LOW-FREQUENCY MICROWAVE RADIOMETER FOR N-ROSS

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Abstract

The all-weather, global determination of sea surface temperature (SST) has been identified as a requirement needed to support naval operations. The target SST accuracy is ±1.0 K with a surface resolution of 10 km. Investigations of the phenomenology and technology of remote passive microwave sensing of the ocean environment over the past decade have demonstrated that this objective is presently attainable. Preliminary specification and trade-off studies have been conducted to define the frequency, polarization, scan geometry, antenna size, and other essential parameters of the Low-Frequency Microwave Radiometer (LFMR). It will be a dual-polarized, dual-frequency system at 5.2 and 10.4 GHz using a 5.9-meter deployable mesh surface antenna. It is to be flown on the Navy-Remote Ocean Sensing System (N-ROSS) satellite scheduled to be launched in late 1988.

1. Introduction

The all-weather, global determination of sea surface temperature (SST) has been identified as a requirement needed to support naval operations. The target SST accuracy is specified as ±0.5 K at a surface resolution of 10 km with an accuracy of ±1.0 K and surface resolution of 25 km acceptable. Passive microwave radiometry has the potential of meeting this requirement.

During the period 1972-78 the Naval Air Systems Command (NAVAIR) supported investigations of the microwave radiometric properties of the ocean and atmosphere which led to the specification of the Remote Ocean-surface Measurement System (ROMS). Although ROMS was not built, the understanding of the phenomenology and technology developed for it directly contributed to subsequent systems. In 1978 NASA launched an experimental sensor, the Scanning Multichannel Microwave Radiometer (SMMR), on both the SEASAT and NIMBUS-7 satellites to explore the all-weather measurement of sea surface temperature, as well as other oceanographic and atmospheric parameters, with microwave radiometry. The SMMR employs a 79-cm diameter antenna and dual-polarized radiometers at 6.6, 10.7, 18.0, 21.0, and 37.0 GHz with the 6.6-GHz frequency primarily chosen for its sensitivity to SST. Results from SMMR indicate that the SST can be measured to an RMS sensitivity ±1.2 K or better with it (1). However, the surface resolution of SMMR at 6.6 GHz is only 150 km.

The next generation of passive microwave sensors planned by NASA was the Large Antenna Multichannel Microwave Radiometer (LAMMR) as part of the sensor complement of the National Oceanic Satellite System (NOSS). LAMMR was planned as a seven-frequency, dual-polarized radiometric system with a four-meter antenna and a performance goal for SST of ±0.5-K precision, ±1.0-K absolute accuracy, and 24-to 36-km spatial resolution. Although NOSS and LAMMR were not built due to funding limitations, the design studies performed and the continuing development of the necessary technology have demonstrated that the SMOP OR is presently attainable.

The Navy-Remote Ocean Sensing System (N-ROSS) is a planned oceanographic satellite in the Navy core program for POM-84 with funding beginning in FY'85 to meet the SMOP OR. The sensor complement of N-ROSS is to include a scatterometer to measure the marine wind field; an altimeter to measure wave spectra, the Earth's geoid, and to locate fronts and eddies; and a Mission Sensor Microwave/Imager (SSM/I) to measure sea ice, precipitation, atmospheric moisture, and surface winds. All-weather measurement of sea surface temperature will require the development of a second passive microwave system. Critical to the development of this system is the selection of the operating frequency and other instrument characteristics compatible with Earth sources of RFI and optimized to functionally integrate with the SSM/I and N-ROSS.

2. Sensitivity and Retrieval Accuracy

A primary criterion for the selection of frequency for the low-frequency microwave radiometer (LFMR) is sensitivity to, and thus the retrieval of, sea surface temperature (SST). The present sensitivity study is limited to the frequency range of 2 to 14 GHz since frequencies below 2 GHz and above 14 GHz are relatively insensitive to SST (2). Three different approaches are used to examine the sensitivity question. They are: (a) theoretical studies, (b) interpretation of satellite data, and (c) the use of aircraft data. The theoretical studies are the most versatile in that wide ranges of environmental conditions can be simulated, and many frequencies and frequency combinations can be examined. Functional relationships are built into the theoretical models providing the freedom to examine various trade-off relationships. Satellite and aircraft data have, of course, the advantage of being actual measurements. They are, however, restricted in frequency and range of environmental conditions. The combination of all three studies provides a more complete basis for the determination of the microwave radiometric sensitivity to SST.

The rate of change of brightness temperature with respect to sea surface temperature, calculated using the geophysical model (3) developed by NRL, is given in Figure 1 as a function of frequency for several mean sea surface temperatures. The climatology (4) of the ocean-atmosphere system used with the model was compiled for mid-latitude summer conditions. The calculations are for vertical polarization of an incidence angle of 53.1°. All the parameters of the ocean-atmosphere system are kept constant except the SST for the calculation of the derivative.

The sensitivity is much greater over the frequency range of 6 to 10 GHz for very warm water, i.e., a SST of 30°C. However, the sensitivity decreases drastically, especially at the higher end of the frequency range, as the water temperature becomes colder. At 10 GHz and beyond, little sensitivity remains for the colder SST values. The sensitivity trend is reversed at the lower end of the frequency range, e.g., between 2 and 3 GHz. These frequencies are more sensitive to colder than to warmer water. Judging from Figure 1 the optimal frequency range for overall sensitivity appears to be in the 4-to 6-GHz range.

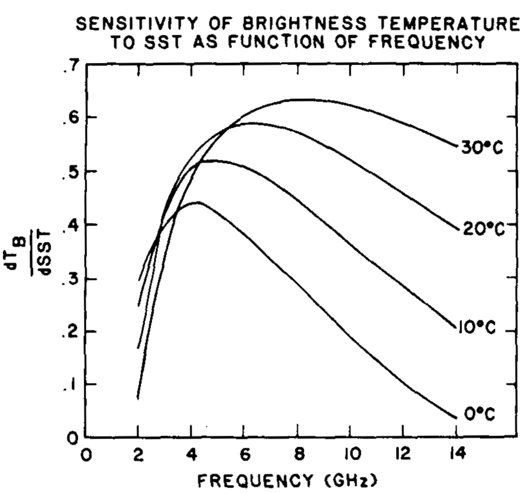

Figure 1. Sensitivity of Brightness Temperature to SST as a Function of Frequency.

The choice of an optimum frequency not only depends on the sensitivity to SST but also on the sensitivity to other environmental parameters. If a given frequency is more sensitive to another parameter, such as wind speed, it will primarily provide information concerning that parameter rather than SST, even though the sensitivity to SST may also be significant. Some of the most significant geophysical parameters for the microwave frequency range of interest are salinity, SST, wind speed, integrated atmospheric liquid water (clouds), and integrated atmospheric water vapor. The changes in the vertically polarized brightness temperature as a function of frequency are depicted in Figure 2 for those geophysical parameters. The incidence angle used in the calculations is again chosen to be the same as that of the SSM/I instrument, 53.1°, since there are advantages to choosing the same scan geometry for the LFMR because of possible mutual support and applications between the two instruments. The sensitivity to SST is dominant between about 2 and 10 GHz. Above about 10 GHz the effects due to water, both liquid and vapor, exceed that of SST while below about 2 GHz salinity effects are greater.

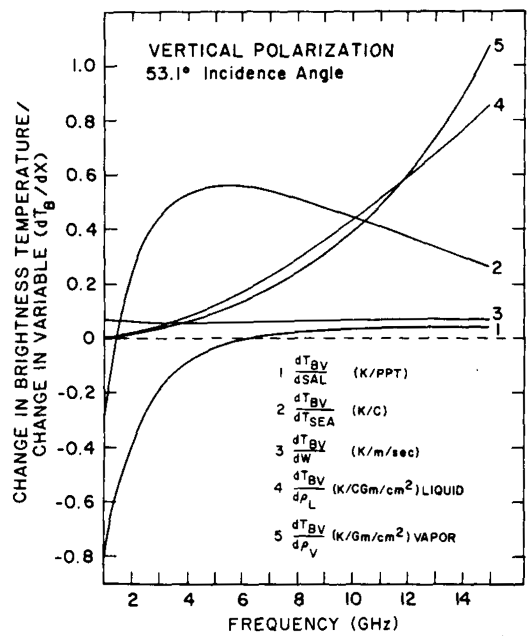

Figure 2. The Sensitivity of Vertical Brightness Temperature to Geophysical Parameters as a Function of Frequency.

However in order to examine the true relative sensitivity to various environmental parameters, the brightness temperature change caused by representative changes in the other relevant parameters must be examined. Assuming that the Navy's operational requirements for the other parameters are met, i.e., residual errors of 1 part per thousand for salinity, 2 m/sec for surface wind speed, 0.01 gm/cm^2 for columnar density of liquid water, and 0.2 gm/cm^2 for columnar density of water vapor along with the minimum requirement of 1°C for SST, the corresponding resultant changes in brightness temperature were calculated. These changes in brightness temperature are given in Figure 3. As to be expected from Figure 2 the salinity effect ceases to be significant for frequencies higher than about 3 GHz, and the vertically polarized brightness temperature is relatively insensitive to wind speed and water vapor. Liquid water is the only serious contender with SST and then only at the higher frequencies, above about 10 GHz.

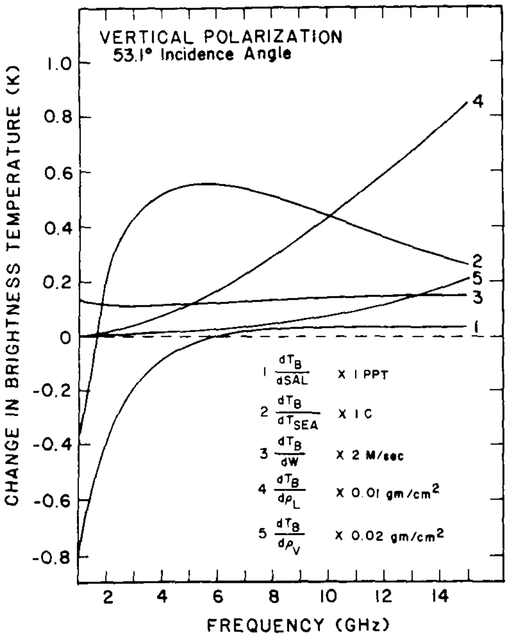

Figure 3. Changes in Vertical Brightness Temperature Caused by Changes in Geophysical Parameters.

Similar calculations are presented for the horizontally polarized brightness temperature in Figure 4. Wind speed and liquid water are the

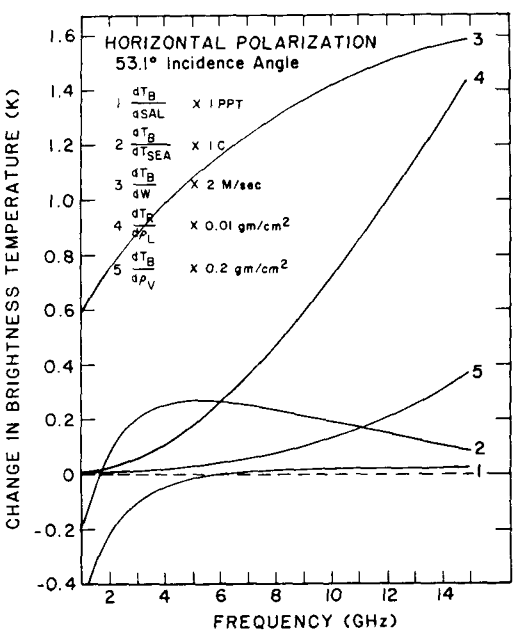

Figure 4. Changes in Horizontal Brightness Temperature Caused by Changes in Geophysical Parameters.

dominating environmental parameters. The sensitivity to water vapor is also higher than that of SST beyond 11 GHz. Thus, horizontal polarization primarily contains information concerning wind speed and liquid water. It therefore provides a means to remove the effect of these parameters from the vertically polarized brightness temperature and enhances the accuracy of the SST estimation. The horizontally polarized brightness temperature of the LFMR could also be used in conjunction with the SSM/I to enhance the retrieval of surface wind speed and liquid-water content.

The theoretical sensitivity studies indicate that a frequency in the 4-to 6-GHz region is optimal for the overall retrieval of SST, and a frequency in the 8-to 10-GHz region is optimal for the retrieval of the SST of warm ocean water. The studies also indicate that both vertical and horizontal linear polarization are required for the retrieval of SST.

3. Satellite Data

Two types of real data are available for the LFMR frequency selection. The first of these is satellite data. Among the satellite instruments that have been flown during the past decade, the only instrument which contains a multiple frequency passive microwave radiometer containing frequencies in the required range of from 4 to about 10 GHz is the Scanning Multichannel Microwave Radiometer (SMMR). Both the SEASAT and the NIMBUS-7 satellites, launched in 1978, carried a SMMR. A number of serious problems complicate the proper interpretation of the SMMR data. However, careful selection of data and definition of retrieval algorithms have led to reasonable retrievals of the SST (1,5).

A study of the sensitivity of the two lowest frequencies (6.6, 10.7 GHz) of the SEASAT SMMR to SST and an analysis of the SST retrieval using these two frequencies were conducted by Frank Wentz of Remote Sensing Systems (RSS) (6). The total mission of SEASAT lasted 104 days, from June 28 to October 10, 1978. Wentz filtered the total SEASAT SMMR data set according to the following criteria: (1) only the middle two of the four 150-km SMMR brightness temperature cells for each scan are used in order to eliminate severe cross-track polarization error, (2) all data within 800 km of land are discarded to avoid side-lobe contamination problems, (3) only night-time data are used to avoid the Faraday rotation effect, sun glitter effect, Sun entering the cold reference horn, and thermal gradients caused by heating effects which make the interpretation of day-time data unreliable, (4) only data from the second half of SEASAT's 3-month period were selected because the 18-GHz channel, which is used in the SST retrieval algorithm, showed a significant time dependent drift during the first half of the period. The climatological data used for comparison with the SEASAT SMMR SST retrievals (7,8) were compiled by NOAA. Table 1 contains the most relevant results from the RSS study. The complete results of the RSS SMMR study are available in a NRL report in preparation (J. P. Hollinger and R. C. Lo, NRL Report 5375, 1984). The slope between the brightness temperature and the climatological SST value is directly proportional to the cross correlation

TABLE 1

STATISTICS FROM THE N-ROSS SST STUDY USING SEASAT SMMR AND CLIMATOLOGY

		SST RETRIEVAL* vs CLIMATOLOGY				BRIGHTNESS TEMPERATURE*** vs CLIMATOLOGY			
		SLOPE****		STD.DEV.**		SLOPE		STD. DEV.**	
		6.6 GHz	10.7 GHz	6.6 GHz	10.7 GHz	6.6 GHz	10.7 GHz	6.6 GHz	10.7 GHz
< 15°C	COLD WATER	1.0152	1.0432	1.85	2.37	0.3491	0.1996	2.95	3.59
15-25°C	TEPID WATER	0.8239	0.7352	1.40	1.63	0.4853	0.4065	1.96	2.41
> 25°C	WARM WATER	1.1269	1.1618	1.24	1.17	0.6379	0.9061	1.05	1.44
< 10 m gm/cm^2	CLEAR	0.9270	0.8874	1.51	1.89	0.4504	0.3668	4.15	4.82
10-25 m gm/cm^2	CLOUDY	0.8697	0.8065	1.78	2.14	0.3513	0.2461	4.65	5.50
25-200 m gm/cm^2	RAIN	0.8686	0.8201	1.77	2.24	0.3090	0.1984	5.06	5.94
< 7 m/s	LIGHT WIND	0.9330	0.8503	1.38	1.68	0.5641	0.5280	2.67	3.05
7-14 m/s	MEDIUM WIND	0.8980	0.8422	1.70	2.10	0.4946	0.4143	3.81	4.56
> 14 m/s	HIGH WIND	0.9487	0.9951	2.05	2.60	0.4633	0.3727	3.19	3.78

* SST RETRIEVALS ARE MADE USING 6.6 H, 6.6 V, (OR 10.7 H, 10.7 V), 18 V and 21 V SMMR CHANNELS.

** STANDARD DEVIATION OF THE DIFFERENCE BETWEEN EITHER THE SST RETRIEVALS OR THE T_B's, AND THE SST CLIMATOLOGY.

*** THE VERTICAL POLARIZED BRIGHTNESS TEMPERATURES ARE USED.

**** SLOPE OF THE REGRESSION LINE BETWEEN THE SST CLIMATOLOGY AND THE PARTICULAR VARIABLE.

coefficient between the two variables. The brightness temperatures are sorted according to the corresponding climatological SST values into cold water, tepid water, and warm water categories. The slope at 10.7 GHz is higher than that at 6.6 GHz for warm water indicating higher sensitivity. The reverse is true for cold and tepid water. This result is in agreement with the theoretical results. The SMMR brightness temperatures were also used to retrieve SST. The retrieval accuracies based upon the 6.6-GHz channels are superior to the retrievals based on the 10.7-GHz channels for all cases of liquid-water content and surface wind speed. The 10.7-GHz retrievals are most accurate for tepid and warm water. This confirms the previous conclusions based on theoretical calculations that the frequency region of 4 to 6 GHz provides the most sensitive overall estimator of the SST except for warm water.

4. Aircraft Measurements

During November-December 1982, NRL conducted a series of airborne radiometric measurements of SST. The instrument complement included the NASA Langley Stepped Frequency Microwave Radiometer (SFMR) (9) and the NRL SSM/I simulator with channels at 19 H and V, 22 V, and 37 H and V mounted on a pallet aboard the NRL RP3A aircraft. The pallet can be tilted to provide incidence angles from nadir to 53 degrees. The SFMR is vertically polarized and is electronically stepped over the range of 4 to 7.5 GHz. The frequencies chosen for data collection are 4.530, 4.994, 6.594, and 7.394 GHz centered on a bandpass of 50 MHz. A precision radiometric thermometer (PRT-5) provides the surface truth measurements of SST. Flights were conducted across the Gulf Stream, the continental shelf off the Norfolk, VA coast, Gulf of St. Lawrence, the Labrador Sea, and Frobisher Bay covering a SST range from 2°to 25° C. Due to various instrumental difficulties and failures, very little of the SFMR data is actually usable for this study. In general the brightness temperature dependence on SST determined from these data is somewhat greater than that from the SEASAT SMMR statistics or the theoretical studies. Even though the extent of the aircraft data is very limited, the results are in general agreement with the thoeretical calculations and substantiate the theoretical approach.

5. Retrieval Accuracy Simulations

The confirmation of the theoretical sensitivity studies by the satellite and aircraft measurement results provides the practical basis for detailed theoretical retrieval and trade-off studies. The range of environmental conditions chosen is given in Table 2 and covers all but the most extreme conditions likely to be encountered. The frequency pairs were chosen to contain a lower frequency from the optimal region of 4 to 6 GHz and a higher frequency which will have greater sensitivity in warmer ocean waters and provide greater spatial resolution. The effects of instrumental noise, ΔT, and of using SSM/I environmental products in the SST retrieval are of particular interest. The SSM/I is expected to provide estimates of wind speed, water vapor, and liquid water at accuracies of 2 m/sec, 0.2 gm/cm^2, and 0.01 gm/cm^2, respectively.

TABLE 2

ENVIRONMENTAL CONDITIONS

SST (C)	-2 to 30
Wind Speed (m/sec)	2 to 17
Salinity (PPT)	33 to 37
Columnar Density of Water Vapor (gm/cm^2)	0.6 to 6.0
Columnar Density of Liquid Water (gm/cm^2)	0.0 to 0.08
Air Temperature (C)	0 to 32

Retrievals based on either 8.6 or 10.7 GHz alone are not adequate to meet the operational requirements using SSM/I products. Retrievals at 4.3 and for the 4.3-, 8.6-GHz combination are shown in Figure 5 and for 5.1 and the 5.1-, 10.7-GHz pair in Figure 6. The additional frequency improves the retrieval results much more significantly than including the SSM/I products implying that the SSM/I products are not necessary for a dual-frequency LFMR. This would relieve constraints on the spacecraft interface design imposed by requiring common lines of sight for both the LFMR and the SSM/I. Another benefit of using a dual-frequency system is redundancy in case of partial failure, such as the loss of one channel. The dual-frequency system also provides higher accuracy and the higher frequency channels provide better surface resolution in warm ocean water regions. The 4.3-, 8.6-GHz combination appears to be slightly better than the 5.2-, 10.7-GHz system in retrieval accuracy. But both of these combinations are adequate to meet the operational requirements if a system noise of about 0.5 K or less can be achieved.

6. RFI, Faraday Rotation, and Sun Glint

A survey of potential RFI sources germane to satellite-borne microwave radiometers was performed at NRL (10) in connnection with design studies for LAMMR. The results show that there is a band at least 200-MHz wide around 4.3 GHz which is relatively emitter free. Similarly, the 400-MHz wide

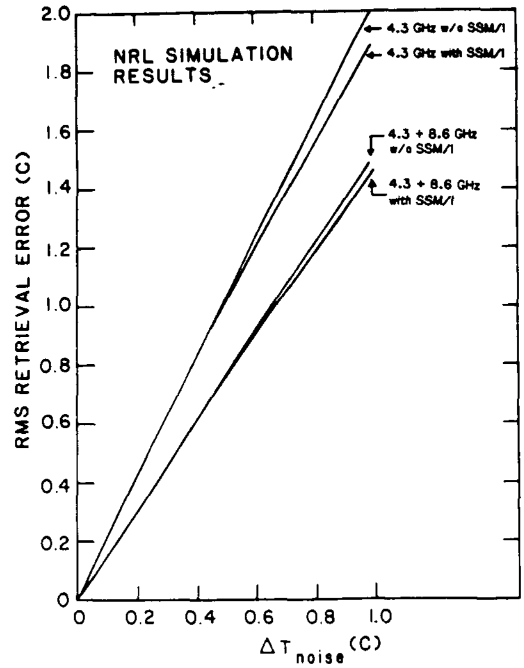

Figure 5. Retrieval Simulations Using 4.3 GHz Alone and 4.3, 8.6 GHz Combination.

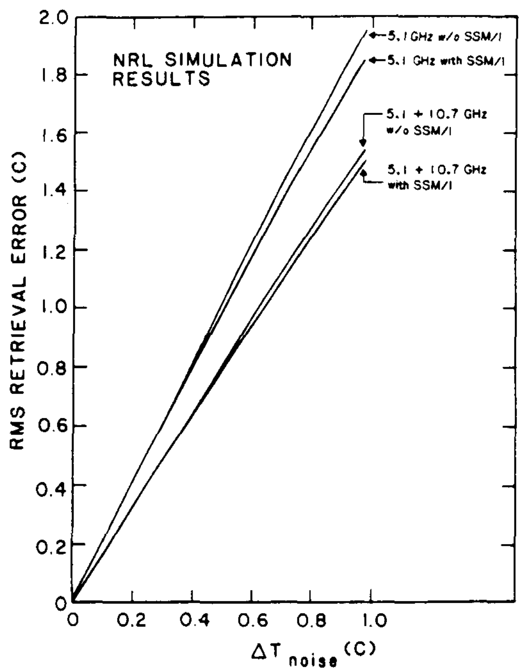

Figure 6. Retrieval Simulations Using 5.1 GHz Alone and 4.3, 8.6 GHz Combination.

band centered around 5.2 GHz has relatively few emitters. Based on this information, tentative frequency combinations for consideration are 4.3, 8.6 GHz and 5.2, 10.4 GHz, with the higher frequency in each pair arbitrarily chosen an octave above the lower frequncy. The 5.2, 10.4-GHz combination is to be preferred on the basis of providing higher surface resolution if other considerations allow it. A more significant RFI parameter is the total power of the radio emitters rather than their number. The study did not address the power emitted and did not survey the whole frequency range of present interest. Further RFI investigations are clearly necessary before a final frequency selection for the LFMR is made.

7. Faraday Rotation

The plane of polarization of microwave radiation propagating upward through the Earth's ionosphere is rotated by an angle, $\Delta\theta$, by Faraday rotation (11). The amount of rotation depends upon the magnitude and orientation with respect to the direction of propagation of the Earth's magnetic field and the density of electrons along the propagation path. It is given by

$$\Delta\theta = \frac{2.36 \times 10^4}{f^2} \int NH \cos\phi \, dr \qquad (1)$$

where f is the observational frequency in Hertz, H is the Earth's magnetic field in Gauss, N is the electron number density in cm^{-3}, and dr is an element of length along the path of integration through the ionosphere in cm (12). Ionospheric Faraday rotation determined from equation (1) using the mean values of 0.47 Gauss for H, 45^o for ϕ, and 3.8×10^{13} cm^{-2} for the integral of N along the propagation path is given in Figure 7 as a function of frequency. Rotation can be as much as three or more times the values given in Figure 7 during the solar sunspot maximum and for extreme values of H $\cos\phi$. It should be noted that N-ROSS is scheduled for launch near sunspot maximum. Thus Faraday rotations of several degrees may be expected at the lower frequencies of interest.

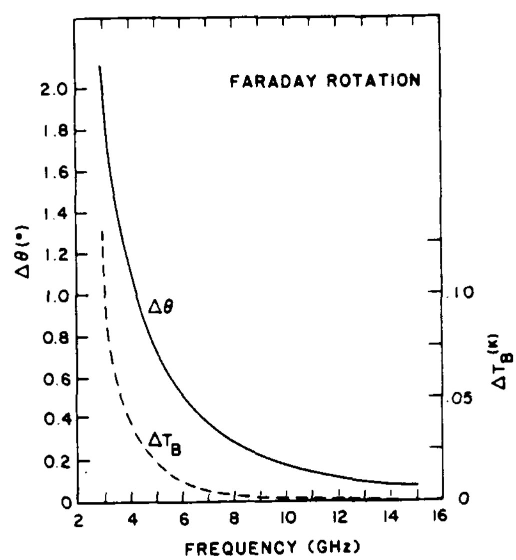

Figure 7. Rotation of the Plane of Polarization and Subsequent Brightness Temperature Error Caused by Ionospheric Faraday Rotation.

The rotation of the plane of polarization by ionospheric Faraday rotation, if uncorrected, will result in an error in the measured vertical and horizontal linearly polarized brightness temperature of ΔT_B given by

$$\Delta T_B = (T_{BV}-T_{BH}) \sin(2\theta+\Delta\theta) \sin \Delta\theta \qquad (2)$$

Here T_{BV} and T_{BH} are the true vertical and horizontal brightness temperatures of the radiation at the Earth's surface, θ is the angular orientation that the plane of reception of the receiving antenna at the satellite makes with respect to the surface vertical, and $\Delta\theta$ is the Faraday rotation. If θ is large compared to $\Delta\theta$,

$$\Delta T_{BV} = (T_{BV}-T_{BH}) \sin 2\theta \sin\Delta\theta \qquad \theta>>\Delta\theta \qquad (3)$$

then ΔT_B is proportional to $\sin \Delta\theta$. This is the case with SMMR where the plane of polarization rotates with scan angle. If θ can be held constant at 0^o, independent of scan angle, then

$$\Delta T_B = (T_{BV}-R_{BH}) \sin^2\Delta\theta \qquad \theta = 0 \qquad (4)$$

and ΔT_B is proportional to $\sin^2\Delta\theta$. This can be a very large difference. For example for $T_{BV}-T_{BH}$ = 100 K, $\theta = 25^o$ and $\Delta\theta = 3^o$, equation (3) gives a brightness temperature of 4 K whereas an error of only 1/4 K results from equation (4) when $\theta = 0$. Therefore, an important design consideration is to maintain the reception plane of polarization aligned with vertical at the Earth's surface independent of scan angle. The expected error, under the mean conditions assumed above, calculated using equation (4) is also plotted in Figure 7 using a value of 100 K for $T_{BV} - T_{BH}$ which is an upper limit over the frequency range being considered. For example, at 4.3 GHz, the error is approximately 0.03 K and may be as large as 0.1 K under severe ionospheric conditions. The error decreases quickly with increasing frequency, and normally will not be important and can be ignored. If necessary, a relatively simple correction can be made to remove the bulk of the effect since Faraday rotation is systematic and well understood. Only if the plane of polarization rotates with scan angle will Faraday rotation be a problem.

Sun glint is caused by the specular reflection of solar radiation from the sea surface. The Sun is very intense at microwave frequencies, especially during periods of high sunspot activity when it can have brightness temperatures as high as 40,000 K at 10 GHz and more than 200,000 K at 5 GHz. Therefore, it can cause a large contribution to the observed brightness temperature when the specular point falls within the footprint of the observing radiometer. The brightness temperature error caused by sun glint is a function of angle relative to the specular angle and the surface roughness of the sea which is primarily a function of wind speed. Studies have been performed (13) for the purpose of defining a cone angle about the direction where sun glint presents a problem in environmental parameter retrievals. Consideration has also been given to the possibility of generating a correction algorithm. These studies indicate sun glint effects can cause brightness temperature increases in excess of 1 K for angles within $\pm 20^o$ of bistatic for the SMMR 6.6-GHz channel. Unfortunately, the sun glint problems cannot be avoided nor be obviated by system design or frequency selection. Fortunately, sun glint problems are minimized by the Sun synchronous early morning orbit planned for N-ROSS. The 98.1^o retrograde N-ROSS orbit is shown in Figure 8 with solar positions at summer and winter solstice and the equinoxes indicated for both a 7:15 a.m. and an 8:15 a.m. equatorial crossing. The limit of the LFMR scan is shown by the small circle labeled "swath edge." There will be no specular solar reflection for any Sun position within this circle. However, under rough surface conditions, scattered solar radiation will be received from directions considerably away from the specular direction (13). Thus, sun glint will be a problem at some scan angles over some portions of the orbit, primarily near the swath edge in the summer. Criteria for its detection and elimination must be determined in a way similar to that done for the SMMR (13) experiment. This problem will have to be addressed in the processing software rather than instrument design.

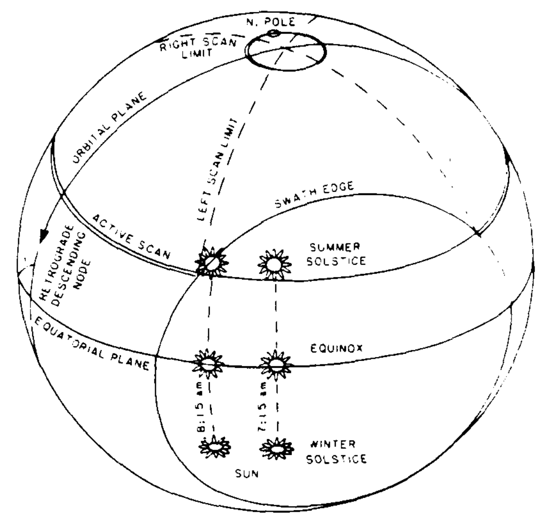

Figure 8. The Relationship Between the Seasonal Sun and the N-ROSS LFMR Scan Geometry.

8. Baseline Model of the LFMR

The sensitivity and retrieval accuracy studies indicate that the 4.3-, 8.6-GHz-frequency combination may be marginally better for SST retrieval than the 5.2-, 10.4-GHz pair. However, any possible slight improvement in SST retrieval accuracy obtainable with the lower frequency combination is negligible compared to the 21-percent increase in surface resolution provided by the higher frequency combination. Since both accuracy and resolution are important considerations, the 5.2-, 10.4-GHz combination will better meet the operational requirement than will the 4.3-, 8.6-GHz pair. Further, uncertainties in the measured brightness temperature caused by Faraday rotation will be about half as large for the higher frequency combination and, since solar intensity decreases with inceasing frequency, sun glint problems will also be somewhat smaller. For these reasons the frequencies of 5.2 and 10.4 GHz are selected over 4.3 and 10.6 GHz for the baseline instrument.

An incidence angle near 50° is required to enable corrections for marine wind speed and a conical scan geometry, similar to that of the SSM/I (14), is indicated for the same reasons that led to its use for SMMR, SSM/I, and LAMMR. The adoption of a scan geometry identical to the SSM/I will facilitate data comparisons between the two instruments and will ease the development of algorithms using different combinations of channels from both systems. Further it will enable a common format and use much of the same software for data display, handling, and distribution. The SSM/I is conically scanned at a 53.1° incidence angle. Measurements of the scene are obtained over a 102.4° scan angle centered on the satellite ground track. A scan period of 1.9 seconds leads to a 12.5-km spacing between successive scans for a satellite altitude of 833 km.

In order to obtain 25-km resolution in the along-track direction at 5.2 GHz, a 5.9-m diameter antenna is required. This would provide 15 x 25 km resolution at 5.2 GHz and 8 x 13 km resolution at 10.4 GHz. The resolution at 10.4 GHz with a 5.9-m antenna is about 10 percent better than the SSM/I at 85.5 GHz. Samples at 7.5-km cross track are required for Nyquist sampling at 5.2 GHz. Nyquist sampling is very important to prevent aliasing and allow the full use of the antenna resolution for locating and mapping thermal fronts and eddies, ice edges, and other surface features. In order to obtain Nyquist sampling at 10.4 GHz as well as at 5.2 GHz, a second dual-polarized 10.4-GHz system must be added. This would be a second feed, offset in both the along-and cross-track directions, so as to provide two series of 10.4-GHz samples spaced by 3.8 km in the along-track direction each scan. Sampling each 3.8 km along the scan direction produces a 3.8-x 3.8-km grid. System temperatures of 250 K are obtainable with FET amplifiers at 5 and 10 GHz. If a calibration scheme similar to that used for the SSM/I can be designed for the LFMR, a total power radiometer can be used. Bandwidths of 300 MHz and 500 MHz are achievable at 5 and 10 GHz and should be compatible with RFI considerations. Ocean scene temperatures would be about 130 K and 150 K leading to RMS noise of 0.44 K and 0.50 K per sample at 5.2 and 10.4 GHz. Sampling both polarizations, with 12-bit precision, will result in 2.7 Kb/s and 10.8 Kb/s data rates at the two instrument conditions, and performance data require a total data rate of 14.0 Kb/s. All of these considerations of sampling, resolution, noise, and data rate for a 5.9-m antenna are summarized in Figure 9.

The 5.9-m antenna, six-channel, Nyquist-sampled system meets the operational requirement in both accuracy and resolution. Since the major expense and weight of the system are required by the antenna, the addition of two dual-polarized radiometers and feeds at 10.4 GHz to a minimum 5.2-GHz system will only marginally increase the weight and power requirements, and the data rate of 14 Kb/s is modest. The dual-frequency, dual-polarized six-channel system provides greater accuracy over a larger range of SST, better surface resolution in warm ocean water regions, a stand-alone system independent of the SSM/I and redundancy in the event of partial system failure.

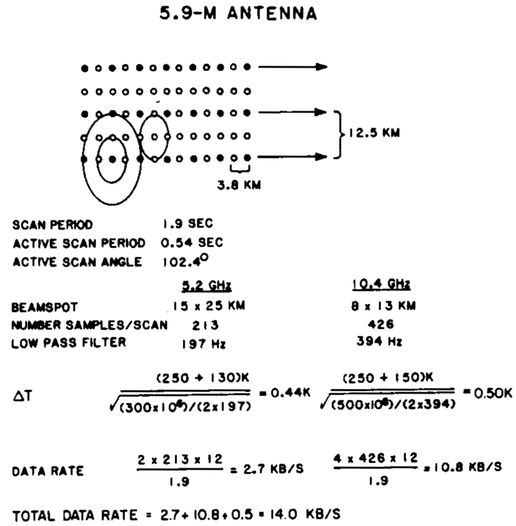

Figure 9. Summary of the Baseline System with a 5.9-Meter Antenna.

Nyquist sampling in both along-and cross-track directions will allow maximum use of the antenna resolution in mapping surface features. It should be noted the data can always be smoothed in post processing to decrease the RMS sample noise and increase retrieval accuracy to the same reduced surface resolution as would have been obtained originally if the data had not been Nyquist sampled. The reverse is not possible. If the scene is not Nyquist sampled, no postprocessing will restore the surface features to the maximum resolution allowed by the antenna.

The baseline system is given in Table 3. The weight, volume, and power requirements given for the antenna and radiometer were obtained from discussions with Harris Corporation and extrapolations from SMMR, SSM/I, and LAMMR.

TABLE 3

BASELINE SYSTEM

Dual Frequency - 5.2 and 10.4 GHz
Dual Polarization - Horizontal and vertical linear polarization
45° Conical Scan (53.1° incidence angle at Earth's surface)
1.9-second period; 102.4° scan width

Antenna - 5.9-m diameter
- 70-lb maximum weight
- 22-ft^3 stowed volume
- 20 watts power
- point accuracy $\pm 0.1^{\circ}$; precision $\pm 0.02^{\circ}$

Resolution - 15 x 25 km - 5.2 GHz
8 x 13 km - 10.4 GHz

Radiometer - Total Power
- Externally Calibrated
- Bandwidth 300 MHz - 5.2 GHz
500 MHz - 10.4 GHz
- ΔT Noise 0.44 K - 5.2 GHz
0.50 K - 10.4 GHz
- 24 lb weight; 24 watts power
- Six Channels (H, V - 5.2 GHz;
2H, 2V - 10.4 GHz)
- Nyquist Sampled; 14.0 Kb/s data rate

Orbit - 833-km Altitude; 98.7 Inclination (Polar Orbit)
- DMSP Constellation
- Three-Year Mission Life

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