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Current and future use of the band near 13.5 GHz by spaceborne active sensors

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1 Introduction and background

1.1 Introduction

The purpose of this Report is to address the continued need of the EESS (active) to access frequencies near 13.5 GHz, the bandwidth requirements, and the scientific feasibility of performing the same measurements in bands other than the band near 13.5 GHz. These requirements will be addressed from the viewpoint of the three major instruments that make use of the band: scatterometers; altimeters; and precipitation radars.

1.2 Background

The World Radiocommunication Conference 2003 (WRC-03) made many changes to the allocations in the 13.75-14 GHz band. Prior to WRC-97, several bands were allocated on a secondary basis to the EESS and the space research service for use by radiolocation stations (i.e. spaceborne active sensors) installed on spacecraft. One of these bands was the 13.4-14 GHz band. WRC-97 decided to allocate the 13.25-13.75 GHz band to the EESS (active) and space research (active) service on a primary basis as a result of the various allocation decisions taken at the Conference with regard to active sensors. However, WRC-97 also saw the need to maintain the 13.75-14 GHz portion of the previous secondary allocation for use by several active sensor instruments that were currently in orbit or were planned and built as their characteristics could not be changed. These provisions were set forth in the Radio Regulations with termination dates of 1 January 2000 and 1 January 2001 for various sensor instruments.

2 Scatterometers

2.1 Use of the band near 13.5 GHz for scatterometers

Scatterometers are radar type devices that measure the near surface vector winds over the oceans. Wind data are critical to determination of regional weather patterns and global climate. No other instrument can provide all weather measurements of the global vector winds.

At the present time, good capability for acquisition of weather data exists over land, but not over the oceans where our only knowledge of surface winds comes from infrequent, and sometimes inaccurate, reports from ships. Since approximately two-thirds of the Earth's surface is covered by oceans, data from scatterometers will play a key role in understanding and predicting complex global weather patterns, ocean circulation, and climate systems.

Two scatterometers that were developed in the United States of America are the NSCAT (NASA scatterometer) that was launched in 1996 on Japan's Advanced Earth Observing Satellite (ADEOS) and the SeaWinds scatterometer which was launched in 1999 on NASA's QuikScat satellite and in 2002 on Japan's ADEOS-II satellite as part of the Earth Observing System (EOS). NSCAT was designed to operate at a center frequency of 13.995 GHz. SeaWinds is a derivative of NSCAT and uses many of the same components, however the center frequency was changed to 13.4 GHz.

2.2 Bandwidth requirements

Existing scatterometer designs near 13.5 GHz use a fixed-frequency, continuous wave pulse to probe the sea surface. The transmitted frequency spectrum is narrow due to the low pulse repetition rate (62 Hz) and large pulse width (5 ms). When the frequency stability of the transmitter and Doppler shifts of frequency are included, the required radio-frequency bandwidth for present-day scatterometers is 1 MHz.

Future scatterometers may use spread spectrum modulation in order to obtain more precise definition of the surface cell where wind measurements are being taken. The bandwidth requirement for these future instruments could be higher than 1 MHz.

2.3 Feasibility of using other bands

Scatterometer measurements, and the derived knowledge about wind vectors, are based on microwave scattering effects over water-surface capillary waves. Measurements at wavelengths comparable to that of the capillary waves caused by water-surface wind interaction is necessary in order to achieve the sensitivity required to measure wind speeds and directions for winds having velocities as low as 3 m/s. Measurements of winds with such velocity are needed to satisfy the requirements for determination of variation in weather and climate. The wavelength in the band near 13.5 GHz is commensurate with the dimensions of the capillary waves produced by low speed winds with the result that the scatterometer is highly sensitive to local winds, especially low wind speeds. At the same time, a scatterometer operating in the band near 13.5 GHz exhibits low sensitivity to non-wind effects such as swells and surface film/surface tension.

Possible alternative bands to the band near 13.5 GHz have been considered. The two bands closest to 13.5 GHz that are currently available to the Earth exploration-satellite service (active) are the 9.5-9.8 GHz and 17.2-17.3 GHz bands. Neither the 9.5-9.8 GHz band nor the 17.2-17.3 GHz band is as desirable for use by scatterometers as the band near 13.5 GHz. This is a consequence of there not being a large body of data on radar scattering from the ocean surface at frequencies other than 13.5 GHz where the Seasat scatterometer operated and 5.3 GHz where the ERS-1 scatterometer operated. Moving to a new band would require redeveloping the algorithm that relates the radar return to the wind speed and direction. The algorithm developed for the 5.3 GHz band required a number of aircraft and tower experiments before launch and more than six months of refinements after the launch of ERS-1. An effort to develop a new algorithm would result in an interruption of the data flow to the science community for the period that is required to gain confidence in the new algorithm. A frequency change will result in some loss of the continuity of the long-term data set for the same reason. Scatterometers operating near 13.5 GHz have higher sensitivity to low wind speeds than scatterometers operating near 5.3 GHz. The low speed wind vectors are important to the studies of the variability of ocean currents. At frequencies above 13.5 GHz, atmospheric attenuation due to water content (e.g. cloud cover and rain) becomes more variable. At 17.2 GHz, it is probably possible to operate a wind scatterometer, however, operating at a frequency of 17.2 GHz or greater would result in degraded performance since the scatterometer would be more sensitive to atmospheric water content and surface film/surface tension effects. At frequencies above 20 GHz, the variability of the atmospheric attenuation would render the instrument useless without other means of measuring the atmospheric variability.

Another factor that makes continued use of the band near 13.5 GHz for scatterometry important is the large amount of data that has been acquired at this frequency over the past 15-20 years. The Seasat scatterometer and the NASA aircraft scatterometer both operated at this frequency, as well as the NSCAT. Continued use of this band for future scatterometers will allow more meaningful cross-comparison of data sets acquired in the future with those from the past. A broader database acquired by instruments operating with similar parameters can be expected to produce a more accurate scientific model.

2.4 Long-term need for operation around 13.5 GHz for scatterometers

There is a long-term requirement to operate spaceborne scatterometers in the band near 13.5 GHz. Scatterometer measurements will be used in operational systems to derive wind speed and wind direction data. These data will be used to measure and predict weather, ocean circulation, and climate, all key factors in management of the environment. As discussed above, only in the band near 13.5 GHz can the required measurement sensitivity be achieved. In addition, only in this band is there an existing database acquired over a period of 15-20 years that can contribute to the value of future scatterometer data interpretation.

The NSCAT scatterometer was constructed to operate at 13.995 GHz.. Protection of NSCAT operations until the year 2000 was ensured by a regulatory provision, which was suppressed by WRC-03. On the other hand, the SeaWinds scatterometer was only in a developmental stage at the time of WRC-97 and its frequency was changed to 13.4 GHz in order to preclude frequency-sharing constraints with respect to the fixed-satellite service. Likewise, any other new scatterometers developed for this frequency range should operate below 13.75 GHz. It is projected that a 100 MHz bandwidth will be needed for future scatterometers in order to improve measurements through the use of alternative modulation techniques. Based on the results of WRC-03, the 13.75-14 GHz band can still be used for scatterometers on a secondary basis, but this use would not be protected from interference by the primary allocated services in this band.

3 Altimeters

3.1 Use of the band near 13.5 GHz for altimeters

A spaceborne radar altimeter is a downward-looking pulsed-radar system mounted on an orbiting spacecraft. They are primarily ocean remote sensing instruments, although there is some interest in the tracking data that they acquire over land and ice surfaces, as implemented on the ERS altimeters. Current and planned radar altimeter missions are designed to meet over ocean requirements; land/ice tracking is a secondary data product.

Altimeters are used to measure range from the satellite to the ocean surface. This very precise height measurement, when combined with very precise orbit determination and corrections for other media effects, provides very accurate global maps of the ocean topography. From this knowledge of topography, the location, speed, and direction of ocean currents worldwide can be calculated. This provides an understanding of ocean circulation and its time variability that is crucial to understanding the Earth’s climate change. Altimeter data can also provide measurements of surface-significant wave height (ocean waves), and backscatter at nadir from which wind speed (but not the wind vector) can be determined. The meteorological forecasting community is interested in the above measurements from any operational system.

Several spaceborne radar altimeters are currently operating in the allocated band near 13.5 GHz such as JASON, ERS and ENVISAT. Radar altimeters are now an operational tool for earth/ocean/air sciences and, as such, will continue to be launched and used long into the future.

The band near 13.5 GHz was chosen long ago based on such considerations as an allocation for radars on spacecraft, wide allocated bandwidth, science objectives, hardware availability, and compatibility with the radiolocation service. The first spaceborne altimeter to use this band was the Skylab S-193 experiment in the early 1970s; since then, there have been many altimeters using this band (GEOS-C, Skylab, GEOSAT, TOPEX-POSEIDON, JASON, ERS-1, ERS-2 and ENVISAT). This use represents a considerable investment in hardware design, hardware development, missions operations, data reduction, software design, scientific analysis, modelling and database construction.

A very large database has been obtained from these altimeters that allow the proper interpretation of current and future altimeter data. These data are very sensitive to the hardware transmission frequencies. A change in operating frequency could negate the applicability of a substantial amount of that existing database. Also, a significant amount of hardware for both inflight use and ground use has been developed in both the United States of America and in Europe that will support future missions. Much of this hardware is designed to operate within the band near 13.5 GHz. Based on the above, the need for altimeters working within this frequency band will extend well into the future. It should be noted that the JASON altimeter alone will operate on multiple satellites through at least 2018.

3.2 Bandwidth requirements

The bandwidths being employed by current and planned altimeters are of the order of 320 MHz (for JASON) to 330 MHz (for ERS). As in any radar system, the precision of the altimeter's height (range) measurement is dependent on the bandwidth used. The JASON altimeter uses pulse compression (chirp full de-ramp stretch) to achieve its fine precision. In JASON, the 320 MHz allows for an effective compressed pulse width of 3.125 ns (46.5 cm basic resolution) before further processing and averaging is done. Ultimately, the precision on the channel near 13.5 GHz is less than 3 cm.

Several studies have been carried out in the ITU-R that examined the need to extend the bandwidth for altimeters to as much as 600 MHz. These studies examined other effects on the accuracy of height measurement including EM-bias, sea-state bias, ionospheric effect, tropospheric effect and orbit determination. It has been concluded that these effects are large enough at the present time to dominate the error budget for the height measurement. A decrease in the 2 to 3 cm height uncertainty achieved by the TOPEX altimeter would not significantly change the total error. Therefore, the bandwidth of 320-330 MHz used by current altimeters will be adequate for missions that are currently envisioned.

In the future, if systematic errors can be significantly reduced by modelling, new instruments, etc. then increasing the bandwidth to as much as 600 MHz may be desirable. Also, in the future, components for altimeters with such wide bandwidths may become much more available and affordable.

There are potential changes to the basic design of altimeters that may produce a need for wider bandwidths: multibeam altimeters, scanning altimeters, and synthetic aperture altimeters fall into this category. Another design that would require a wider bandwidth is for an altimeter that would decorrelate its along-track measurement by use of frequency agility or frequency hopping. Several such designs have been studied in concept but are not currently supported by any flight project.

Another reason that bandwidths greater than 320-330 MHz may be needed is to accommodate both an altimeter and a scatterometer on the same spacecraft.

Based on the results of WRC-97, an allocated bandwidth of 500 MHz is now available since the lower limit of the band allocated for active sensors was extended downward from 13.4 GHz to 13.25 GHz. It is concluded that this allocation could accommodate both present and potential future needs for spaceborne altimeters near 13.5 GHz.

3.3 Feasibility of using other bands

It is not at all desirable to move altimeter operations to other bands. First of all, there is a very large database from altimeters operating in the band near 13.5 GHz. This database has established many facets required for altimetry, such as electromagnetic bias of the sea surface at 13.6 GHz, an exact model of the interaction of the surface features and the RF pulse, atmospheric effects on the RF attenuation and delay, and spacecraft attitude effects on the return waveshape just to name a few. Translating all of this data to another frequency would be a considerable task if it could be done at all without actual flight data. Currently, the JASON altimeter has a secondary frequency (5.3 GHz) for determining ionospheric effects. The following requirements would be applicable to any new frequency chosen:

– at whatever frequency an altimeter was designed to operate, it would require a minimum of 320 MHz of bandwidth to meet current precision requirements. Anything less would give degraded performance which would be unacceptable to the science community;

– the altimeter is intended to be an all weather instrument. It is required to obtain ocean surface data 90% to 95% of the time. At allocated frequencies above 20 GHz, the altimeter measurement would be degraded by both clouds and rain. At a frequency of 13.6 GHz, these effects can be compensated for except during very heavy rains. At 35 GHz, these effects would degrade the altimeter operation. The attenuation and delay changes could not be adequately compensated for and mission objectives could not be met;

– at the lower frequencies (below 5.0 GHz), the hardware would become considerably larger and heavier. To obtain the required signal/noise ratios for precision tracking at lower frequencies would require larger antennas. Since future missions are being directed as smaller, lower cost, and more lightweight systems, this would not be feasible. Other problems, such as inadequate allocated bandwidth, exist in all of the lower frequency bands.

3.4 Continued need for frequencies around 13.5 GHz for altimeters

The only allocated band where altimetric mission requirements can be met is the band near 13.5 GHz where extensive databases have evolved, and where simulators, models and space-qualified hardware have been developed. Future designs can be accommodated since the lower band edge of the existing allocation near 13.5 GHz was shifted down in frequency from 13.4 GHz to 13.25 GHz.

4 Precipitation radars (PR)

4.1 The use of band near 13.5 GHz by PR

Although there are several frequencies allocated to spaceborne radars (e.g. 10 GHz, 13.5 GHz, 17 GHz and 35 GHz), the 13.5 GHz band was selected as the most suitable frequency for precipitation radars, especially single-band radars such as the tropical rain measuring mission (TRMM) PR. The major system requirements which determine the frequency selection are:

a) dynamic range and sensitivity of rainfall measurements,

b) instantaneous field-of-view (IFOV) vs. antenna size, and

c) signal-to-ground clutter ratio.

It is concluded that using the frequencies higher than 13.5 GHz cannot adequately satisfy the requirement a), and that the requirements b) and c) are difficult to meet with the use of the frequencies lower than 13.5 GHz.

The TRMM PR, which was the only spaceborne precipitation radar appearing before the year 2000, was developed by NASDA, Japan. The Global Precipitation Measurement (GPM) mission has also been studied in relation to global hydrological studies (such as GEWEX). For this mission, the 13.5 GHz band is also essential, and it would be the best choice to use the same frequency as TRMM from the cost and schedule point of view and from data continuity considerations.

4.2 Bandwidth requirements

Since the range resolution requirement for the PR is not as severe as other spaceborne radars such as SAR and altimeters, the receiver bandwidth of the precipitation radar is expected to be fairly narrow (at most several megahertz). However, the following facts should be considered:

- *Frequency agility:* In order to achieve high accuracy in rain echo power estimates in a short time, the frequency agility technique, which uses multiple carrier frequencies several megahertz apart from each other and transmits pulses sequentially or alternatively, will be employed. Although the bandwidth of each frequency is the same as that of non-frequency-agility radar, the total bandwidth required is significantly larger. For example, the TRMM PR used two frequencies 6 MHz apart from each other, and each frequency channel had a 3 dB bandwidth of 0.6 MHz. To achieve a sufficient attenuation of 60 dB, a total bandwidth of 12 MHz is required, which is used for the FSS earth station – PR interference study. In general, the number of frequency channels will be limited to three or four, so the total bandwidth required will be between 20-40 MHz depending upon the number of channels and the frequency separation.
- *Pulse compression radar:* For future missions, pulse compression techniques will be employed in order to achieve a higher resolution, a high sensitivity and/or high accuracy in rain echo power estimates. The bandwidth of a pulse-compression radar will be at least several times wider than non-pulse-compression radar, but much less than the bandwidth of spaceborne altimeters.
- *RF bandwidth:* Although the final bandwidth of a radar receiver is determined by a narrow band-pass filter, it is necessary to evaluate the response of the radar receiver to out-of-band interference signals, because the bandwidth of the receiver front-end up to the IF unit at which the narrow band-pass filtering is performed is generally much wider. This can cause the saturation of the receiver front-end. The out-of-band interference signal may also appear in the radar video signal due to the finite attenuation of the band-pass filters.

In summary, the bandwidth of future spaceborne precipitation radars would be at most 30-40 MHz. Consideration of the receiver RF bandwidth, which is generally much wider than the final pass band, is also necessary.

4.3 Feasibility of using other bands

This section considers the frequencies suitable for the TRMM and future space rain measurement missions (based upon the above general discussion). It begins with the case of single-band radar followed by a brief discussion on dual-band radar. The single-band radar is used not only for TRMM but is also considered as a baseline instrument for any follow-on missions.

4.3.1 Measurement dynamic range

Frequencies higher than 17 GHz cannot satisfy the requirement of rain rate measurement dynamic range between about 1 mm/h and 50 mm/h throughout the precipitation layer, which is based on a statistical study of tropical oceanic rainfall. The 35 GHz band is a candidate for the measurement of precipitation at higher latitudes where light rainfall and snow would be dominant, i.e. for measurement of minimum precipitation rates starting around 0.1 mm/h. For tropical rainfall, however, this frequency is too high to obtain a sufficient dynamic range throughout the precipitation layer due to the attenuation within this layer at 35 GHz.

4.3.2 Instantaneous field of view (IFOV)

In order to achieve an IFOV of the order of 5 km from a typical LEO altitude of 500 km, the beamwidth should be about 0.01 rad (~0.6°). That is, the antenna size should be about 100 λ or greater. In the case of the TRMM PR, the antenna size is about 2 m × 2 m^2 (~ 92 λ). This size has been determined from the scientific requirement for the IFOV, the limitation in antenna fabrication accuracy and the size of launching rocket fairing.

To achieve the same IFOV with a lower frequency, a larger antenna size would be required which makes the antenna fabrication and the interfaces with the spacecraft and the rocket more difficult. A conclusion in the TRMM PR feasibility study was that the use of 10 GHz or lower frequencies was technically difficult. Although the situation may change to some extent depending upon the spacecraft and rocket capabilities, the use of frequencies lower than 10 GHz, which requires an antenna of about 5 m or larger, is not feasible for a PR on board a spacecraft.

4.3.3 Signal-to-clutter ratio (*S*/*C*)

The requirement of the *S*/*C* depends upon the minimum rainfall rate that should be measured. There are two types of surface clutters to be considered; one is the clutter caused by antenna side lobes and the other is that caused by range side lobes appearing in the receiver filter output pulse. The latter can be particularly serious in the case of pulse-compression radars. The maximum surface clutter can reach about 60 dB higher that the rain echo corresponding to the 1 mm/h rain, which requires very low antenna side-lobe levels. TRMM PR antenna aperture distribution adopts a Taylor weighting with $SL = -35$ dB to achieve low side-lobe level characteristics. A performance analysis has demonstrated that the PR can achieve the minimum *S*/*C* of about 4 dB for 0.7 mm/h rain rate. If the frequency is lowered to 10 GHz, however, the strength of rain echo relative to surface clutter will decrease by about 6 dB, which will cause loss of rain detection capability at light rain rates.

In summary, the use of frequencies lower than 10 GHz for spaceborne rain radar is difficult from the signal-to-clutter point of view.

4.3.4 Frequencies for dual-band radars

In the case of dual-band radars in order to achieve wider dynamic range and higher accuracy in precipitation retrieval, the selection of radar frequencies becomes more complicated. If the major objective is rain measurement, combinations of 10 and 24 GHz, 13.5 and 35 GHz, and 13.5 and 24 GHz would be desirable. If the objective is to measure both rain and cloud, the frequency selection would be an independent decision process of a single-band rain radar and a single-band cloud radar.

In either case, the frequencies near 13.5 GHz will remain essential for future dual (or multiple) band radars, as it provides global coverage (both tropical and higher latitude rain) as regards the dynamic range of measurement, and is technically feasible with respect to the requirements of spatial resolution and signal clutter.

4.4 Continued need for operation around 13.5 GHz

For the single-band radars, such as the TRMM PR used for tropical rainfall measurement, frequencies near 13.5 GHz are essential because:

- from the measurement dynamic range point of view, 17 GHz and higher are too much attenuated to retrieve the precipitation rates throughout the precipitation layer for the higher precipitation rates;
- a shift in frequency from near 13.5 GHz to near 10 GHz would require significant design changes in the radar to achieve the same resolution and sensitivity, although advances in antenna technology may make the use of lower frequencies feasible for some future missions.

The importance of frequencies near 13.5 GHz also holds for the future dual-band radars. This band has been used for several spaceborne scatterometers and altimeters. The heritage and databases in radar hardware and scattering cross-section data are very useful for continuing development of the spaceborne PR. Since the TRMM PR used the band near 13.5 GHz, many algorithms have been developed for this frequency, which can work only around 13.5 GHz. In addition, an airborne radar at this frequency has been developed by NASA's Jet Propulsion Laboratory and a second radar was developed by Communications Research Laboratory, Japan, for TRMM radar algorithm testing and validation.

Considering the past heritage, databases and on-going efforts, it is essential to keep frequencies near 13.5 GHz for current and future spaceborne PR.

5 Summary and conclusions

This Report has addressed the use of the band near 13.5 GHz, the bandwidth requirements, and the feasibility of using bands other than the band near 13.5 GHz to satisfy mission requirements. This Report also addressed the long-term need to access spectrum near 13.5 GHz from the view point of three major active sensor applications currently operational in the band: scatterometers; altimeters; and precipitation radars (as well as precipitation radars for future applications). Based on these studies, the following are concluded:

– *For scatterometers:*
  – in the late 1990s scatterometers operated at a centre frequency of 13.995 GHz; current scatterometers were modified to operate at 13.402 GHz;
  – current generations of scatterometers require bandwidths up to 1 MHz near the 13.5 GHz band;
  – the use of bands above and below the band near 13.5 GHz that are allocated for use by radars on-board satellites is not an acceptable alternative on the basis of economic investments that have been made to develop databases; data reduction algorithms, and ground and space-qualified equipment; and the optimality of the frequency band for the physical phenomenon being observed; and
  – the use and protection of scatterometer operations centred at 13.995 GHz was required until the year 2000, after which scatterometers operating below 13.75 MHz were implemented.

– *For altimeters:*
  – the first generation of altimeters used bandwidths of approximately 320 MHz centred at 13.60, 13.65 and 13.80 GHz;
  – a bandwidth of up to 600 MHz may be required to accommodate both an altimeter and a scatterometer on the same spacecraft;
  – the use of bands above and below the band near 13.5 GHz band that are allocated for use by radars on board satellites is not an acceptable alternative on the basis of: economic investments that have been made to develop databases; data reduction algorithms, and ground and space-qualified equipment; and the optimality of the frequency band for the physical phenomenon being observed;
  – access to the 13.75-14 GHz band was required through 1997 for TOPEX-POSEIDON and through 2000 for ERS. The altimeters on both JASON and ENVISAT were moved down in frequency so that they do not require access to the 13.75-14 GHz band; and
  – if 330 MHz is the maximum bandwidth required, future altimeters will operate in the band 13.25-13.75 GHz. If missions that require wider bandwidths are identified, they could be accommodated in the band 13.25-13.75 GHz.

- *For precipitation radars:*
  - the most recent generation of precipitation radars were flown on board TRMM at 13.796 GHz and 13.802 (two-channel frequency agility) with a receiver bandwidth of 0.6 MHz, and require a bandwidth of 12 MHz (13.793-13.805 GHz);
  - a bandwidth of up to several tens of MHz may be required to accommodate precipitation radars of future generations;
  - the use of bands above and below the band near 13.5 GHz that are allocated for use by active spaceborne sensors operating in the EESS (active) is not an acceptable alternative on the basis of dynamic range of measurement (for tropical rainfall), IFOV and spacecraft design requirement;
  - considering past heritage, databases and on-going efforts, it is essential to keep frequencies around 13.5 GHz for current and future spaceborne precipitation radars.