processing of Thermal Infrared Images. *Photogrammetric Engineering and Remote Sensing, 55,* pp. 1311-1321.

	Amount of Shift to Crossover (rim)			
Channel	-AT	0	+ΔT	Temperature
ch3 ± 0.2°C	106	1 1 3	117	16.11 -16.51°C
ch4 ± 0.25°C	122	113	102	16.06 -16.56°C

Table 1. Example of the possible variation in the crossover position as a function of signal: noise.

List of Figures

Figure 6. Pre-flight system response functions for the Castaic Lake dataset with the position of the ozone atmospheric band superimpose] on the position of the system response functions. Note according to the pre-flight system response functions only TIMS channel 4 is strongly affected by the ozone absorption band.

Figure 7. A to E - Brightness temperatures derived from TIMS channels 1 through 6 over an area of water in the Castaic Lake dataset after calibration and atmospheric correction by using profiles with varying amounts of ozone, as a function of increasing wavelength shift, 7F - Brightness temperature spectra for six TIMS channels at the crossover position in Figures 7A to E and an example of the spectrum produced if too large a wavelength shift is applied to data (ozone=1.0, shift= 150 rim).

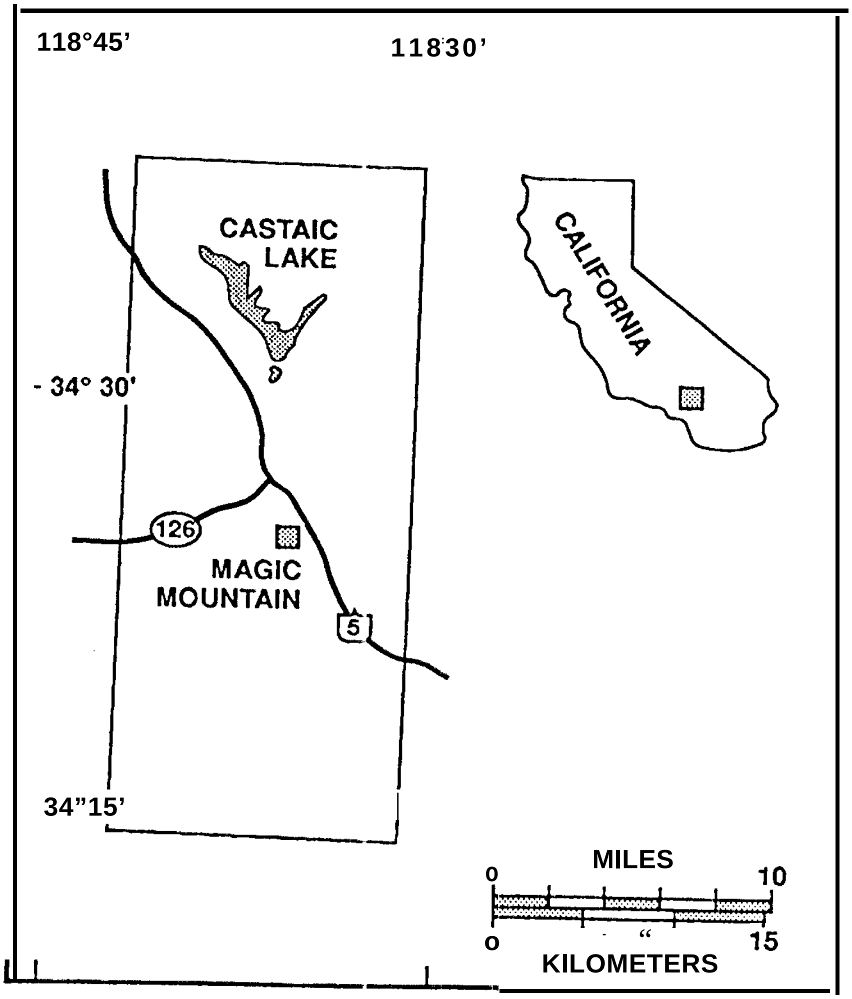
Figure 8. Brightness temperature spectra extracted from an area of wet halite 5 by 5 pixels assumed to be spectrally flat target for the four Death Valley datasets after calibration and correction for atmospheric effects with LOWTRAN 7 using the atmospheric inputs from the default mid-latitude summer profile.

Figure 9. Brightness temperature spectra extracted from an area of wet halite 5 by 5 pixels assumed spectrally flat after shifting and calibration and atmospheric correction.

Figure 10. Brightness temperature spectra extracted from an area of wet halite 5 by 5 pixels assumed spectrally flat after shifting and calibration and atmospheric correction with the total

column water vapor reduced by 70%.

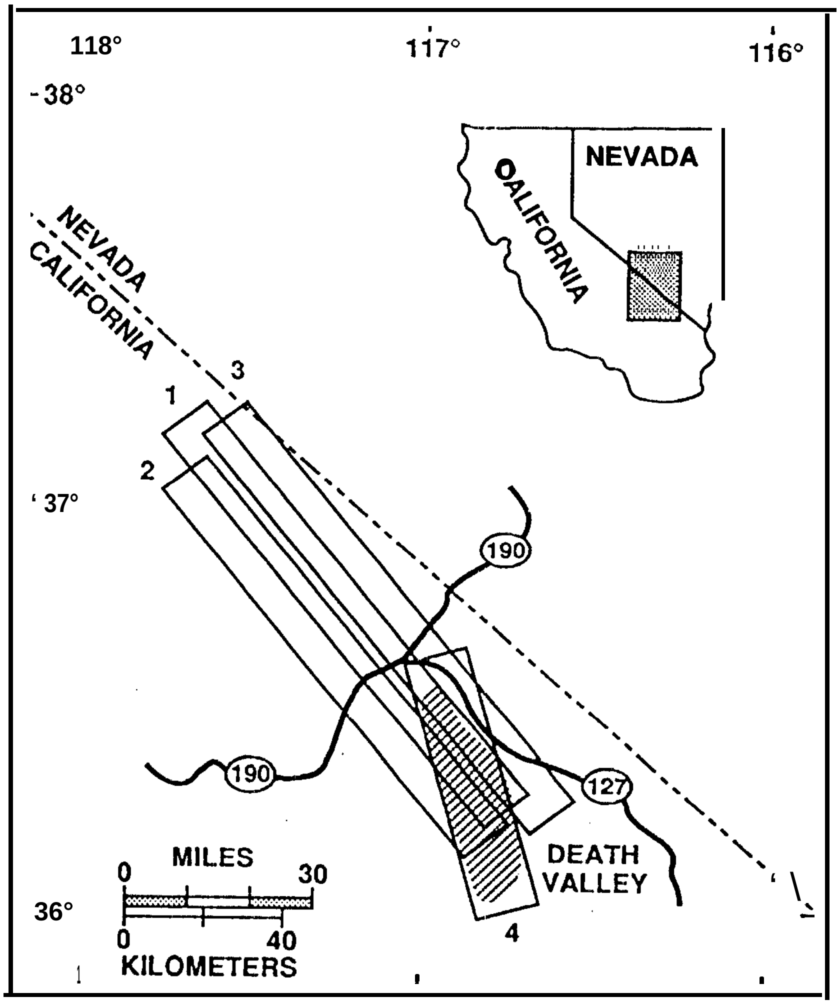
Figure 11. Amount of shift calculated from the Castaic Lake and Death Valley datasets as a function of time that TIMS was airborne in the ER-2.



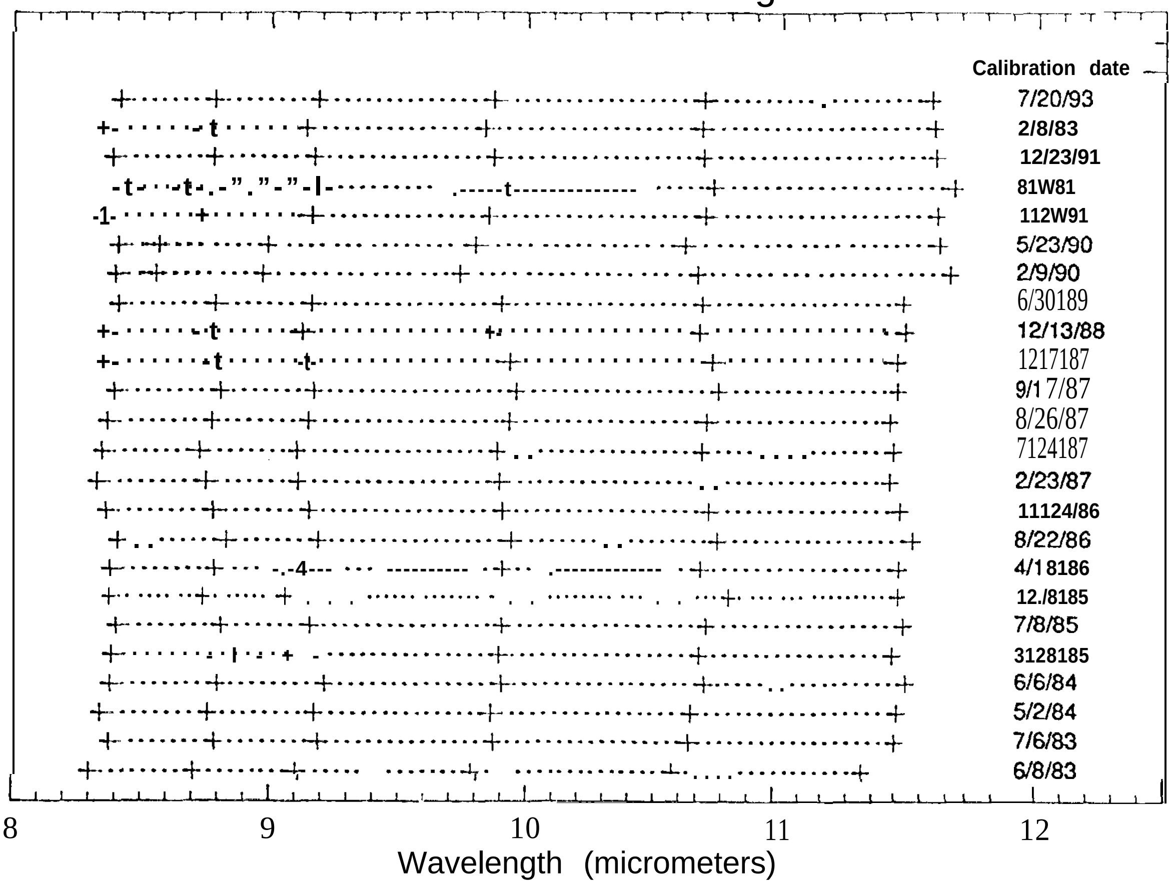
118°45'
118̇30'
CASTAIC
LAKE
CALIFORNIA
- 34° 30'
126
MAGIC
MOUNTAIN
5
34"15'
MILES
0
10
0
15
KILOMETERS

Hock & Chao 1994

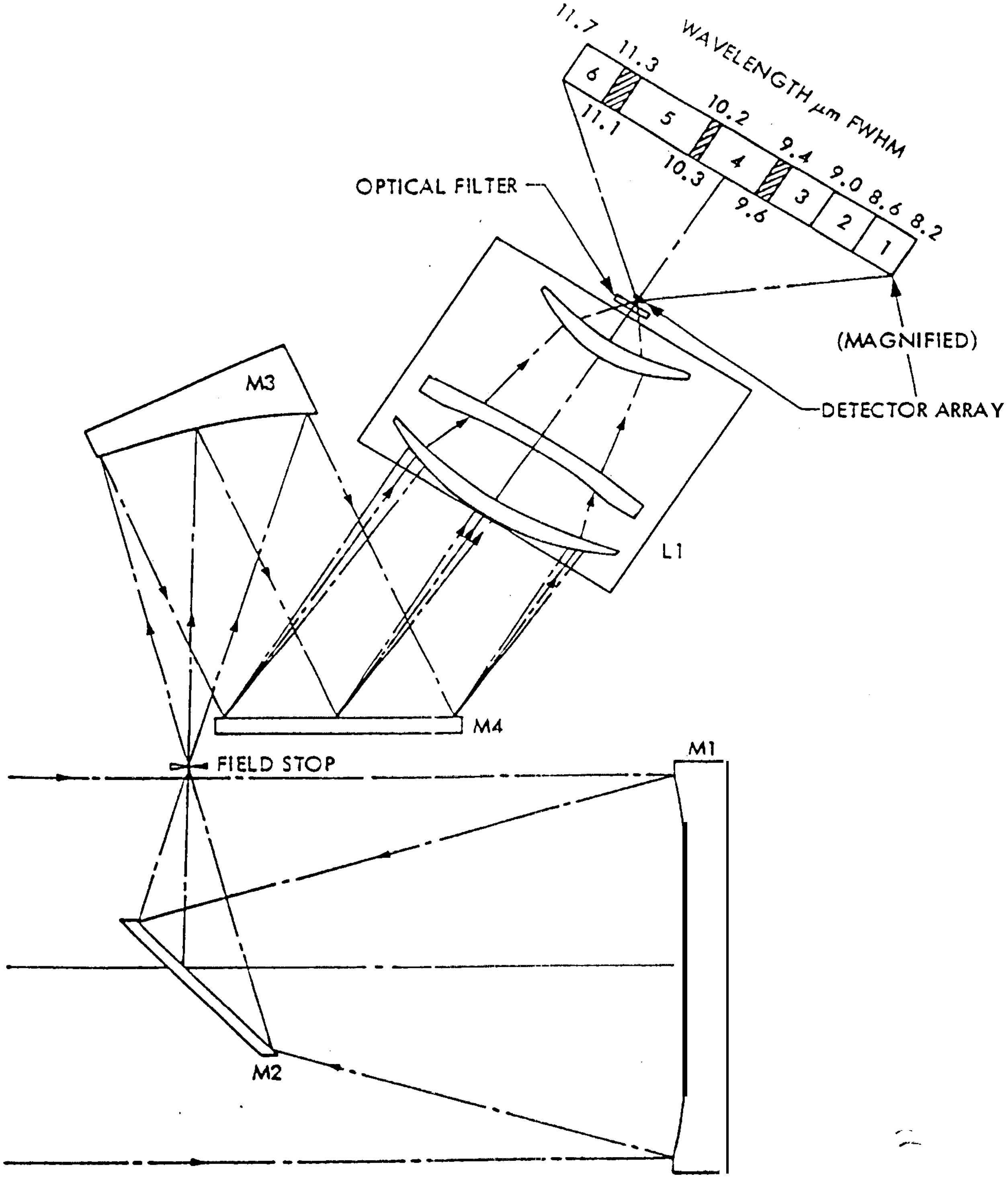
Fig 4B



TIMS central wavelength

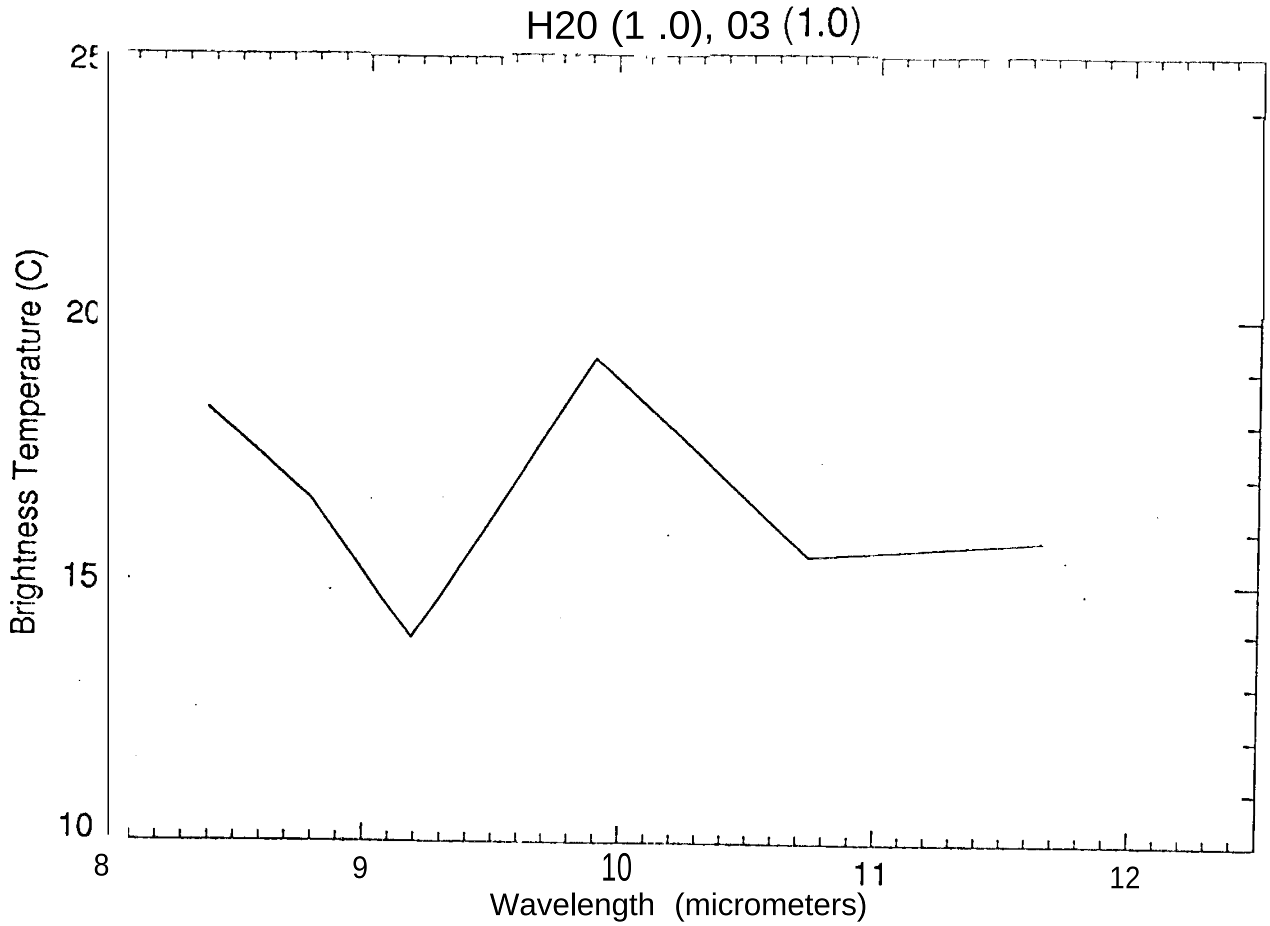


Hook & Okada 1994 Figure 3



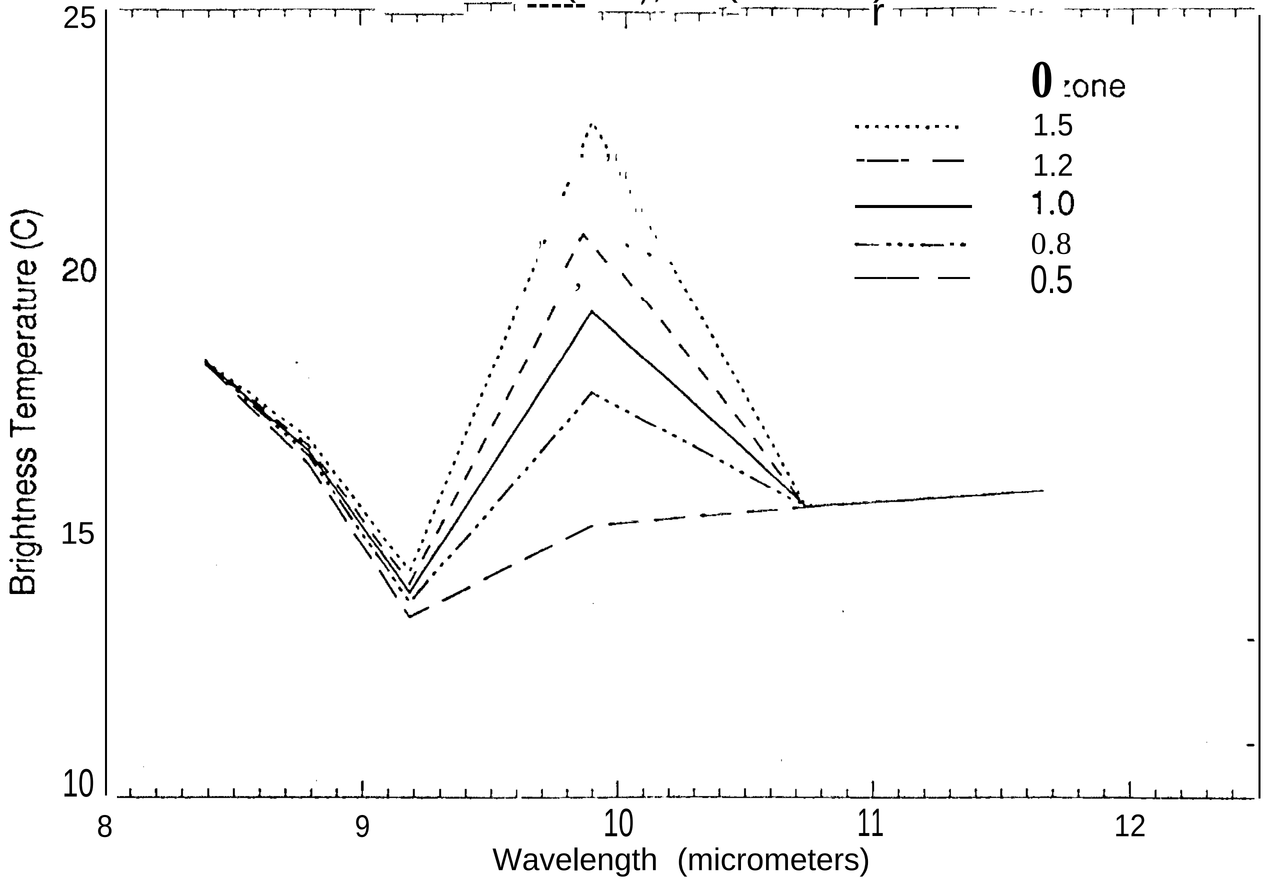
Fock & Okada 1994

Fig

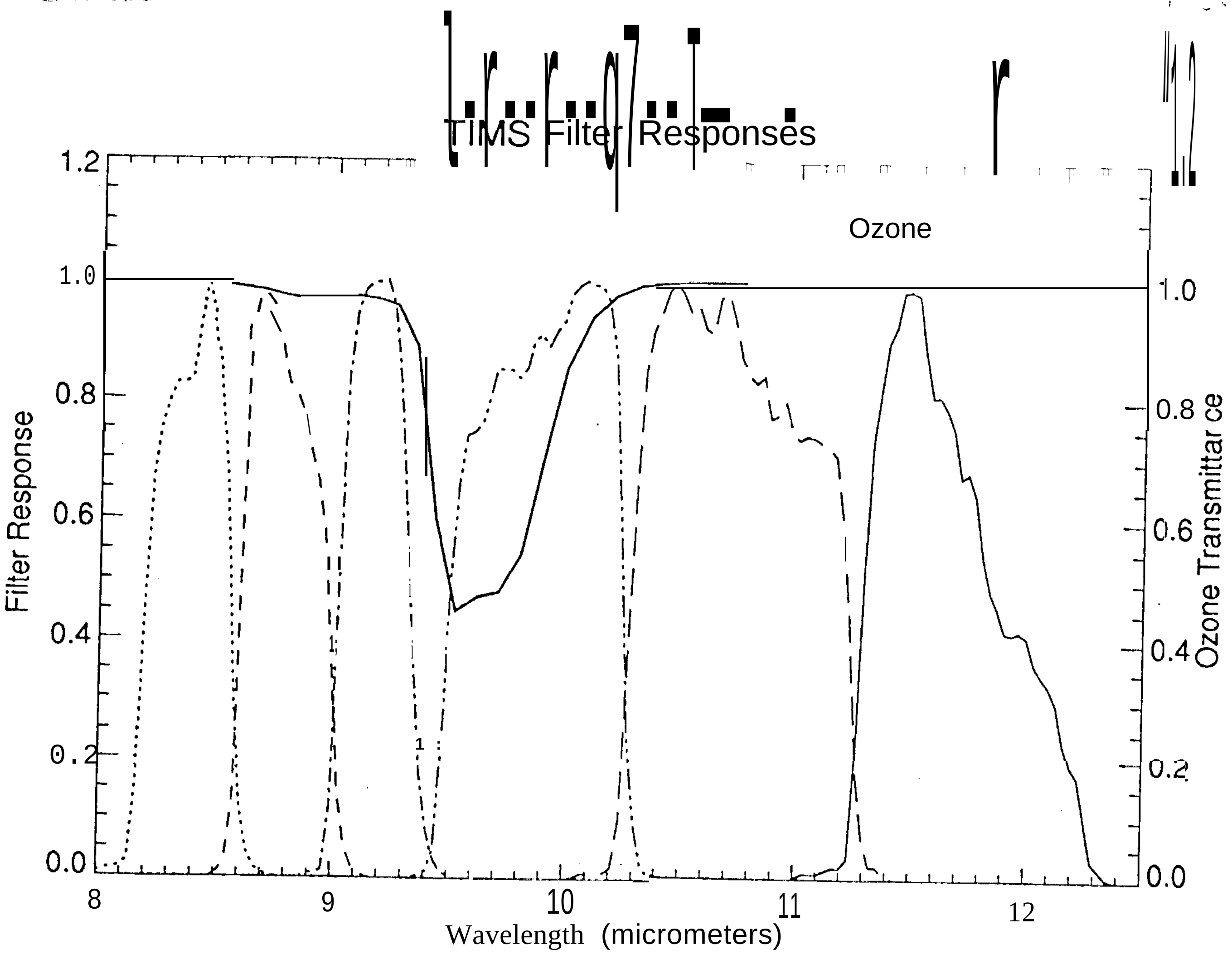


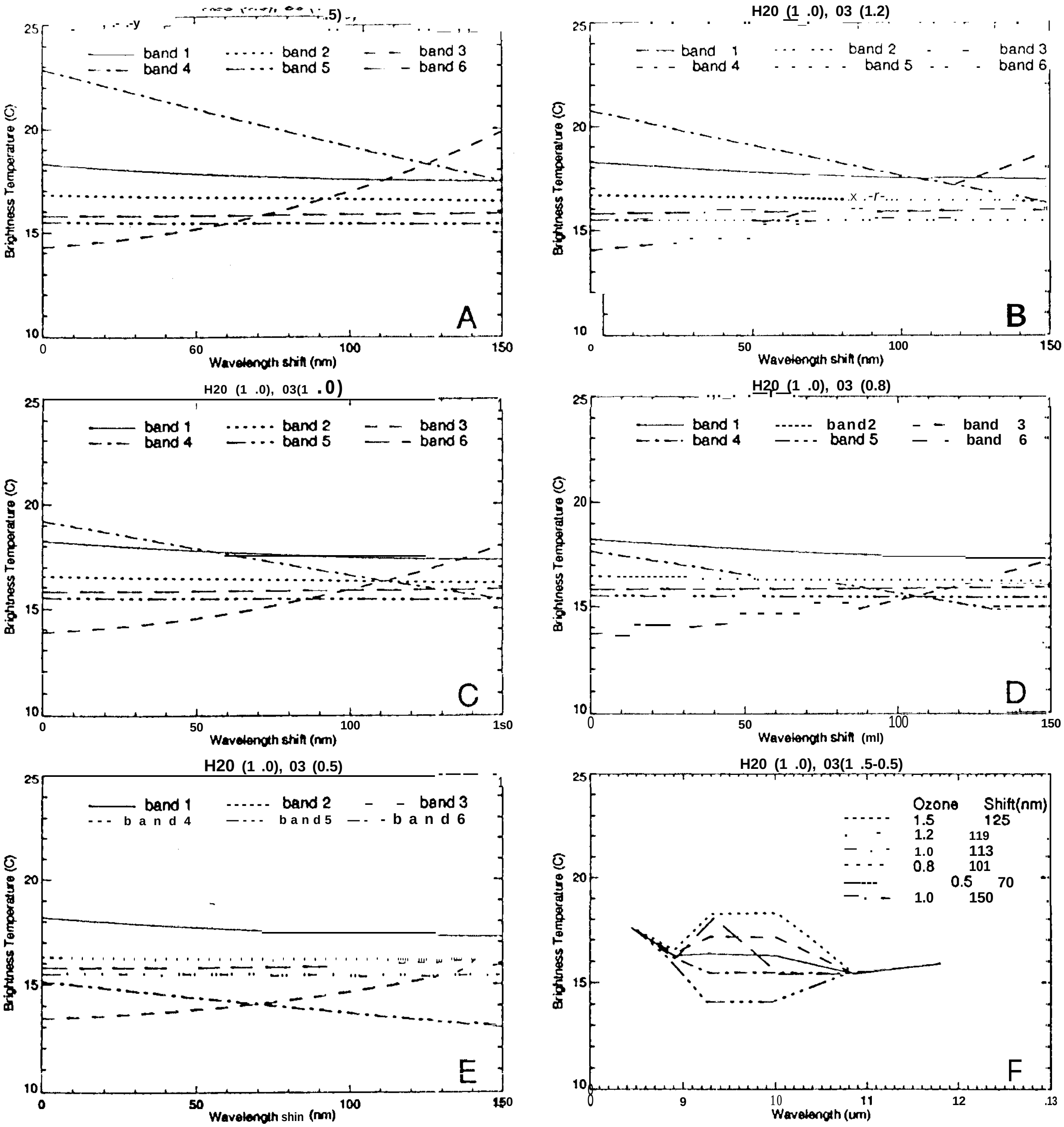
Hook & Okada 199- Fig

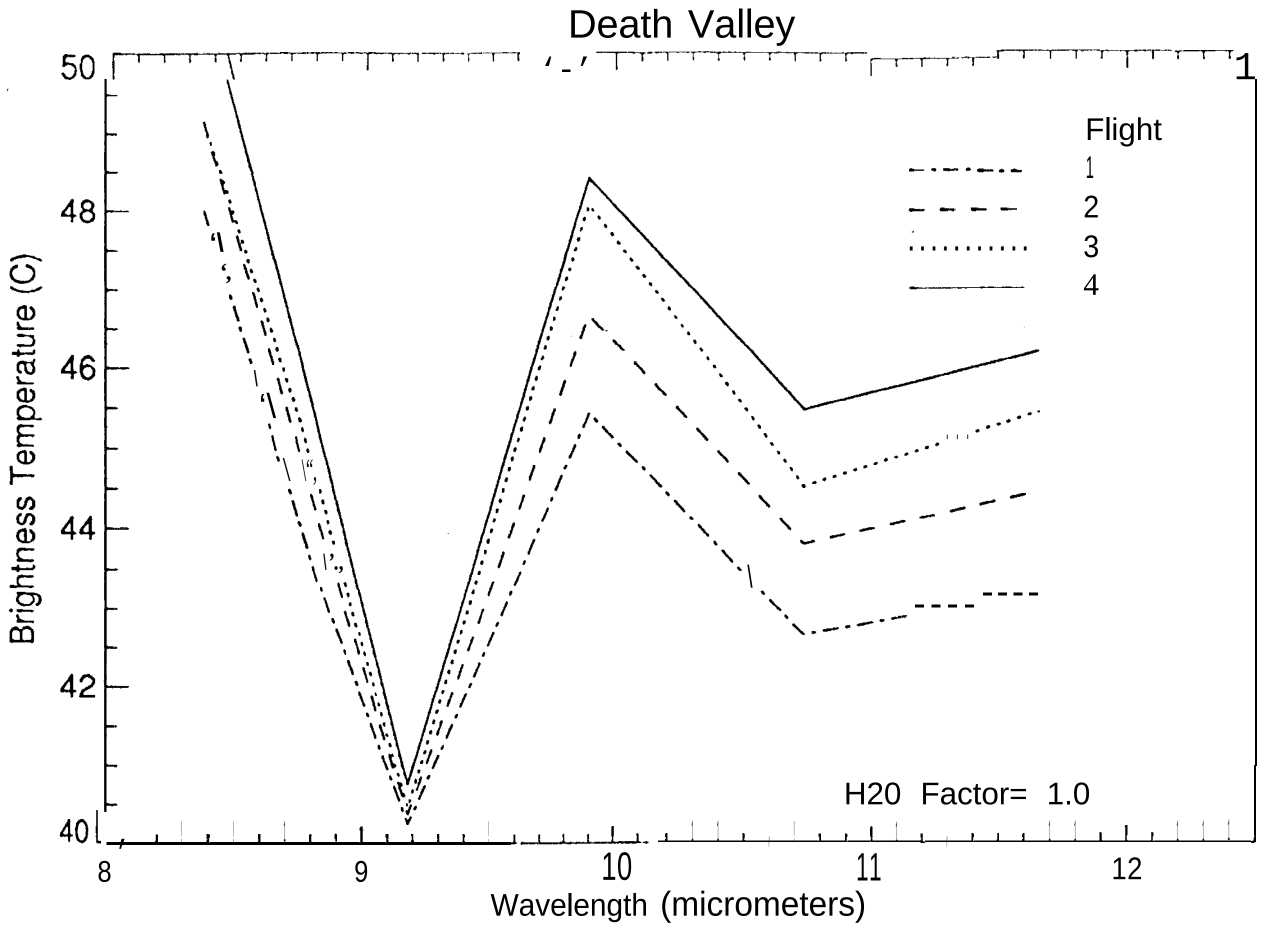
H20 (1.0), 03 (1 .5-0.5)



Hook & Okada 1994




H20 (1 .0), 03 (1.2)
H20 (1 .0), 03(1 .0)
H20 (1 .0), 03 (0.8)
H20 (1 .0), 03 (0.5)
H20 (1 .0), 03(1 .5-0.5)
band 1
band 2
band 3
band 4
band 5
band 6
Brightness Temperature (C)
Wavelength shift (nm)
Wavelength (um)
Ozone
Shift(nm)
1.5 125
1.2 119
1.0 113
0.8 101
0.5 70
1.0 150
A
B
C
D
E
F


Death Valley
Brightness Temperature (C)
50
48
46
44
42
40
8
9
10
11
12
Wavelength (micrometers)
Flight
1
2
3
4
H20 Factor= 1.0

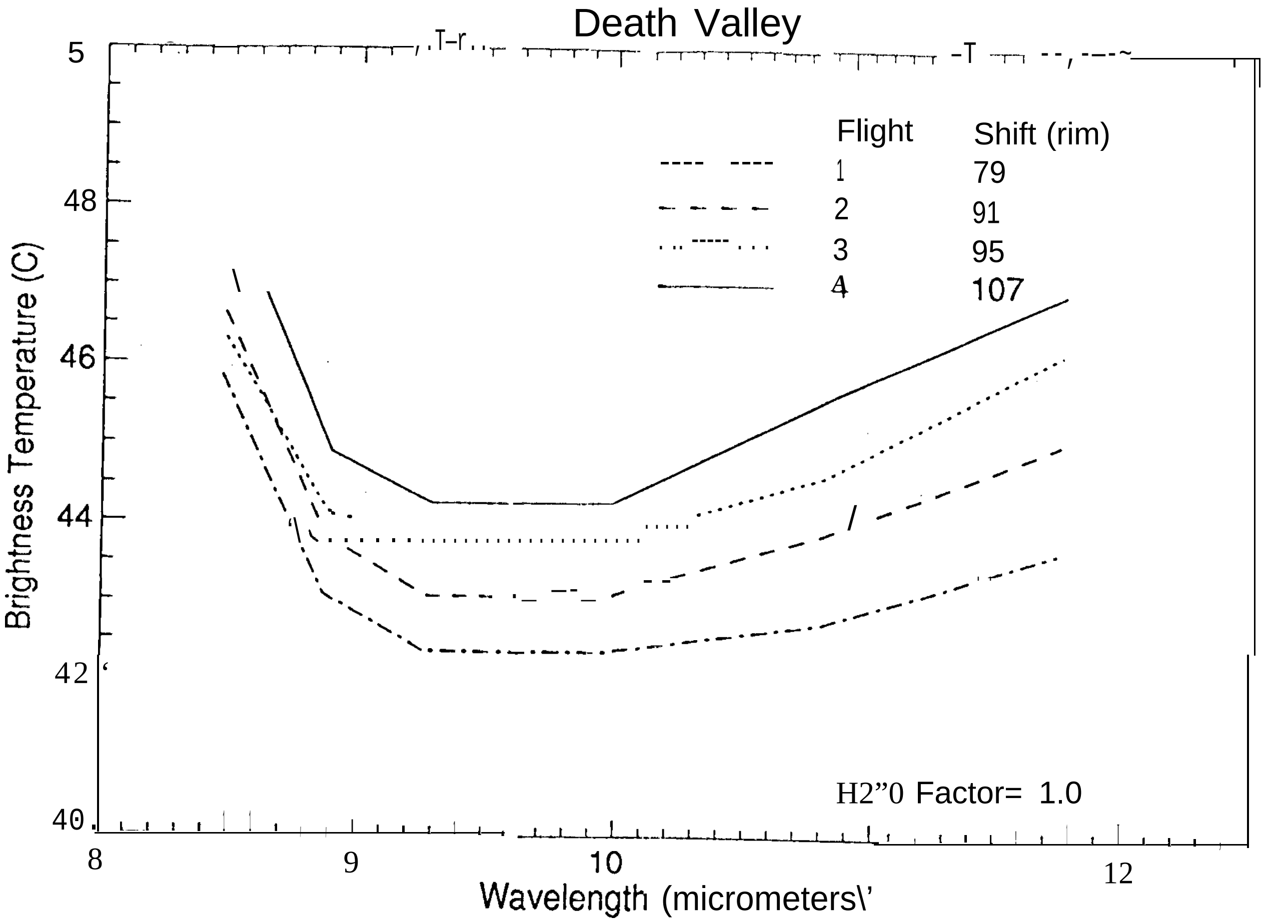

Death Valley
Flight
Shift (rim)
1
79
2
91
3
95
4
107
H2"0 Factor= 1.0
Brightness Temperature (C)
5
48
46
44
42
40
8
9
10
12
Wavelength (micrometers\'

Fig 10

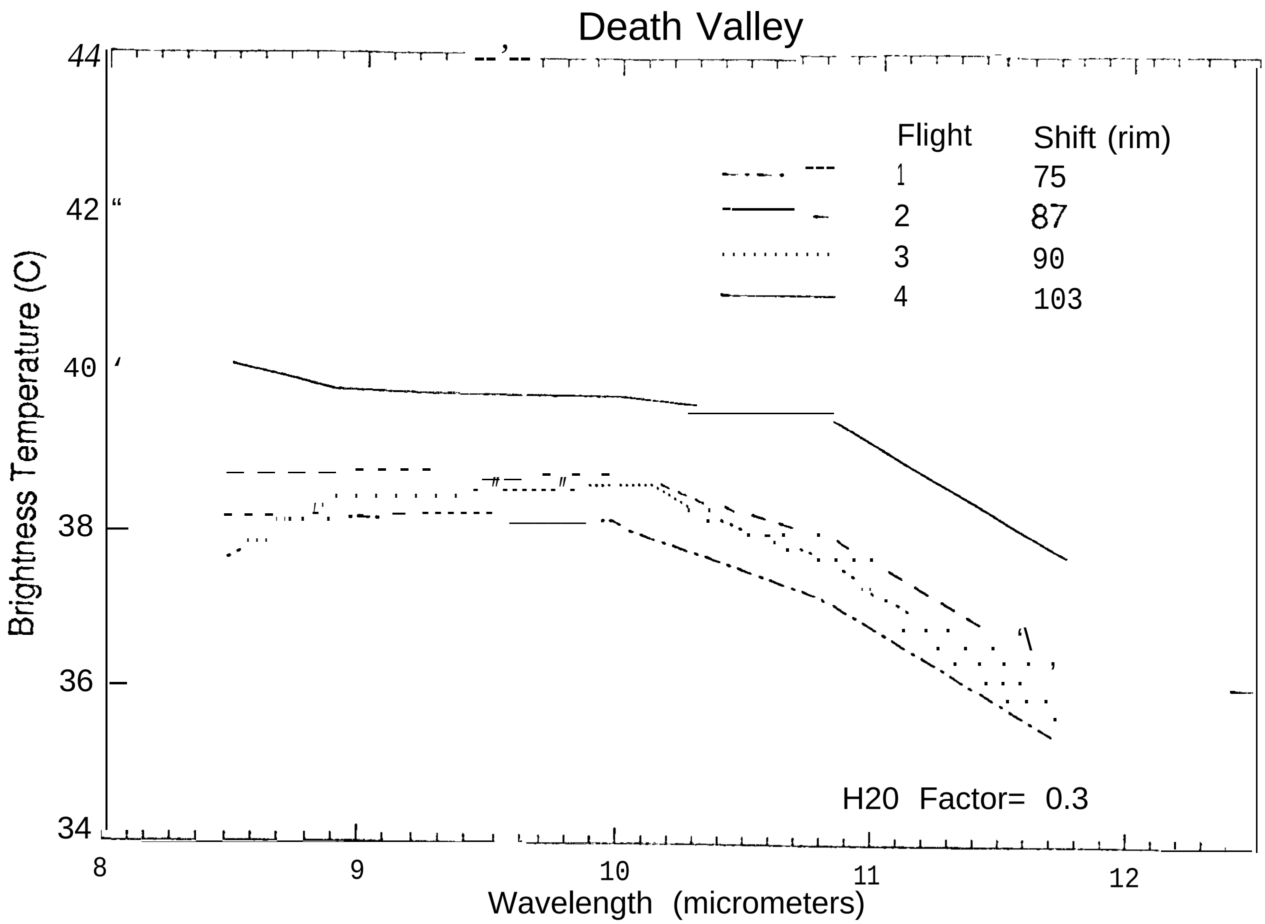
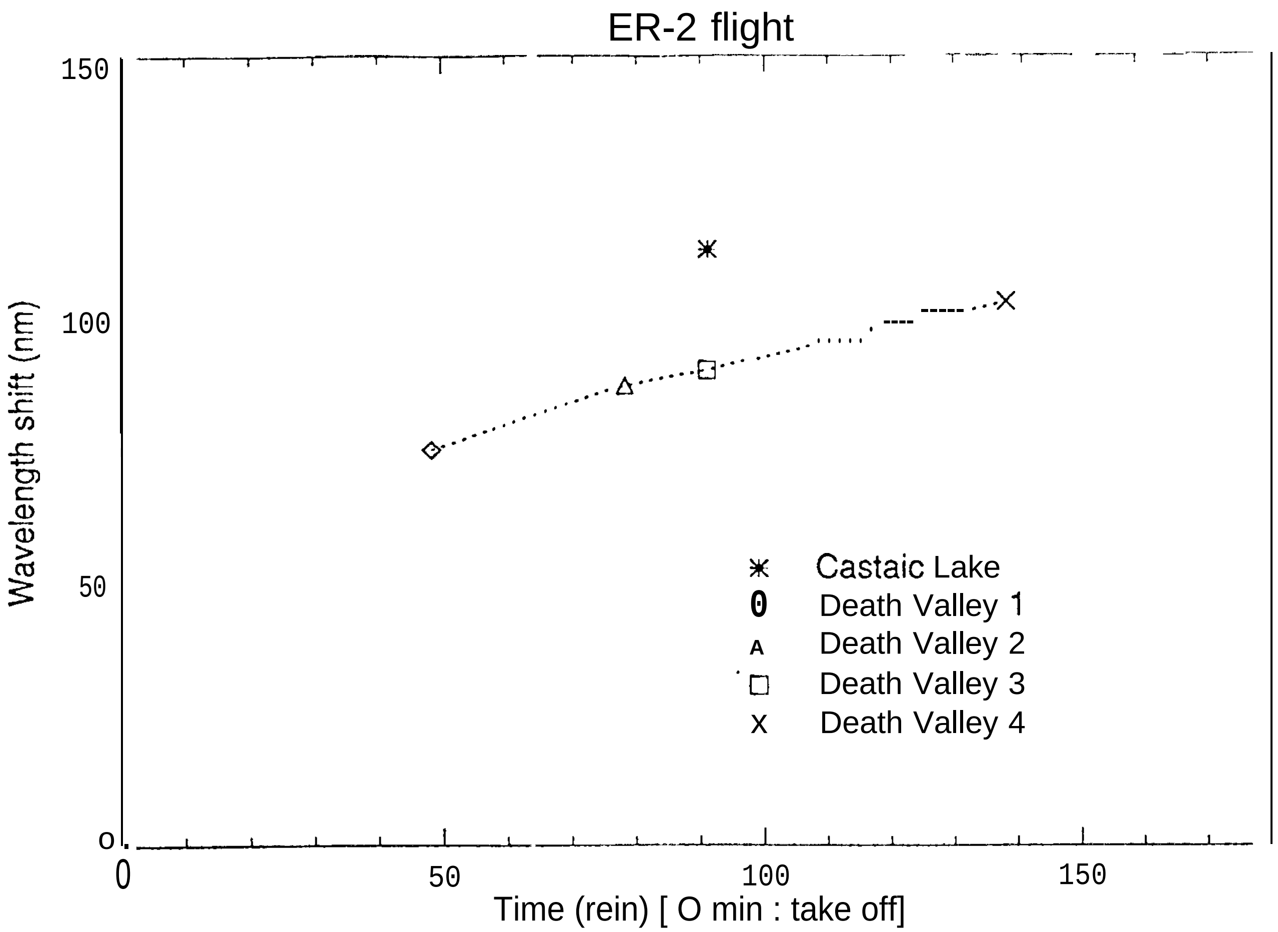

Death Valley
Brightness Temperature (C)
Wavelength (micrometers)
Flight
Shift (rim)
1
75
2
87
3
90
4
103
H20 Factor= 0.3
44
42
40
38
36
34
8
9
10
11
12

Fig 11


ER-2 flight
150
100
50
0
Wavelength shift (nm)
Castaic Lake
Death Valley 1
Death Valley 2
Death Valley 3
Death Valley 4
0
50
100
150
Time (rein) [O min : take off]